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ORIGINAL ARTICLE

Assessment of structural risks using the fuzzy weighted Euclidean FMEA and block diagram analysis

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Abstract

Failure mode and effects analysis (FMEA) is a risk assessment method in products, processes, or systems for appropriate corrective actions. Although FMEA techniques are used in various industries, it has been criticized for several shortcomings. First, conventional FMEA entirely depends on qualitative evaluation. Second, traditional FMEA does not consider the functional influence between components of a system, meaning that it cannot be applied to systems-complicated influence relationships. Third, risk priority number (RPN) in traditional FMEA, which is evaluated in crisp values of severity (S), occurrence rate (O), and the probability of not detecting the failure (D), can lead to a RPN distortion problem in which contradictory interpretations of RPN result from, respectively, reasonable risk factors. In order to overcome these shortcomings, this paper proposes a new risk assessment method using importance risk priority number (IRPN). The IRPN, which is composed of structural and relational importance, is attained by taking a three-dimensional geometric approach to fuzzy weighted Euclidean (FWE) FMEA and risk block diagram analysis. The proposed risk assessment method is applied in the numerical example and empirical example of the thin film transistor liquid crystal display (TFT-LCD) products. Comparison results with previous FMEA methods show that the proposed method not only overcomes the shortcomings of previous FMEA methods, such as the RPN distortion, but is also useful for assessing the structural risks that involve functional influence between risks. In addition, a three-dimensional approach based on fuzzy logic is more analytical and applicable than previous methods.

Keywords Failure mode and effect analysis · Fuzzy weighted Euclidean · Block diagram analysis · Relational importance · Structural importance

1 Introduction

Failure mode and effects analysis (FMEA) is a systematic, proactive method for evaluating a system's safety and reliability. FMEA was developed as a formal design methodology by the aerospace industry in the 1960s [1]. In the 1980s, the procedures for performing a well-designed FMEA were described in US military standard MIL-STD-1629A [2]. Recently, FMEA has been widely adopted in many industries such as aerospace, military, automobile, and electricity.

In conventional FMEA, a risk priority number (RPN) is applied to assess a system's potential failure mode. RPN is commonly calculated by the multiplication of three risk factors—the severity of the failure (S), the failure occurrence rate (O), and the probability of not detecting the failure (D). Each risk factor is evaluated using a 10-point scale, and failure modes with high RPN values are more important and have a higher risk priority than those with lower RPN values. Failure modes can be ranked in accordance with the RPN score, and then, proper corrective or preventive actions can be taken [3]. However, the previous RPN method has been criticized for multiple shortcomings, the most egregious of which are summarized below [4]:

- FMEA has not considered relative importance among S, O, and D; therefore, it can cause RPN distortion problems. RPN distortion is phenomenon in which contradictory

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interpretations result from, respectively, reasonable risk factors. It is because the three risk factors are of the same importance or equally weighted with respect to failure mode. Thus, it can cause an erroneous assessment of RPN values, which may actually be lower than other combinations of failure modes despite these others being potentially more serious. For example, when failure mode 1 with an RPN of 54 ($9 \times 3 \times 2$) is a lower risk priority than failure mode 2 with RPN 120 ($4 \times 5 \times 6$), failure mode 2 has a higher priority for appropriate corrective actions despite the high severity of the consequences for failure in failure mode 1.

- Different sets of S, O, and D ratings can have the same RPN result even though their hidden risk implications may be totally different. For example, failure mode 1 with an RPN of 80 ($8 \times 2 \times 5$) and failure mode 2 with an RPN of 80 ($4 \times 5 \times 4$) have the same value, but have different meanings, as failure mode 1 has abnormally high severity.
- The mathematical formula for calculating RPN is sometimes questionable and sensitive to variability when evaluating risk factors. Small variations in specific risk factors may lead to vastly different effects on the RPN that are out of proportion with the values of other factors. For example, failure modes 1 and 2 have the same RPN values of 80 for ($8 \times 2 \times 5$) and ($4 \times 5 \times 4$). If the occurrence of each failure type increases by one, the RPN value of 120 ($8 \times 3 \times 5$) for failure mode 1 is much higher than the RPN value of 96 ($4 \times 6 \times 4$) for failure mode 2.
- Conventional RPN methods do not consider direct/indirect relationships between components or sub-systems, because it has the assumption that PRN is evaluated in an independent assessment environment where there are no relationships between other failure modes. In other words, previous RPN methods do not consider functional influences between system components. This is not appropriate for actual failure mechanisms.

Many researchers have proposed various alternative methods to improve questionable RPN methods. Wang et al. [5] proposed an approach that combined FMEA and the Boolean representation method. Fuzzy logic is applied to FMEA to better reflect real-world uncertainty. Bowles and Pelaez [1], Xu et al. [6], Wang et al. [7], and Liu et al. [8] proposed RPN methods to use fuzzy logic. In addition, the decision-making trial and evaluation laboratory (DEMATEL) technique was introduced for risk assessment [9–12]. It has the advantage of analyzing the severity and relationships between components of a system. However, the previous methods could not completely overcome the shortcomings of FMEA and caused another biased ranking problem in FMEA analysis.

