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Reprioritization of failures in a silane supply system using an intuitionistic fuzzy set ranking technique

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Abstract Most of the current failure mode, effects, and criticality analysis (FMECA) methods use the risk priority number (RPN) value to evaluate the risk of failure. However, the traditional RPN methodology has been criticized to have several shortcomings. These shortcomings are addressed in this paper. Therefore, an efficient and simplified algorithm to evaluate the risk of failure is needed. This paper proposes a new approach, which utilizes the intuitionistic fuzzy set ranking technique for reprioritization of failures in a system FMECA. The proposed approach has two major advantages: (1) it resolves some of the shortcomings of the traditional RPN method, and (2) it provides an evaluation of the redundancy place, which can assist the designer in making correct decisions to make a safer and more reliable product design. In numerical verification, an FMECA of a silane supply system is presented as a numerical example. After comparing results from the proposed method and two other approaches, this research found that the proposed approach can reduce more duplicate RPN numbers and get a more accurate, reasonable risk ranking.

Keywords Failure mode, effects, and criticality analysis · Risk priority number · Intuitionistic fuzzy sets

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1 Introduction

Failure mode, effects, and criticality analysis (FMECA) is a structural and preventive reliability analysis technology. The purpose of FMECA is to verify possible failure modes and also discuss the reason for failure, which should yield preventive and improved strategies, thereby raising product reliability. From the failure mode, any unit's fault can be discussed and improved. Failure mode has a significant effect on working objectives and should have priority strategies that formulate to solve it and prevent failures.

FMECA was first developed as a formal design methodology in the 1960s by the aerospace industry with their obvious reliability and safety requirements. The American army began using FMECA in the 1970s, and in 1974 it produced the army standard "MIL-STD-1629: procedures for performing a failure mode effects and criticality analysis". In 1980, there also was a second print of MIL-STD-1629A (US Department of Defense Washington, DC 1980). Today, FMEA has been adopted in many places, such as the aerospace, military, automobile, electricity, mechanical, and semiconductor industries. FMECA combines failure mode and effect analysis (FMEA) with criticality analysis (CA). In order to assign limited resources to the most serious risk items, FMEA uses the risk priority number (RPN) methodology to rank and assess the design risk of potential failure modes. The RPN is developed by assigning potential failure modes a rank from 1 to 10, with respect to the severity of the failure mode effect (S), its probability of occurrence (O), and the likelihood of its being detected in later design evaluation tests (D). The RPN is a mathematical product of the three aforementioned factors, calculated as $S \times O \times D \in [1, 1{,}000]$. A failure mode that has a higher RPN is assumed to be more important and is given a higher priority than those with lower RPN values.

The fundamental problem with FMECA is that it attempts to quantify risk without adequately quantifying the factors that contribute to risk. Bowles (2003) proposed an assessment of RPN prioritization in an FMECA. He points out that the traditional RPN, though well documented and easy to apply, is seriously flawed from a technical perspective. In particular cases, the RPN can be misleading. Also, Sankar and Prabhu (2001) proposed a modified approach for prioritization of failure modes in FMEA called risk priority rank (RPR). This technique extends risk prioritization beyond the conventional RPN method. The ranks 1 through 1,000 are used to represent increasing risk of the 1,000 possible severity-occurrence-detection combinations. Wang et al. (1995) proposed an inductive bottom-up risk identification and estimation methodology, combining FMECA and the Boolean representation method (BRM). However, it might be difficult to construct Boolean representation tables for some components of a system, especially during the early conception and design phases, when the relationships between components are unclear or difficult to precisely represent.

Bowles and Pelaez (1995) were the first persons to propose a technique using membership function in FMECA. This approach uses fuzzy logic to directly work with linguistic terms in making criticality assessments. Xu et al. (2002) proposed a fuzzy logic-based FMEA technique and a prototype assessment expert system. It broadens the method by Bowles and Pelaez (1995) from only criticality analysis to failure modes and effects analysis, and it constructs a fuzzy assessment system to perform it. It is useful for constructing an FMEA using the information and an expert's expertise, which often is uncertain or vague in the design phase; in particular, a mechanical system usually has no crisp inputs and outputs, and the relationships between the failure modes and effects are very complex, subjective, and qualitative. In 2003, an improved FMEA methodology, which utilizes the fuzzy rules base and grey relation theory to model the entire system, was presented by Pillay and Wang (2003). However, these methods have the same problem of high duplication rate. Seyed-Hosseini et al. (2006) proposed the decision making trial and evaluation laboratory (DEMATEL) approach for reprioritization of failures in a system. The method is an effective procedure for analyzing the structure and relationships between components of a system or a number of available alternatives. However, the calculation of this approach is very complex and time-consuming. To overcome the aforementioned shortcomings and the shortcomings of the conventional RPN calculation, this paper proposes a new technique for reprioritization of failures in a system FMECA.

This paper is organized into six sections. Section 2 discusses the traditional RPN method and its shortcomings. Section 3 introduces the definition of the intuitionistic fuzzy set and its operations. Section 4 proposes a new approach for FMECA and describes an algorithm of the intuitionistic fuzzy set ranking technique. An example that is drawn from a silane supply system is used with the intuitionistic fuzzy set ranking technique for reprioritization of failures in FMECA. Some comparisons with the listed approaches are then discussed in Sect. 5. The final section makes conclusions based on our findings.

2 RPN methodology

In this section, we will introduce the components of RPN calculation, severity, occurrence, and detection, with respect to the types of scales on which they are measured. We will also point out the shortcomings of the conventional RPN.