This study aimed to propose a new risk assessment method for FMEA based on fuzzy weighted Euclidean (FWE) and risk block diagram (RBD) analysis. The proposed method not only overcomes the shortcomings of traditional FMEA, but is also a useful application with which to adopt a structural approach to consider functional influences and relative importance between failure modes. The priority ranking of failure modes is derived from the importance risk priority number (IRPN), which is composed of relational importance and structural importance. There are two examples in the illustrative study: numerical example and empirical example of a thin film transistor liquid crystal display (TFT-LCD). The TFT-LCD example is adopted to verify the proposed method. Finally, the result is compared with the conventional RPN method and previous methods. Therefore, Fig. 1 shows the process of the proposed risk assessment method.

This paper is organized as follows. Section 2 explains the proposed IRPN method which is composed of relational importance and structural importance. Section 3 provides the illustrative study of two examples. Section 4 presents the conclusion.

2 Proposed IRPN method

2.1 FRPN computation

Suppose that there are l cross-functional experts for assessing risk in an FMEA team responsible for the assessment of m potential causes of failure or potential failure modes; where $CF_i(i = 1, \cdots, m)$ with respect to n risk factors $RF_j(j = 1, \cdots, n)$. In the FMEA analysis, there are three risk factors in cases: "the severity of the failure (S)," "the failure occurrence rate (O)," and "the probability of not detecting the failure (D)." Each expert has a weight $\lambda_k\ (k = 1, \cdots, l)$, satisfying '$\sum_{k=1}^{l} \lambda_k = 1$' to consider the experts' weight in the FMEA process. In that case, the notation is defined as

- $\tilde{x}_{ij}^k = \left(x_{ijL}^k, x_{ijM}^k, x_{ijU}^k\right)$: The fuzzy rating provide by k^{th} expert on the assessment of CF_i with respect to RF_j
- $\tilde{w}_j^k = \left(w_{jL}^k, w_{jM}^k, w_{jU}^k\right)$: The fuzzy weight of risk factors RF_j given by k^{th} expert.

Then, it can be aggregated by

$$\tilde{x}_{ij} = \sum_{k=1}^{l} \lambda_k \tilde{x}_{ij}^k = \left(\sum_{k=1}^{l} \lambda_k x_{ijL}^k, \sum_{k=1}^{l} \lambda_k x_{ijM}^k, \sum_{k=1}^{l} \lambda_k x_{ijU}^k\right) = \left(x_{ijL}, x_{ijM}, x_{ijU}\right) \tag{1}$$

$$\tilde{w}_j = \sum_{k=1}^{l} \lambda_k \tilde{w}_{ij}^k = \left(\sum_{k=1}^{l} \lambda_k w_{jL}^k, \sum_{k=1}^{l} \lambda_k w_{jM}^k, \sum_{k=1}^{l} \lambda_k w_{jU}^k \right) = \left(w_{jL,}, w_{jM}, w_{jU} \right) \quad (2)$$

where $i = 1, 2, \cdots, m$ and $j = 1, 2, \cdots, n$.

$\tilde{x}_{ij}$ is the aggregated fuzzy rating of CF_i with respect to RF_j and $\tilde{w}_j$ is the aggregated fuzzy weight of RF_j. The fuzzy values ($x_{ijL,}, x_{ijM}, x_{ijU}$), respectively, denote the lower bound, the median, and upper bound values in the Fuzzy set.

Chang and Cheng [10] improved the FMEA model by using RPN method with fuzzy ordered weighted average (OWA). Liou and Wang [13] proposed an FMEA model using FRPN based on the fuzzy weighted average (FWA). However, the previous FMEA methods may cause biased ranking results that create difficulties in the risk ranking due to the increased deviation between the lower and upper bounds of FRPN. Therefore, this study proposes a novel FMEA method with a geometric approach to use the risk space-diagram (RSD). The RSD can create less varied results between the lower and upper bounds of FRPN due to the projection of the three-dimensional space according to the Euclidean norm. Then, FRPN based on fuzzy weighted Euclidean (FWE) is obtained to prioritize the ranking of cause of failure (CF).

The RSD was developed based on the three risk factors: the severity of the failure (S), the failure occurrence rate (O), and the probability of not detecting the failure (D). Let $\tilde{x}_{i1} = \tilde{S}_i$, $\tilde{x}_{i2} = \tilde{O}_i$, and $\tilde{x}_{i3} = \tilde{D}_i$; Fig. 1 demonstrates the configuration and interrelations of the risk factors and FRPN in a one-coordinate system [14]. Each cause of failure has its own RSD in Fig. 2; the axis in the coordinate represents the risk factors of the i^{th} cause of failure. In the RSD, $FRPN_{iL}$ denotes the lower bound of $FRPN_i$, which is a combination of S_{iL}, O_{iL}, and D_{iL}. Similarly, $FRPN_{iU}$ denotes the upper bound of $FRPN_i$. The initial point $O\,(0, 0, 0)$ denotes the minimum index and the vertex point; $G\,(10, 10, 10)$ denotes the maximum index. As seen from the RSD, the larger the FRPN, the closer the upper bound is to point G.

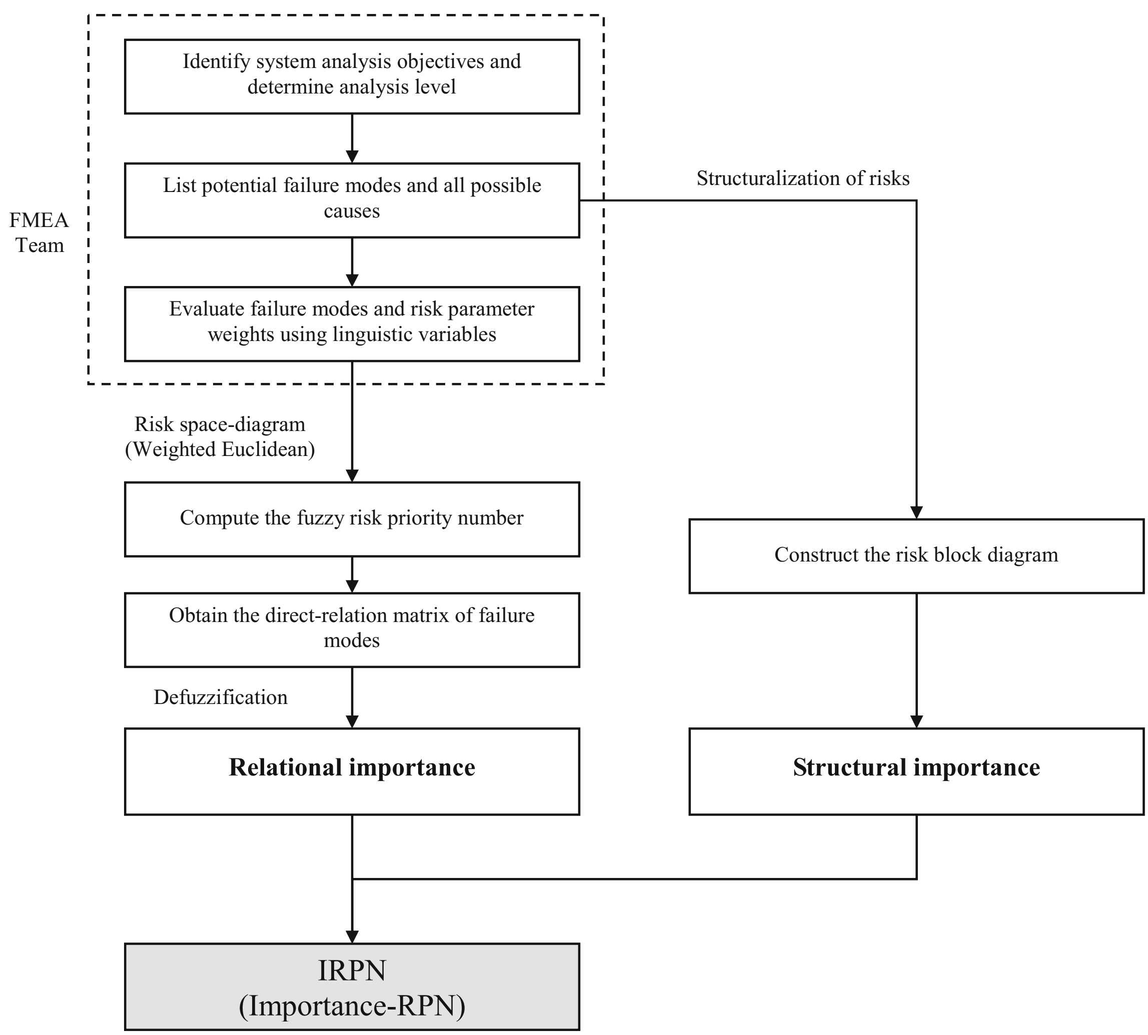

Fig. 1 The process of the IRPN method

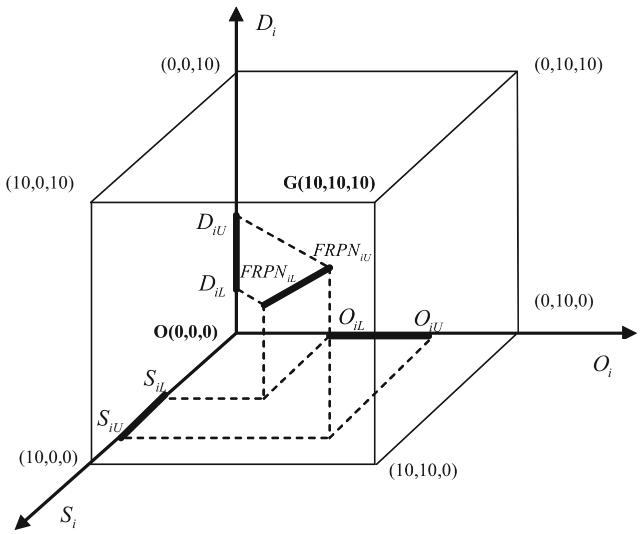

Fig. 2 Risk space diagram (RSD) of i^{th} cause of failure

Euclidean distance in the RSD is employed to calculate $FRPN_{iL}$ and $FRPN_{iU}$. Considering the discrepancy in the risk factors, FRPN is calculated in the form of fuzzy weights. According to FWE, $FRPN_i$ is expressed as a multiplicative weighted formula, given by the following:

$$\widetilde{FRPN}_i = \frac{\sqrt{\sum_{j=1}^{n} \widetilde{w_j}^2 \left(\tilde{x}_{ij} - x_{ij,min}\right)^2}}{\sqrt{\sum_{j=1}^{n} \widetilde{w_j}^2 \left(x_{ij,max} - x_{ij,min}\right)^2}} \tag{3}$$

where the risk factor j can be three. In Fig. 1, $x_{ij,\min}$ and $x_{ij,\ max}$ indicate the minimum and maximum index of x_{ij}.

2.2 Importance coefficient

As mentioned in Sect. 1, conventional FMEA has a disadvantage that it is evaluated based on a single failure mode or cause of failure. Therefore, the proposed method takes into account cases where many causes of failure (CF) can affect multiple failure modes. This is called hierarchical and structural risks or multiple failure modes [5]. Analyzing multiple failure modes requires considering the relative importance between failure modes and their impact on other failure modes. In this study, the importance coefficient is composed of relational importance (RI) which refers to the relative importance between other failure modes and structural importance (SI) which is presented by the impact on other failure modes. Then, the importance risk priority number (IRPN) is used as the importance coefficient. CF's risk priorities are determined in accordance with the IRPN.

2.2.1 Relational importance

The relational importance is obtained by using the decision-making trial and evaluation laboratory (DEMATEL) method. DEMATEL is a comprehensive method for building and analyzing structural models involving causal relationships between risk factors; it is useful for graphically visualizing the complex structure of causal relationships. RI indicates the degree of functional influence between causes of failure or potential failure modes using the DEMATEL method. The procedure for deriving RI is as follows.

Step 1: Set up the initial direct-relation fuzzy matrix F

$$\tilde{F} = \begin{bmatrix} 0 & \tilde{f}_{12} & \cdots & \tilde{f}_{1b} \\ \tilde{f}_{21} & 0 & \cdots & \tilde{f}_{2b} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{f}_{a1} & \tilde{f}_{a2} & \cdots & 0 \end{bmatrix}, \tag{4}$$

where $\tilde{f}_{ab}$ is obtained via pair-wise relation analysis in terms of the influences between CF_a and CF_bin triangular fuzzy sets $\tilde{f}_{ab}$. Therefore, all the principal diagonal elements $\tilde{f}_{aa}$ of matrix F are always zero.

Step 2: Normalize the initial direct-relation fuzzy matrix X

$$\tilde{\mathrm{X}} = \frac{\tilde{F}}{s}, \tag{5}$$

where $\mathrm{s} = \max_a \left(\sum_{b=1}^{n} f_{ab} \right)$.

Step 3: Obtain the total-relation fuzzy matrix T

$$\tilde{\mathrm{T}} = \lim_{k \to \infty} \left(\tilde{X} + \tilde{X}^2 + \cdots + \tilde{X}^k \right) = \tilde{X}\left(I - \tilde{X}\right)^{-1}, \tag{6}$$

when $\lim_{k \to \infty} \tilde{X}^k = O$.

In the same way, $\tilde{t}_{ij}$ is the triangular fuzzy set.

Step 4: Obtain the fuzzy value of relational importance

$$RI_i = \sum_{j=1}^{n} \tilde{t}_{ij}, \tag{7}$$

where $i = 1,2,\cdots,\mathrm{n}$.

Step 5: Obtain the crisp RI value (defuzzification).

The last step in fuzzy analysis is defuzzification, which converts fuzzy set into crisp values. The previous research generally applied a center of gravity method [15]. The defuzzified RI value can be expressed as follows:

$$RI_i = \frac{RI_{iL} + RI_{iM} + RI_{iU}}{3}. \tag{8}$$

2.2.2 Structural importance

The previous research did not consider the degree of direct/indirect relationships with regard to the relative importance between other failure modes. This study proposes the structural importance (SI), the weighted degree, in which the causes of failure produce malfunctions or failures in the structural system as the degree of relationships [16, 17]. It is obtained by Birnbaum importance measure as risk block diagram analysis. Some causes of failure play a more important role in causing or contributing to the system failure than others. The concept of structural importance implies the influence of CF on failure. The structural importance is assigned as a numerical value between 0 and 1, where 1 signifies the highest level of importance. Obtaining the structural importance requires that the state vector is

$$\tilde{s}_{ij} = \left(s_{1j}, s_{2j}, \cdots, s_{mj}\right), \tag{9}$$

where s_{ij} is the binary variable, $s_{ij} = 1$ if causes of failure i with risk factor j occur, or $s_{ij} = 0$ if causes of failure i with risk factor j do not occur.