2.1 Conventional RPN method

Traditionally, the prioritization of failures for corrective actions is performed by developing an RPN method. The RPN is developed by assigning each potential failure mode a rank from 1 to 10 with respect to the severity of the failure mode effect (*S*), its probability of occurrence (*O*), and the likelihood of its being detected in subsequent design evaluation tests (*D*). Tables 1, 2, and 3 show the

Table 1 Suggested evaluation criteria and ranking system for the severity of effects for a design FMEA

Effect	Criteria: severity of effect	Rank
Hazardous	Failure is hazardous, and occurs without warning. It suspends operation of the system and/or involves noncompliance with government regulations	10
Serious	Failure involves hazardous outcomes and/or noncompliance with government regulations or standards	9
Extreme	Product is inoperable with loss of primary function. The system is inoperable	8
Major	Product performance is severely affected but functions. The system may not operate	7
Significant	Product performance is degraded. Comfort or convince functions may not operate	6
Moderate	Moderate effect on product performance. The product requires repair	5
Low	Small effect on product performance. The product does not require repair	4
Minor	Minor effect on product or system performance	3
Very minor	Very minor effect on product or system performance	2
None	No effect	1

Table 2 Suggested evaluation criteria and ranking system for the occurrence of failure in a design FMEA

Probability of failure	Possible failure rates	Rank
Extremely high: failure almost inevitable	≧1 in 2	10
Very high	1 in 3	9
Repeated failures	1 in 8	8
High	1 in 20	7
Moderately high	1 in 80	6
Moderate	1 in 400	5
Relatively low	1 in 2,000	4
Low	1 in 15,000	3
Remote	1 in 150,000	2
Nearly impossible	≦1 in 1,500,000	1

criteria and ranking system (Ford Motor Company 1988) for these parameters. The RPN value, ranging from 1 to 1,000, is a mathematical product of the three parameters; i.e., $S \times O \times D \in [1,\ 1,000]$. Failure modes with high RPN values are assumed to be more important and are given higher priorities than those with lower RPN values.

2.2 The shortcomings of the conventional RPN

The shortcomings of the conventional RPN have been analyzed extensively by Sankar and Prabhu (2001) and Bowles (2003). The first shortcoming is that RPN elements are not equally weighted with respect to one another in terms of risk. As a result, some (S, O, D) scenarios produce RPN values that are lower than other combinations but potentially more dangerous. For example, the scenario (extreme severity, relatively low rate of occurrence, high detection), with an RPN of $8 \times 4 \times 3 = 96$, is lower than the scenario (minor severity, relatively low rate of occurrence, very remote detection), with an RPN of $3 \times 4 \times 9 = 108$, even thought it should have a higher priority for corrective action.

Table 4 RPN scale statistical data

Incorrect assumption	Actual statistical data
The average of all RPN values is roughly 500	The average RPN value is 166
Roughly 50% of RPN values are above 500 (the median is near 500)	6% of all RPN values are above 500 (the median is 105)
There are 1,000 possible RPN values.	There are 120 unique RPN values

The second shortcoming is that the RPN scale itself has some nonintuitive statistical properties. The initial and correct assumption observation is that the scale starts at 1 and ends at 1,000, often leading to incorrect assumptions in the middle of the scale. Table 4 contains some common faulty assumptions (Sankar and Prabhu 2001). The RPN scale is not continuous. It indeed has many "holes" in the scale. That means that many of the numbers in the range of 1–1,000 cannot be formed from the product of S, O, and D. While it is true that the numbers cover a range from 1 to 1,000, 88% of that range is actually empty; only 120 of the 1,000 numbers can be generated from the product of S, O, and D. Thus, all multiples of 11 (i.e., 11, 22, 33, …, 990) cannot be formed and are hence excluded. Similarly, all multiples of 13, 17, 19, etc. are excluded. 1,000 is the largest number, but 900 is the second largest followed by 810, 800, 729, and 720.

The third shortcoming of the conventional RPN method is that the RPN elements have many duplicate numbers. Because 1,000 numbers are produced from the product of S, O, and D, but only 120 of them are unique, there must be many duplicate numbers. Figure 1 shows the 1,000 RPN numbers that are generated from all possible combinations (Bowles 2003). Note that nearly every RPN value is

Table 3 Suggested evaluation criteria and ranking system for the detection of a cause of failure or failure mode in a design FMEA

Detection	Criteria: likelihood of detection by design control	Rank
Absolute uncertainty	Design control does not detect a potential cause of failure or subsequent failure mode; or there is no design control	10
Very remote	Very remote chance the design control will detect a potential cause of failure or subsequent failure mode	9
Remote	Remote chance the design control will detect a potential cause of failure or subsequent failure mode	8
Very low	Very low chance the design control will detect a potential cause of failure or subsequent failure mode	7
Low	Low chance the design control will detect a potential cause of failure or subsequent failure mode	6
Moderate	Moderate chance the design control will detect a potential cause of failure or subsequent failure mode	5
Moderately high	Moderately high chance the design control will detect a potential cause of failure or subsequent failure mode	4
High	High chance the design control will detect a potential cause of failure or subsequent failure mode	3
Very high	Very high chance the design control will detect a potential cause of failure or subsequent failure mode	2
Almost certain	Design control will almost certainty detect a potential cause of failure or subsequent failure mode	1

Table 5 Combinations of *S*, *O*, and *D* that yield an RPN of 36

S	*O*	*D*	*S*	*O*	*D*	*S*	*O*	*D*
1	4	9	3	2	6	6	1	6
1	6	6	3	3	4	6	2	3
1	9	4	3	4	3	6	3	2
2	2	9	3	6	2	6	6	1
2	3	6	4	1	9	9	1	4
2	6	3	4	3	3	9	2	2
2	9	2	4	9	1	9	4	1

nonunique, some being recycled as many as 24 times. In general, each of the rankings can be formed in several different ways (only six RPN values are formed by a single, unique combination of *S*, *O*, and *D*). For example, as shown in Table 5, 36 can be formed from 21 different combinations of *S*, *O*, and *D*.

The fourth shortcoming of the conventional RPN method is the difficulty with judging evaluation criteria. For example, it may be difficult or even impossible to precisely determine the probability of failure events in FMECA. In addition, it uses available information and an expert's expertise, which is often uncertain or vague in the design phase. In particular, a highly technical system usually has no crisp inputs or outputs, and the relationships between the associated failure modes and effects are very complex, both subjectively and qualitatively.

3 Intuitionistic fuzzy set methodology

In this section, we introduce the definitions and properties of the intuitionistic fuzzy set methodology and seven arithmetic operations of the methodology.

3.1 Definitions and properties of intuitionistic fuzzy sets

Zadeh (1965) proposed fuzzy sets to describe fuzzy phenomena under a specific attribute. A fuzzy set F is a class of objects, along with a grade of membership function. This membership function, $\mu_F(x)$, $x \in X$, assigns a grade membership to each object that ranges between 0 and 1. This single value combines the evidence for $x \in X$ and the evidence against $x \in X$, without indicating how much there is of each value. The notion of an intuitionistic fuzzy set was proposed by Atanassov (Atanassov 1983). An intuitionistic fuzzy set A for a given underlying set E is represented by a pair $\langle \mu_A, v_A \rangle$ of functions $E \rightarrow [0, 1]$. For $x \in E$, $\mu_A(x)$ gives the degree of membership to A, and $v_A(x)$ gives the degree of non-membership; moreover, $0 \leq \mu_A(x) + v_A(x) \leq 1$ must hold.

The uncertainty of x can be described as the differential value of $(1 - v_A(x)) - \mu_A(x)$. If the differential value is small, it means that the value of x is more certain. If the differential value is great, it means that the computation is more uncertain about x. When $1 - v_A(x) = \mu_A(x)$, the intuitionistic fuzzy set A regresses to a fuzzy set. Obviously, when $1 - v_A(x) = \mu_A(x) = 1$ or $1 - v_A(x) = \mu_A(x) = 0$, the intuitionistic fuzzy set A regresses to a crisp set. From the above results, crisp sets and fuzzy sets can be viewed as special cases of intuitionistic fuzzy sets. Therefore, using intuitionistic fuzzy set can describe vague objects in our daily life in more detail. Figure 2 shows an intuitionistic fuzzy set explanation of a real number R.

3.2 Arithmetic operations of intuitionistic fuzzy sets

We define the set operations of intuitionistic fuzzy sets based on definitions presented by Atanassov (1986). For every two intuitionistic fuzzy sets A and B, the following operations and relations are valid:

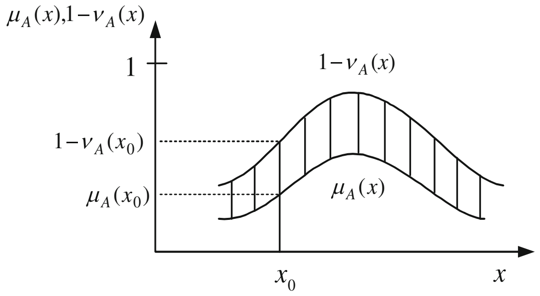
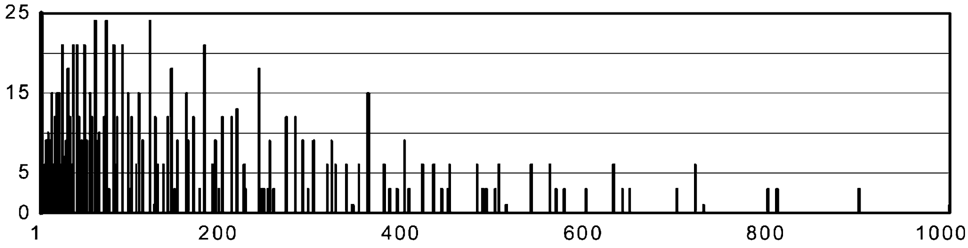


Fig. 2 Intuitionistic fuzzy set explanation of a real number R

Fig. 1 Histogram of RPN values generated from all possible combinations



(1) $A \subset B \text{ iff } (\forall x \in E)(\mu_A(x) \leq \mu_B(x) \& \nu_A(x) \geq \nu_B(x))$;
(2) $A = B \text{ iff } A \subset B \,\&\, B \subset A$;
(3) $\overline{A} = \{\langle x, \nu_A(x), \mu_A(x)\rangle | x \in E\}$;
(4) $A \cap B = \{\langle x, \min(\mu_A(x), \mu_B(x)), \max(\nu_A(x), \nu_B(x))\rangle | x \in E\}$;
(5) $A \cup B = \{\langle x, \max(\mu_A(x), \mu_B(x)), \min(\nu_A(x), \nu_B(x))\rangle | x \in E\}$;
(6) $A + B = \{\langle x, \mu_A(x) + \mu_B(x) - \mu_A(x) \cdot \mu_B(x), \nu_A(x) \cdot \nu_B(x)\rangle | x \in E\}$;
(7) $A \cdot B = \{\langle x, \mu_A(x) \cdot \mu_B(x), \nu_A(x) + \nu_B(x) - \nu_A(x) \cdot \nu_B(x)\rangle | x \in E\}$;

From these equations, it follows directly that $A + B$ is an intuitionistic fuzzy set.

4 Proposed approach

The traditional RPN method, as pointed out in Sect. 2.2, has four main shortcomings: (1) the RPN elements are not equally weighted with respect to one another in terms of risk; (2) the RPN scale itself has some nonintuitive statistical properties; (3) the RPN elements have many duplicate numbers; and (4) there is difficulty in judging evaluation criteria. Therefore, to overcome the aforementioned shortcomings, a new method using an IFS ranking technique to evaluate the orderings of risk for failure problems is proposed in this section.

4.1 The reason to use IFS

Conventional RPN calculation uses crisp values to represents the *S*, *O,* and *D* on a numerical scale from 1 to 10. These rankings are then multiplied to give the RPN. However, it often is hard to give a direct and correct numerical value of the *S*, *O,* and *D* by crisp values. In many real-life cases, the decision data of human judgments with preferences are vague, so that the traditional ways of using crisp values are inadequate. To deal with the vagueness of human thought and expression in making decisions, the fuzzy set theory is very helpful. Therefore, the parameter is being described as fuzzy variables, and this result is a more realistic and flexible reflection of the real situation.

4.2 Rank risk of failure operation using the IFS ranking technique

In terms of implementing arithmetic operations of the intuitionistic fuzzy set in FMECA, we use the vague fault-tree analysis definition proposed by Chang et al. (2006) to find degrees of influence of every unit as follows. Figure 3 shows a triangle intuitionistic fuzzy set explanation of a *T* unit fault.