Then, the structure function of the system is

$$\phi\left(\tilde{s}_{ij}\right) = \begin{cases} 1 & if \quad system \quad is \quad functioning\,(not \quad failure) \\ 0 & if \quad system \quad is \quad not \quad functioning\,(failure) \end{cases}. \tag{10}$$

The structural importance of the cause of failure is

$$SI_{\phi}(i) = \frac{1}{2^{m-1}} \sum_{\left\{\tilde{s}_{ij} \middle| s_{1j}=1\right\}} \left[\phi\left(1_i, \tilde{s}_{ij}\right) - \phi\left(0_i, \tilde{s}_{ij}\right)\right]. \tag{11}$$

This needs to be normalized for comparison with other causes of failure. The normalized SI is

$$\mathrm{SI}_i = \frac{SI_{\phi}(i)}{r}, \tag{12}$$

where $r = \sum_{i=1}^{m} SI_{\phi}(i)$.

3 Illustrative study

3.1 Numerical example

This section presents a numerical example to illustrate the effectiveness of the proposed method. Suppose that an engineering system has two failure modes (FM) and three causes of failure (CF) whose risk block diagram is shown in Fig. 3.

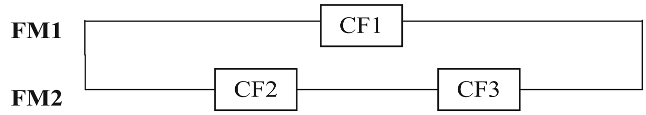

Fig. 3 A risk block diagram of two FMs and three CFs

The fuzzy values of CFs are obatined from fuzzy assessment information by (1) and (2). The FRPNs based on FWE are calculated by (3). Therefore, the IRPNs are combined with the relational importance using (4), (5), (6), (7), and (8) of Sect. 2.2.1 and structural importance using (9), (10), (11), and (12) of Sect. 2.2.2. The numerical values are shown in Table 1. By using these values, the results of relational importance, structural importance, and IRPN are shown in Table 2.

The results show that the priority rankings are CF1, CF2, and CF3 in order. CF1 and CF3 have the same S, O, D, and RPN value in traditional FMEA. However, the IRPN results show priority ranking change such as CF1 > CF3 because the proposed method uses a structural approach by taking account of both functional influences and relative importance between failure modes and cause of failure. The fuzzy assessment information of CF2 and CF3 shows RPN distortion phenomenon. However, the IRPN result of CF2 > CF3 shows that RPN distortion is alleviated. In this way, the proposed method has an effect on preventing the RPN distortion by using the importance coefficient which combines relational importance and structural importance.

3.2 Empirical example

In the empirical example, the proposed risk assessment method is applied in the thin film transistor liquid crystal display (TFT-LCD) product. TFT-LCD data about medium-sized LCD displays and modules was drawn from a professional LCD manufacturer, W corporation, in Taiwan [9–11]. The fuzzy-FMEA assessment of TFT-LCD products identified by an FMEA team is presented in Table 3. An example of TFT-LCD product has 11 potential failure modes and 15 causes of failure.

The hierarchy tree and risk block diagram (RBD) with regard to the failure of TFT-LCD products are shown in Figs. 4 and 5. RBD can be constructed from a hierarchy tree where the potential failure modes are in parallel and the causes of failure are in series.

3.3 IRPN computation

The FMEA team is composed of five experts who have different weights, which are assumed to be 0.3, 0.25, 0.2, 0.15, and 0.1. The experts evaluate the causes of failure with respect to three risk factors S, O, and D. The fuzzy assessment

Table 1 Aggregated fuzzy assessment information and FRPNs of numerical example

			S	O	D	FRPN
1	FM1	CF1	(3, 5, 7)	(3, 5, 7)	(3, 5, 7)	(3, 5, 7)
2	FM2	CF2	(5, 7, 9)	(3, 5, 7)	(0, 1, 3)	(4.84, 6.49, 7.82)
3	FM2	CF3	(3, 5, 7)	(3, 5, 7)	(3, 5, 7)	(3, 5, 7)
$\tilde{W}$			(0.75, 1, 1)	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	

Table 2 Relational importance, structural importance, and IRPN of numerical example

No.		Relational importance (RI)	Defuzzified RI	Structural importance (SI)	Normalized SI	IRPN
FM1	CF1	(0.3837, 0.6395, 0.8952)	0.6395	0.75	0.4286	0.2741
FM2	CF2	(0.6187, 0.8302, 1)	0.8163	0.5	0.2857	0.2332
FM2	CF3	(0.3837, 0.6395, 0.8952)	0.6395	0.5	0.2857	0.1827

information and weights of risk factors for the five experts are given by Liu et al. [11]. Then, the five experts' fuzzy assessments are calculated by (1) and (2). Eventually, the FRPNs of each CF are calculated by (3) from RSD as presented in Table 4.