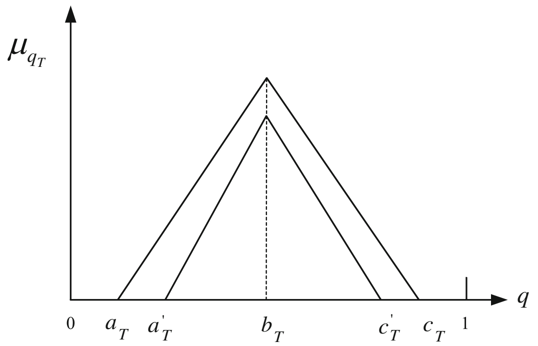


Fig. 3 Triangle intuitionistic fuzzy set is an explanation of the *T* unit fault

Definition 4.1. Influence degrees for removing the *i*th unit Let q_{T_i} represent that q_T is not included the *i*th unit of a failure interval (delete the *i*th unit). *V* denotes the difference between q_T and q_{T_i} *The larger value of V* represents the *i*th unit has a greater influence on; then

$$V(q_T, q_{T_i}) \equiv (a_T - a_{T_i}) + (a'_T - a'_{T_i}) + (b_T - b_{T_i}) + (c'_T - c'_{T_i}) + (c_T - c_{T_i}) \tag{1}$$

where $q_T = (a_T, a'_T, b_T, c'_T, c_T)$ and $q_{T_i} = (a_{T_i}, a'_{T_i}, b_{T_i}, c'_{T_i}, c_{T_i})$.

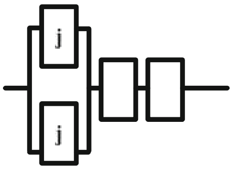
When a product's safety standard is high, the prediction's result should be relied on. However, if the result does not match the standard, the designer should improve its design by using redundant place analysis. Redundant place analysis can assist the designer in making correct decisions to make a more reliable product design with better safety. For example, suppose that the *j*th unit has the lowest reliability, as shown in Fig. 4; adding a redundant *j*th unit could improve the system's reliability.

Definition 4.2. Influence degree for adding the *j*th unit *Let* R_{T_j} *represent that* R_T *adds the redundant jth unit of reliability. U denotes the difference between* R_T *and* R_{T_j}*. The larger of U represents adding the redundant jth unit, which can increase the reliability on* R_T*; then*

$$U(R_T, R_{T_j}) \equiv (a_T - a_{T_j}) + (a'_T - a'_{T_j}) + (b_T - b_{T_j}) + (c'_T - c'_{T_j}) + (c_T - c_{T_j}) \tag{2}$$

where $R_T = (a_T, a'_T, b_T, c'_T, c_T)$ *and* $R_{T_j} = (a_{T_j}, a'_{T_j}, b_{T_j}, c'_{T_j}, c_{T_j})$.

Fig. 4 Reliability block diagram of adding a redundant *j*th unit



4.3 The procedure of the proposed approach

According to the definitions in Sect. 3, we propose a model, consisting of nine steps, for risk priority analysis. In Sect. 5, an example that is drawn from a silane supply system is used for illustrative purposes to demonstrate our proposed approach. The nine steps are described as follows.

Step 1 Verify the system's compound and working purpose

Conduct the first step of FMECA, which should allow us to understand the contents, system compound, and the product's working purpose.

Step 2 Determine analysis level

The normal analysis is distinguished by five layers: system, detail system, model, module, and unit.

Step 3 Establish system of reliability block diagram

A reliability block diagram can explain units' relationships in parallel and series.

Step 4 List potential failure modes

Based on historical data and past experiences, list the failure modes of each FMECA member.

Step 5 Establish the FMECA table

Arrange failure mode content in an FMECA table. List the reasons of failure mode occurrence.

Step 6 Define system unit fault interval

Unit fault can cause the breakdown of the whole system. Define the triangle intuitionistic fuzzy set for each unit fault according to the experts' experiences.

Step 7 The priority for assessing fault risk

By Definition 4.1, we delete the ith unit from the reliability block diagram and calculate $V(q_T, q_{T_i})$, $\forall i$. Use V to rank the influential power of each unit for the system.

Step 8 Assessing redundant systems

By Definition 4.2, we add the redundant jth unit to the reliability block diagram and calculate $U(R_T, R_{T_j})$, $\forall j$. Use U to rank the increasable reliability for the whole system.

Step 9 Analyze the results and provide suggestions.

5 An illustrative example

In this section, an illustrative example of a silane supply system in a TFT-LCD process is presented in order to demonstrate the procedure that is proposed in this paper. The TFT-LCD process uses various kinds of highly responsive and dangerous materials with a high risk of ignition, explosion, and toxicity. Silane is a chemical compound, which has the chemical formula SiH_4 that is required in the TFT-LCD process. The silane supply system has no color, reacts with air, has a suffocating effect, is readily combustible in the presence of air, and releases uncrystallized SiO_2 smoke. Under high temperature or fire, if the pressure regulator of the steel bottle contains silane malfunctions, it can cause an explosion.

The FMECA of a silane supply system is shown in Table 6. The data is from a midsized manufacturing factory located in Hsinchu Science Park in Taiwan (Wang 2006). The reliability block diagram of a silane supply system accident is shown in Fig. 5.

5.1 Conventional RPN method

The conventional RPN method consists of rating the potential failures from 1 to 10 with respect to their severity, probability of occurrence, and detection and multiplying the three numbers together. The RPN value is used to prioritize the actions. The RPN of the silane supply system shown in Table 7.

5.2 Fuzzy RPN method

Bowles et al. (Bowles and Pelaez 1995) were the first to propose the fuzzy RPN method. This approach uses fuzzy logic for directly working with linguistic terms in making criticality assessments. In fuzzy rule base analysis, the linguistic variable is determined to be the probability of occurrence (O), the severity (S), and the detection (D). Each of the three linguistic variables is described by five linguistic terms: *Remote*, *Low*, *Moderate*, *High,* and *Very High*. The interpretations of these linguistic terms are given in Table 8 (Pillay and Wang 2003). Using Table 8 as a guide, users can rank the severity, occurrence, and detection for the failure mode on a scale, such as those in Figs. 6, 7, and 8.