According to the results of FRPN and RBD, we can obtain each CF's relational importance and structural importance. The relational importance is obtained by using the DEMATEL method. As shown in Fig. 6, it is the total-relation fuzzy matrix

Table 3 Failure modes and causes of failure of the TFT-LCD product

No.	Potential failure modes	Causes of failure
1	Greyscale display defect (FM1)	1. Poor grammar curve design (CF1)
2	Uneven splotches at edges and corners of LCD (FM2)	1. Edge and interior delta and not the same (CF2)
3	Uneven splotches at edges and corners of LCD (FM2)	2. Silver paste and perimeter sealant material characteristics (CF3)
4	Uneven splotches at edges and corners of LCD (FM2)	3. Conductive material unable to cover the CP dot area (CF4)
5	Flickering display (FM3)	1. Moisture seeps into the Vcom CP dot and reduces conductivity (CF5)
6	Flickering display (FM3)	2. Liquid crystal resistance too low (CF6)
7	Flickering display (FM3)	3. Insufficient Cst capacitance setting (CF7)
8	No display (FM4)	1. Short circuit by particle 2. ITO scratch (CF8)
9	Missing pixels (FM5)	1. Etching failure 2. Particle remains on LCD internal (CF9)
10	Missing lines (FM6)	1. Etching failure 2. Particle remains on LCD internal (CF9)
11	Contrast ratio (FM7)	1. Poor operation by operators (CF10)
12	Crosstalk (FM8)	1. ITO impedance too high 2. Vth cannot meet the IC Vop 3. Bias level tolerance too large (CF11)
13	Liquid crystal response time too slow (FM9)	1. Liquid crystal selection error 2. Cell gap setting error (CF12)
14	Poor high-temperature contrast (FM10)	1. Liquid crystal clearing point too low (CF13)
15	Poor high-temperature contrast (FM10)	2. Spacer leaking light (CF14)
16	Bright region transmissiveness too low (FM11)	1. Poor liquid crystal Δn and LCD cell gap matching (CF15)

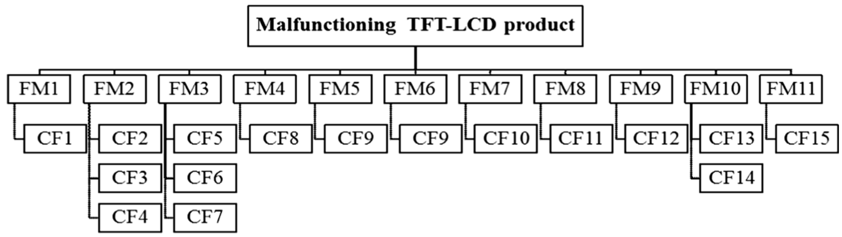

Fig. 4 The hierarchy tree for malfunctioning TFT-LCD products

$\tilde{T}$ of the TFT-LCD product for Eq. (6). Finally, the fuzzy values of relational importance and defuzzified values can be obtained using Eq. (7) and (8). The next procedure is obtaining the structural importance of the causes of failure from RBD of Fig. 5, and the structural importance is normalized. Eventually, the importance risk priority numbers (IRPN) of the TFT-LCD product are calculated by relational importance and structural importance, as shown in Table 5.

3.4 Comparisons and discussions

Verification of the effectiveness of the proposed risk assessment method is performed by comparing the proposed method using IRPN with other methods: the traditional FMEA, the ordered weighted geometric average (OWGA) and DEMATEL method [9], the fuzzy ordered weighted average (OWA) and DEMATEL method [10], and the FWA and fuzzy DEMATEL method [11]. Table 6 shows the comparison results for the priority-ranked cause of failure.

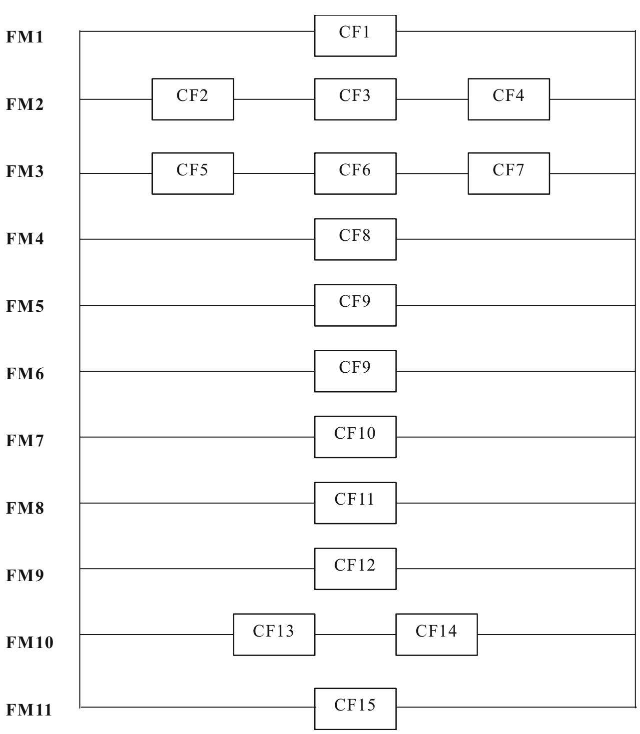

Fig. 5 A risk block diagram for malfunctioning TFT-LCD products

This paper analyzes the results in three aspects: structural, analytical, and applicable. The features of the proposed method are presented as follows.