The support value for each of these linguistic terms is determined by taking the weighted average of the support values given by each expert. Hence, the support values for the linguistic terms describing the risk can be summarized as: Low (0.5), Fairly Low (1.5), Moderate (2.5), Fairly

Table 6 The FMECA of the silane supply system

No.	Potential failure mode	Cause of failure	Severity	Occurrence	Detection
A01	Steel bottle operation (FM1)	Bottle variety error (CF1)	6	4	5
A02	Steel bottle operation (FM1)	Turn over (CF2)	6	4	7
A03	Steel bottle operation (FM1)	Hit (CF3)	6	7	7
A04	Steel bottle operation (FM1)	Took apart wrong gas bottle (CF4)	7	5	6
A05	Nitrogen purge (FM2)	Manual valve close wrong (CF5)	5	6	6
A06	Nitrogen purge (FM2)	Gas valve broken (CF6)	5	4	6
A07	Nitrogen purge (FM2)	Not enough nitrogen (CF7)	5	4	4
A08	Nitrogen purge (FM2)	Fix pressure valve broken (CF8)	4	3	6
A09	Nitrogen purge (FM2)	Pipe loose (CF9)	5	2	5
A10	Valve (FM3)	Spring lost efficacy (CF10)	5	4	6
A11	Valve (FM3)	Loosened valve (CF11)	6	2	4
A12	Steel bottle connection (FM4)	Broken (CF12)	5	3	4
A13	Steel bottle connection (FM4)	Not tightened enough (CF13)	5	4	4
A14	Gasket (FM5)	Low quality (CF14)	6	5	5
A15	Gasket (FM5)	Installation error (CF15)	6	4	4
A16	Gasket (FM5)	Not replaced (CF16)	5	4	3
A17	Fix pressure valve (FM6)	Valve adjustment error (CF8)	4	4	6
A18	Fix pressure valve (FM6)	Wrong setting (CF17)	4	4	5
A19	Exhaust (FM7)	No action (CF18)	7	5	4
A20	Exhaust (FM7)	Insufficient exhaust displacement (CF19)	4	2	7
A21	Sprinkler (FM8)	No action (CF18)	6	3	4
B01	Pumping line (FM9)	Dry pump shut down (CF20)	6	4	5
B02	Pumping line (FM9)	Pipe line blocked (CF21)	6	8	7
B03	Pumping line (FM9)	Bellow, check value burn out (CF22)	5	5	5
B04	Pumping line (FM9)	Loosened valve (CF11)	5	6	7
C01	Absorbable pot (FM10)	Absorbable pot saturated (CF23)	4	6	3
C02	Local scrubber (FM11)	Wrong setting (CF17)	4	2	3
C03	Local scrubber (FM11)	Pipe line blocked, pump broken (CF21)	3	6	2
C04	Local scrubber (FM11)	Exhaust line blocked (CF24)	4	2	3
C05	Local scrubber (FM11)	Not enough cold air and too much exhaust gas (CF25)	4	2	3
C06	Local scrubber (FM11)	O2 testing failure (CF26)	4	2	3

High (6.5), and High (8.5). These results are then defuzzified using the weighted mean of maximum (WMoM) method (Bowles and Pelaez 1995) to obtain a ranking, as shown in Table 9. For the detailed WMoM method, please refer to Bowles and Pelaez's paper (Bowles and Pelaez 1995).

5.3 Proposed method

The triangle intuitionistic fuzzy set of each unit fault in silane supply system failure is obtained from a domain expert based on his experience, as shown in Table 10.

Ranking risk according to the relative importance of each unit fault allows the users to assign limited resources to the most serious risk items. We calculated the difference in intuitionistic fuzzy failure between the overall "silane supply system accident" and deleted the nodes in the second level (denoted as $V(q_T, q_{T_i})$, $i = A1, A2, A3, \ldots, C06$), based on Definition 4.1, and the results are shown in Table 11.

In order to examine the silane supply system failure's redundancy place, we use Definition 4.2 to calculate the increase of system reliability by each unit's redundancy place. The results are organized in Table 11.

According to the results shown in Table 11, if B02's redundancy increases, the silane supply system's reliability can rise from $\langle[(0.999094484, 0.999431880, 0.999737564); 0.7], [(0.998986982, 0.999431880, 0.999857941); 0.8]\rangle$ to $\langle[(0.999182004, 0.999497543, 0.999780053); 0.7], [(0.998998955, 0.999497543, 0.999870240); 0.8]\rangle$.

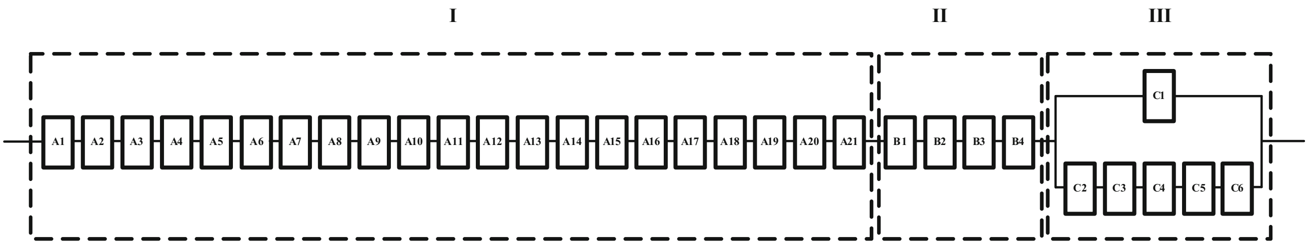


Fig. 5 The reliability block diagram of a silane supply system accident

Table 7 The RPN of the silane supply system

No.	Potential failure mode	Cause of failure	Severity	Occurrence	Detection	RPN
A01	FM1	CF1	6	4	5	120
A02	FM1	CF2	6	4	7	168
A03	FM1	CF3	6	7	7	294
A04	FM1	CF4	7	5	6	210
A05	FM2	CF5	5	6	6	180
A06	FM2	CF6	5	4	6	120
A07	FM2	CF7	5	4	4	80
A08	FM2	CF8	4	3	6	72
A09	FM2	CF9	5	2	5	50
A10	FM3	CF10	5	4	6	120
A11	FM3	CF11	6	2	4	48
A12	FM4	CF12	5	3	4	60
A13	FM4	CF13	5	4	4	80
A14	FM5	CF14	6	5	5	150
A15	FM5	CF15	6	4	4	96
A16	FM5	CF16	5	4	3	60
A17	FM6	CF8	4	4	6	96
A18	FM6	CF17	4	4	5	80
A19	FM7	CF18	7	5	4	140
A20	FM7	CF19	4	2	7	56
A21	FM8	CF18	6	3	4	72
B01	FM9	CF20	6	4	5	120
B02	FM9	CF21	6	8	7	336
B03	FM9	CF22	5	5	5	125
B04	FM9	CF11	5	6	7	210
C01	FM10	CF23	4	6	3	72
C02	FM11	CF17	4	2	3	24
C03	FM11	CF21	3	6	2	36
C04	FM11	CF24	4	2	3	24
C05	FM11	CF25	4	2	3	24
C06	FM11	CF26	4	2	3	24