- Structural: The proposed method can prioritize the causes of failure considering the degree of relative importance in the structural systems. The traditional FMEA did not take into account the relative importance as shown in Sect. 1. In this study, the prioritization of causes of failure was obtained from the importance risk priority number (IRPN) based on structural importance and relational importance. As shown in Table 3, CF9 is the most important because CF9 has an impact on two failure modes (FM5 and FM6). Therefore, CF9 must be assigned a higher priority than other causes [9–11]. Similarly, the raised priority of CF1, CF12, and CF15 is derived from adopting their structural importance based on the risk block diagram analysis. The result of the proposed method shows CF6 < CF1, CF14 < CF12, and CF5 < CF15 in comparison with the other methods.
- Analytical: The priority change of CF1, CF10, and CF15 resulted from using the weighted Euclidean distance for calculating the fuzzy risk priority number (FRPN). The proposed method results in CF10 < CF15 < CF1, whereas CF15 < CF1 < CF10 in the previous methods. The three-dimensional geometric approach to FRPN based on FEW is more analytical and useful method than FRPN based on FWA because it reduces the deviation between the lower and upper bounds of FRPN. CF10 < CF15 < CF1 in the proposed method is a more valid result. In conclusion, the proposed method could prevent the biased ranking problem.
- Applicable: The proposed method is more effective in differentiating the risk priorities of causes of failure that have the same RPN values. While more than one cause of failure can have the same PRN value in traditional FMEA, such as CF1 and CF8 (RPN = 48), CF5 and

Table 4 Aggregated fuzzy assessment information and FRPNs of causes of failure

			S	O	D	FRPN
1	FM1	CF1	(4.4, 6.4, 8.4)	(0.75, 2.5, 4.5)	(1.5, 3.5, 5.5)	(4.28, 5.9, 7.28)
2	FM2	CF2	(3, 5, 7)	(0.35, 1.7, 3.7)	(1, 3, 5)	(2.91, 4.6, 6.09)
3	FM2	CF3	(3, 5, 7)	(0.55, 2.1, 4.1)	(0.45, 1.9, 3.9)	(2.91, 4.62, 6.09)
4	FM2	CF4	(3, 5, 7)	(1, 3, 5)	(0.35, 1.7, 3.7)	(2.92, 4.7, 6.27)
5	FM3	CF5	(4, 6, 8)	(1.7, 3.7, 5.7)	(0.25, 1.5, 3.5)	(3.9, 5.65, 7.13)
6	FM3	CF6	(4, 6, 8)	(1.4, 3.4, 5.4)	(2.2, 4.2, 6.2)	(3.9, 5.63, 7.21)
7	FM3	CF7	(4, 6, 8)	(0.6, 2.2, 4.2)	(0.55, 2.1, 4.1)	(3.89, 5.52, 6.86)
8	FM4	CF8	(6.1, 8.1, 9.55)	(0.3, 1.6, 3.6)	(1.6, 3.6, 5.6)	(5.92, 7.38, 8.01)
9	FM5	CF9	(5, 7, 9)	(0.9, 2.8, 4.8)	(3.4, 5.4, 7.4)	(4.86, 6.48, 7.91)
10	FM6	CF9	(5, 7, 9)	(0.9, 2.8, 4.8)	(3.4, 5.4, 7.4)	(4.86, 6.48, 7.91)
11	FM7	CF10	(3.9, 5.9, 7.9)	(1, 3, 5)	(3.3, 5.3, 7.3)	(3.79, 5.52, 7.15)
12	FM8	CF11	(2.8, 4.8, 6.8)	(2.2, 4.2, 6.2)	(1.6, 3.6, 5.6)	(2.77, 4.69, 6.54)
13	FM9	CF12	(3, 5, 7)	(1.8, 3.8, 5.8)	(0.5, 2, 4)	(2.94, 4.79, 6.47)
14	FM10	CF13	(4, 6, 8)	(0.3, 1.6, 3.6)	(0.25, 1.5, 3.5)	(3.88, 5.48, 6.78)
15	FM10	CF14	(4, 6, 8)	(0.45, 1.9, 3.9)	(1, 3, 5)	(3.88, 5.5, 6.86)
16	FM11	CF15	(4.5, 6.5, 8.5)	(0.25, 1.5, 3.5)	(0.35, 1.7, 3.7)	(4.37, 5.93, 7.11)
$\tilde{W}$			(0.67, 0.92, 1)	(0.16, 0.41, 0.66)	(0, 0.11, 0.36)	

CF14 (RPN = 36), and CF2, CF4, and CF12 (RPN = 30), the proposed method can distinguish these from other using fuzzy assessments [10]. In addition, this method can prevent RPN distortion by using the importance coefficient. The RPN distortion phenomenon in the traditional RPN method was observed in CF8 with RPN 48 (8 × 2 × 3) and CF11 with RPN 80 (5 × 4 × 4). CF8 should be managed with higher priority than CF11 because a CF8 occurrence can create serious damage, even though it rarely happens. Therefore, the ranking of CF8 is increased as shown in Table 6.