5.4 Comparisons and discussion

The results obtained for the FMECA using the proposed approach are collated with the results obtained from the conventional RPN method and are presented in Table 12. From Table 12, we can see that the RPN values of units A04 and B04 are both 210. From Table 7, the values of *S*, *O*, and *D* are 7, 5, and 6 for unit A04 and 5, 6, and 7 for unit B04; hence an RPN of 210 is obtained. Although the RPN values for both units are the same, the risk levels are different. This difference can be obviously identified when the intuitionistic fuzzy set ranking technique is applied. The

Table 8 Interpretations of the linguistic terms

Linguistic term	Probability of occurrence	Severity	Detection
Remote	It would be very unlikely for these failures to be observed even once	A failure that has no effect on system performance; thus, operator probably will not notice	Remains undetected until the system performance degrades to the extent that the task will not be completed
Low	Likely to occur once, but unlikely to occur more frequently	A failure that would cause slight annoyance to the operator, but would cause no deterioration to the system	Remains undetected until system performance is severely reduced
Moderate	Likely to occur more than once	A failure that would cause a high degree of operator dissatisfaction or that causes noticeable but slight deterioration in system performance	Remains undetected until system performance is affected
High	Nearly certain to occur at least once	A failure that causes significant deterioration in system performance and/or leads to minor injuries	Remains undetected until inspection or test is carried out
Very high	Nearly certain to occur several times	A failure that would seriously affect the ability to complete the task or cause damage, serious injury, or death	Failure remains undetected; such a defect would almost certainly be detected during inspection or test

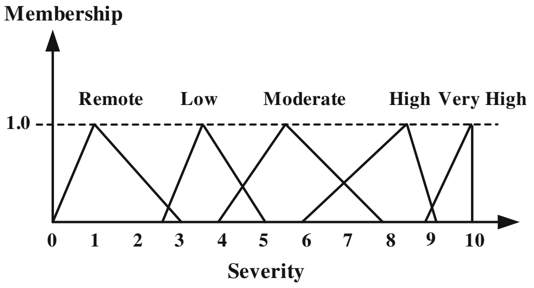


Fig. 6 The membership value of severity

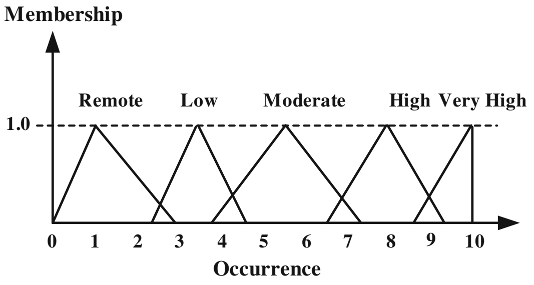


Fig. 7 The membership value of occurrence

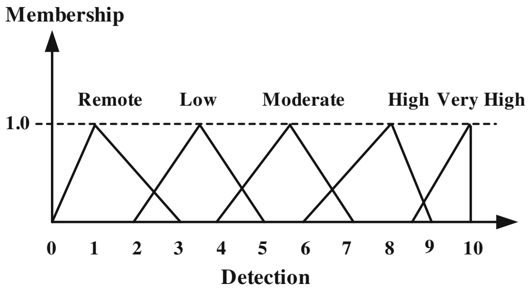


Fig. 8 The membership value of detection

results of our proposed method show that unit B04 has a higher priority compared with unit A04. However, the conventional RPN method puts these two units at the same priority.

On the other hand, the ranking that is produced by the fuzzy RPN method does not differentiate the units with the same linguistic terms that describe the factor that is considered. For example, *S*, *O*, and *D* for units A01, A15, and B01 are assigned as Moderate High, Low Moderate, and Low Moderate, respectively, and the defuzzified ranking is 2.241 for all three units (Table 9). Although the RPN for all three units are the same, the risk levels are different. This difference can be obviously identified when the intuitionistic fuzzy set ranking technique is applied. The results of the proposed method show that unit B01 has a higher priority compared with units A01 and A15. However, the fuzzy RPN method puts these three units at the same priority. The reprioritization that is obtained from the intuitionistic fuzzy set ranking technique in terms of criteria is:

B02 > A03 > B04 > A04 > A05 > A02 > A14 >
A19 > B03 > B01 > A01 > A10 > A06 >
A15 > ··· > C06,

which is different from the conventional RPN prioritization—i.e.,

B02 > A03 > A04,
B04 > A05 > A02 > A14 > A19 > B03 > A01, A06,
A10, B01 > A15, A17 > ··· > C06,

and also is different from the fuzzy RPN prioritization—i.e.,

Table 9 FMEA using the fuzzy RPN method

No.	Severity	Occurrence	Detection	Risk	Defuzzified ranking
A01	Moderate High	Low Moderate	Low Moderate	0.496 FL, 0.086 M, 0.081 FH	2.241
A02	Moderate High	Low Moderate	Moderate High	0.173 FL, 0.496 M, 0.0810 FH	2.701
A03	Moderate High	Moderate High	Moderate High	0.200 M, 0.296 FH, 0.081 H	5.394
A04	Moderate High	Moderate	Moderate High	0.373 M, 0.469 FH	4.728
A05	Low Moderate	Moderate	Moderate High	0.064 FL, 0.688 M	2.415
A06	Low Moderate	Low Moderate	Moderate High	0.496 FL, 0.086 M	1.648
A07	Low Moderate	Low Moderate	Low Moderate	0.064 L, 0.496 FL, 0.086 M	1.534
A08	Low Moderate	Low	Moderate High	0.625 FL, 0.038 M	1.557
A09	Low Moderate	Remote	Low Moderate	0.064 L, 0.495 FL	1.386
A10	Low Moderate	Low Moderate	Moderate High	0.496 FL, 0.086 M	1.648
A11	Moderate High	Remote	Low Moderate	0.081 L, 0.495 FL	1.359
A12	Low Moderate	Low	Low Moderate	0.064 L, 0.625 FL	1.407
A13	Low Moderate	Low Moderate	Low Moderate	0.064 L, 0.496 FL, 0.086 M	1.534
A14	Moderate High	Moderate	Low Moderate	0.610 M, 0.081 FH	2.969
A15	Moderate High	Low Moderate	Low Moderate	0.496 FL, 0.086 M, 0.081 FH	2.241
A16	Low Moderate	Low Moderate	Remote Low	0.064 L, 0.496 FL, 0.086 M	1.534
A17	Low Moderate	Low Moderate	Moderate High	0.084 FL, 0.084 M	2.000
A18	Low Moderate	Low Moderate	Low Moderate	0.496 FL, 0.086 M	1.648
A19	Moderate High	Moderate	Low Moderate	0.469 M, 0.097 FH	3.186
A20	Low Moderate	Remote	Moderate High	0.173 L, 0.495 FL, 0.110 M	1.419
A21	Moderate High	Low	Low Moderate	0.625 FL, 0.081 M	1.615
B01	Moderate High	Low Moderate	Low Moderate	0.496 FL, 0.086 M, 0.081 FH	2.241
B02	Moderate High	High	Moderate High	0.173 M, 0.507 FH, 0.081 H	5.804
B03	Low Moderate	Moderate	Low Moderate	0.064 FL, 0.610 M	2.405

Table 9 continued

No.	Severity	Occurrence	Detection	Risk	Defuzzified ranking
B04	Low Moderate	Moderate	Moderate High	0.064 FL, 0.507 M	2.388
C01	Low Moderate	Moderate	Remote Low	0.710 FL, 0.110 M	1.634
C02	Low Moderate	Remote	Remote Low	0.495 L, 0.110 FL	0.682
C03	Remote Low	Moderate	Remote Low	0.020 L, 0.343 FL	1.445
C04	Low Moderate	Remote	Remote Low	0.495 L, 0.110 FL	0.682
C05	Low Moderate	Remote	Remote Low	0.495 L, 0.110 FL	0.682
C06	Low Moderate	Remote	Remote Low	0.495 L, 0.110 FL	0.682

Table 10 The possible range of elementary item failures

Failure possibility	a_i	a_i'	b_i	c_i'	c_i	$1 - v_A(x)$	$\mu_A(x)$
A01	2.27E-07	8.27E-07	8.27E-06	2.27E-05	8.27E-05	0.9	0.8
A02	0.87E-05	0.87E-05	2.87E-05	4.87E-05	4.87E-05	1	1
A03	1.92E-05	2.92E-05	3.92E-05	4.92E-05	5.92E-05	1	0.9
A04	1.34E-05	1.34E-05	3.34E-05	5.34E-05	5.34E-05	1	0.9
A05	1.37E-06	5.37E-06	1.37E-05	5.37E-05	8.37E-05	0.8	0.7
A06	0.28E-05	1.28E-05	2.28E-05	3.28E-05	4.28E-05	0.9	0.8
A07	0.94E-05	0.94E-05	1.94E-05	2.94E-05	2.94E-05	1	0.9
A08	0.05E-05	0.92E-05	1.72E-05	2.52E-05	3.39E-05	0.9	0.8
A09	0.10E-05	0.10E-05	1.19E-05	2.20E-05	2.20E-05	0.9	0.9
A10	0.29E-05	0.29E-05	2.29E-05	4.29E-05	4.29E-05	1	1
A11	1.02E-06	1.52E-06	1.02E-05	1.87E-05	1.98E-05	0.8	0.7
A12	0.56E-05	0.56E-05	1.56E-05	2.56E-05	2.56E-05	1	0.9
A13	0.50E-05	0.50E-05	1.93E-05	3.30E-05	3.30E-05	1	1
A14	0.48E-05	1.48E-05	2.48E-05	3.48E-05	4.48E-05	0.9	0.8
A15	0.25E-05	0.25E-05	2.11E-05	4.25E-05	4.25E-05	0.9	0.7
A16	3.75E-06	5.75E-06	1.75E-05	2.25E-05	3.15E-05	0.9	0.9
A17	1.12E-05	1.12E-05	2.12E-05	3.12E-05	3.12E-05	0.9	0.8
A18	0.46E-05	0.96E-05	1.96E-05	2.96E-05	3.46E-05	0.9	0.7
A19	0.32E-05	1.32E-05	2.32E-05	3.32E-05	4.32E-05	0.9	0.9
A20	0.28E-05	0.67E-05	1.38E-05	2.09E-05	2.48E-05	0.8	0.7
A21	0.24E-05	1.24E-05	1.74E-05	2.24E-05	3.24E-05	0.9	0.9
B01	0.50E-05	1.05E-05	2.30E-05	3.55E-05	4.10E-05	0.8	0.7
B02	1.23E-05	4.25E-05	6.57E-05	8.76E-05	1.20E-04	0.9	0.8
B03	0.31E-05	1.31E-05	2.31E-05	3.31E-05	4.31E-05	0.9	0.7
B04	1.53E-05	1.53E-05	3.53E-05	5.53E-05	5.53E-05	0.8	0.7
C01	2.56E-05	2.56E-05	3.44E-05	4.87E-05	4.87E-05	0.9	0.8
C02	0.85E-06	0.85E-06	1.35E-05	2.71E-05	2.71E-05	0.9	0.7
C03	2.59E-05	2.59E-05	4.59E-05	6.59E-05	6.59E-05	0.9	0.8
C04	0.59E-05	0.89E-05	1.39E-05	1.89E-05	2.69E-05	0.8	0.8
C05	0.50E-05	0.50E-05	1.33E-05	2.10E-05	2.10E-05	1	0.9
C06	0.52E-05	0.92E-05	1.22E-05	1.52E-05	1.92E-05	0.9	0.8