4 Conclusion

This study proposed a new risk assessment methodology by failure mode and effects analysis (FMEA) based on fuzzy weighted Euclidean (FWE) and risk block diagram (RBD) analysis to assess the risks in structural systems in which influence relationships are complicated. The proposed method prioritizes failure modes by developing importance risk priority numbers (IRPN) that are composed of relational importance and structural importance. The illustrative study presented two examples: numerical example and empirical example

<table>
<tr><td></td><td>CF1</td><td>CF2</td><td>…</td><td>CF14</td><td>CF15</td><td>FM1</td><td>FM2</td><td>…</td><td>FM10</td><td>FM11</td></tr>
<tr><td>CF1</td><td rowspan="6" colspan="5">0</td><td>(0.27,0.37,0.46)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>CF2</td><td></td><td>(0.18,0.29,0.38)</td><td></td><td></td><td></td></tr>
<tr><td>CF3</td><td></td><td>(0.18,0.29,0.38)</td><td></td><td></td><td></td></tr>
<tr><td>M</td><td>M</td><td>M</td><td>M</td><td>M</td><td>M</td></tr>
<tr><td>CF14</td><td></td><td></td><td></td><td>(0.24,0.34,0.43)</td><td></td></tr>
<tr><td>CF15</td><td></td><td></td><td></td><td></td><td>(0.27,0.37,0.44)</td></tr>
<tr><td>FM1</td><td rowspan="5" colspan="5">0</td><td rowspan="5" colspan="5">0</td></tr>
<tr><td>FM2</td></tr>
<tr><td>M</td></tr>
<tr><td>FM10</td></tr>
<tr><td>FM11</td></tr>
</table>

Fig. 6 Total-relation fuzzy matrix of the TFT-LCD products

Table 5 Relational importance and structural importance and importance risk priority number

No.		Relational importance (RI)	Defuzzified RI	Structural importance (SI)	Normalized SI	IRPN
FM1	CF1	(0.2705, 0.3734, 0.4606)	0.3682	0.0045	0.1173	0.0432
FM2	CF2	(0.1844, 0.2908, 0.3850)	0.2867	0.0006	0.0168	0.0048
FM2	CF3	(0.1845, 0.2921, 0.3853)	0.2873	0.0006	0.0168	0.0048
FM2	CF4	(0.1849, 0.2971, 0.3963)	0.2928	0.0006	0.0168	0.0049
FM3	CF5	(0.2470, 0.3571, 0.4507)	0.3516	0.0006	0.0168	0.0059
FM3	CF6	(0.2466, 0.3562, 0.4562)	0.3530	0.0006	0.0168	0.0059
FM3	CF7	(0.2459, 0.3490, 0.4336)	0.3429	0.0006	0.0168	0.0057
FM4	CF8	(0.3748, 0.4671, 0.5068)	0.4495	0.0045	0.1173	0.0527
FM5	CF9	(0.6149, 0.8192, 1.0000)	0.8114	0.0045	0.1173	0.0952
FM6	CF9	(0.6149, 0.8192, 1.0000)	0.8114	0.0045	0.1173	0.0952
FM7	CF10	(0.2401, 0.3490, 0.4522)	0.3471	0.0045	0.1173	0.0407
FM8	CF11	(0.1751, 0.2966, 0.4135)	0.2951	0.0045	0.1173	0.0346
FM9	CF12	(0.1862, 0.3032, 0.4093)	0.2996	0.0015	0.1173	0.0351
FM10	CF13	(0.2458, 0.3467, 0.4258)	0.3394	0.0015	0.0391	0.0133
FM10	CF14	(0.2458, 0.3482, 0.4337)	0.3426	0.0045	0.0391	0.0134
FM11	CF15	(0.2765, 0.3750, 0.4494)	0.3669	0.0045	0.1173	0.0430

of a thin film transistor liquid crystal display (TFT-LCD). In the empirical example, the TFT-LCD example was given to verify the proposed method. The priority rankings of causes of failure were obtained to examine the application. The results were compared with the conventional RPN method, the OWGA and DEMATEL method [9], the fuzzy OWA and DEMATEL method [10], and the FWA and fuzzy DEMATEL method [11]. Comparison results showed that the proposed methods had advantages over the previous methods in aspect of structural approach, analytical and useful, and applicable. In particular, the proposed method prevented RPN distortion according to the example of CF8 and CF11. This method also considered the interdependence and relative importance between failure modes in the example of raising the priorities of CF12 and CF15. The proposed risk assessment method could help the decision-makers to find the

Table 6 Comparison between the proposed method and other methods

No.	Traditional FMEA	OWGA and DEMATEL ($\alpha = 0.7$)	Fuzzy OWA and DEMATEL ($\alpha = 0.7$)	FWA and fuzzy DEMATEL	The proposed method
CF1	5	5	4	5	3
CF2	9	9	12	14	15
CF3	15	15	15	15	14
CF4	9	10	12	13	13
CF5	7	7	7	6	11
CF6	4	6	5	3	10
CF7	12	12	9	10	12
CF8	5	3	2	2	2
CF9	3	1	1	1	1
CF10	1	2	3	4	5
CF11	2	4	6	8	7
CF12	9	11	12	11	6
CF13	12	13	9	12	9
CF14	7	8	7	9	8
CF15	12	14	9	7	4

critical causes of failure for risk management. We need to further improve this method in a further study by applying other risk assessment cases.

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