Table 11 Values of the $V(q_T, q_{T_i})$ and $U(R_T, R_{T_j})$

No.	$V(q_T, q_{T_i})$	$U(R_T, R_{T_j})$
A01	0.000114622	0.000114614
A02	0.000143392	0.000143387
A03	0.000195871	0.000195863
A04	0.000166879	0.000166871
A05	0.000157706	0.000157696
A06	0.000113914	0.000113909
A07	0.000096930	0.000096928
A08	0.000085931	0.000085929
A09	0.000057851	0.000057850
A10	0.000114407	0.000114403
A11	0.000051196	0.000051196
A12	0.000077940	0.000077939
A13	0.000095227	0.000095223
A14	0.000123907	0.000123904
A15	0.000111008	0.000111005
A16	0.000080937	0.000080935
A17	0.000105925	0.000105923
A18	0.000097926	0.000097924
A19	0.000115913	0.000115909
A20	0.000068946	0.000068945
A21	0.000086935	0.000086933
B01	0.000114922	0.000114910
B02	0.000219972	0.000219944
B03	0.000115413	0.000115409
B04	0.000176375	0.000176370
C01	0.000000019	0.000000019
C02	0.000000002	0.000000002
C03	0.000000007	0.000000007
C04	0.000000002	0.000000002
C05	0.000000001	0.000000001
C06	0.000000001	0.000000001

$$\mathrm{B02} > \mathrm{A03} > \mathrm{A04} > \mathrm{A19} > \mathrm{A14} > \mathrm{A02} > \mathrm{A05} > \mathrm{B03} > \mathrm{B04} > \mathrm{A01},\ \mathrm{A15},\ \mathrm{B01} > \cdots > \mathrm{C02},\ \mathrm{C04},\ \mathrm{C05},\ \mathrm{C06}.$$

The results shown in Table 12 indicate that the conventional RPN method yields 11 unique RPN values among 31 items when the risk of failure in a silane supply system is ranked. These elements are formed by a single combination of *S*, *O*, and *D*. We then find that the fuzzy RPN method results in 18 unique RPN values. This paper focuses on system reliability combined with the intuitionistic fuzzy set ranking technique applied to FMECA. The proposed intuitionistic fuzzy set ranking RPN method is compared with both the conventional RPN and the fuzzy RPN methods. The intuitionistic fuzzy set ranking RPN method yields 27 unique RPN values among 31 items. This shows that a more accurate ranking can be achieved by applying our proposed intuitionistic fuzzy set ranking RPN technique to FMECA.

6 Conclusion

This paper has proposed a novel technique for the reprioritization of failure modes in FMECA. It is useful when conducting FMECA using available information and an expert's expertise, which is often uncertain or vague in the design phase. In particular, a highly technical system usually has no crisp inputs or outputs, and the relationships between the associated failure modes and effects are very complex, both subjectively and qualitatively. This paper focuses on system reliability and proposes an intuitionistic fuzzy set ranking technique specifically to reduce the occurrence of duplicate RPN numbers. The proposed method can resolve some inherent shortcomings of the conventional RPN method. It provides the designer with a systematic approach to identify high-risk areas and attain explicit levels of safety by identifying and implementing ways to reduce the hazard frequency of occurrence and the extent of the respective consequences.

Moreover, a silane supply system is employed as an illustrative example to compare the results obtained from using the conventional RPN method, the fuzzy RPN method proposed by Bowles and Pelaez (1995), and the proposed method. We find that our proposed approach is very effective in RPN prioritization. The proposed method provides the analyst with the flexibility to decide which factor is more important to the analysis, and the outcome of the analysis will provide valuable information for the decision-making process. The proposed approach also provides an evaluation of redundancy place, which can assist the designer in making correct decisions to make a safer and more reliable product design.

The advantages of the proposed intuitionistic fuzzy set ranking technique are as follows:

(1) The proposed method can reduce the occurrence of duplicate RPN numbers.
(2) The failure information in FMECA is described as intuitionistic fuzzy variables, which are more realistic and flexible in reflecting real situations.
(3) The results of the analysis provide more accurate and effective information for the decision-making process.
(4) The proposed approach also provides an evaluation of redundancy place, which can assist the designer in making correct decisions to make a safer and more reliable product design.

Table 12 Ranking comparison

No.	RPN	Fuzzy RPN	Intuitionistic fuzzy	Ranking RPN	Ranking fuzzy RPN	Ranking intuitionistic fuzzy
A01	120	2.241	0.000114622	9	10	11
A02	168	2.701	0.000143392	5	6	6
A03	294	5.394	0.000195871	2	2	2
A04	210	4.728	0.000166879	3	3	4
A05	180	2.415	0.000157706	4	7	5
A06	120	1.648	0.000113914	9	12	13
A07	80	1.534	0.000096930	11	16	17
A08	72	1.557	0.000085931	12	15	20
A09	50	1.386	0.000057851	15	20	24
A10	120	1.648	0.000114407	9	12	12
A11	48	1.359	0.000051196	16	21	25
A12	60	1.407	0.000077940	13	19	22
A13	80	1.534	0.000095227	11	16	18
A14	150	2.969	0.000123907	6	5	7
A15	96	2.241	0.000111008	10	10	14
A16	60	1.534	0.000080937	13	16	21
A17	96	2.000	0.000105925	10	11	15
A18	80	1.648	0.000097926	11	12	16
A19	140	3.186	0.000115913	7	4	8
A20	56	1.419	0.000068946	14	18	23
A21	72	1.615	0.000086935	12	14	19
B01	120	2.241	0.000114922	9	10	10
B02	336	5.804	0.000219972	1	1	1
B03	125	2.405	0.000115413	8	8	9
B04	210	2.388	0.000176375	3	9	3
C01	72	1.634	0.000000019	12	13	26
C02	24	0.682	0.000000002	18	22	28
C03	36	1.445	0.000000007	17	17	27
C04	24	0.682	0.000000002	18	22	28
C05	24	0.682	0.000000001	18	22	29
C06	24	0.682	0.000000001	18	22	29

The intuitionistic fuzzy data are from the $V(q_T, q_{T_i})$ column shown in Table 11

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