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Research Article

Advanced FMECA Method Based on Intuitionistic 2-Tuple Linguistic Variables and the Triangular Fuzzy Analytic Hierarchy Process

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Failure mode effects and criticality analysis (FMECA) is a commonly adopted approach to defining, assessing, and reducing possible failures in designs, systems, processes, products, and services. Traditional FMECA ranks the failure modes of products based on a risk priority number (RPN), which is obtained by multiplying the risk elements. Conventional FMECA has the shortcomings of badly handling unknown information and unreasonably assessing RPNs. To deal with these issues, an advanced FMECA method based on intuitionistic 2-tuple linguistic variables (I2LVs) and the triangular fuzzy analytic hierarchy process (TFAHP) is proposed. In this method, the fuzzy evaluation of risk elements given by different FMECA members is represented by I2LVs, which can efficiently handle unknown information. The TFAHP method is adopted to assess the weights of risky elements and rank the risk priorities of different failure modes. Finally, an application case of an insulated-gate bipolar transistor is used to verify the effectiveness and robustness of the proposed method.

1. Introduction

Failure mode effects and criticality analysis (FMECA) is typically adopted to identify, evaluate, and reduce existing or underlying errors and failures in system designs or processes [1]. Due to its simplicity and high efficiency, FMECA has been widely applied in some industries, such as the nuclear, aerospace, transportation, and manufacturing industries [2–9]. In traditional FMECA [10–13], every failure mode is assessed using three risk elements: detection (D), severity (S), and occurrence (O). The risk factors for the failure modes are integers between 1 and 10. By multiplying the D , S, and O values, a risk priority number (RPN) can be acquired. Although traditional FMECA has been proven to be a useful way to assess possible product failures in various areas, some shortcomings and limitations remain. For example, the hazard analysis is highly subjective and ignores the uncertainties of the actual intermediate state and the fuzzy nature of the language information. Moreover, risk factors are not weighed, meaning that they are taken to be equally valuable. These shortcomings lead to errors between traditional FMECA evaluations and actual results, which significantly limits their effectiveness.

To overcome these shortcomings and limitations, a reasonable evaluation can be made by using fuzzy numbers and linguistic variables instead of exact values. George et al. [14] and Mangeli et al. [15] converted language descriptions into triangular and trapezoidal fuzzy numbers or linguistic variables in FMECA. Xiao [16] and Liu et al. [17] used D numbers to more flexibly and intuitively represent the attribute information in an FMECA multiple criteria decision. Wang et al. [18] identified an exceptional fuzzy number and proposed a corresponding fuzzy RPN to identify the risk priority of failures. However, these

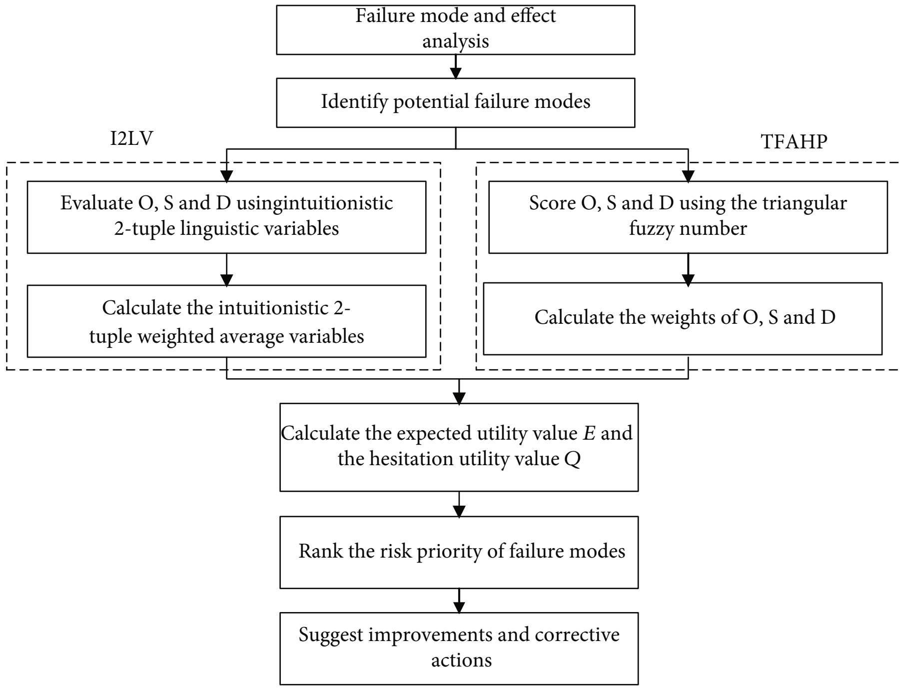

Figure 1: Implementation process of the advanced FMECA method.

Table 1: Judgment matrix.

Risk factor	O	S	D
O	(0.5,0.5,0.5)	(0.35,0.43,0.51)	(0.54,0.63,0.72)
S	(0.49,0.57,0.65)	(0.5,0.5,0.5)	(0.63,0.72,0.82)
D	(0.28,0.37,0.45)	(0.18,0.28,0.37)	(0.5,0.5,0.5)

evaluations also have shortcomings; e.g., the evaluation implies that the linguistic description of the subject is affiliated with the set and cannot use linguistic descriptions that are not affiliated with the set, such as the hesitation that a decision-maker cannot judge. Therefore, intuitionistic 2-tuple linguistic variables (I2LVs) [19, 20] consisting of language terms and explicit numbers can be used to describe the risk factors. I2LVs use qualitative linguistic terms to express criterion membership and nonmembership. This can summarize the ambiguity of linguistic information better than intuitionistic fuzzy numbers and linguistic variables can, thereby reflecting the actual situation more reliably and truthfully.

In addition, given the limitations of traditional FMECA (which does not weigh the risk elements), many researchers have tried to use the multiple-criteria decision-making (MCDM) methods instead of typical RPN methods to prioritize failure modes. Liu et al. [21] combined vague numbers and the VIKOR method to propose a new FMEA method that is particularly applicable to MCDM problems with confusing and incommensurable (comprising various units) standards. Alencar et al. [22] proposed an MCDM model to rank the possible causes of failure by considering more attributes and using the same methodological support as in MCDM. Ju et al. [23] and Geum et al. [24] used grey relation projection (GRP) and grey relation analysis (GRA) methods to decide the weight and risk priority of failure modes. The triangular fuzzy analytic hierarchy process (TFAHP) [25] is a widely used comprehensive evaluation method. Compared with traditional evaluation methods, TFAHP introduces triangular fuzzy numbers in an expert scoring process, making the evaluation results more reasonable, accurate, and operable.

To clarify the fuzzy information of FMECA and improve the accuracy of the analysis, a new FMECA method based on I2LVs and TFAHP is proposed. The I2LVs are adopted to describe the vague evaluation of the risk elements by FMECA members, while TFAHP is used to assess the weights of the risk elements and comprehensively rank the risk priorities of the failures. This method is suitable for the FMECA of various products that have multiple failure modes.

2. Preliminaries

2.1. Intuitionistic 2-Tuple Linguistic Variables. The 2-tuple linguistic variables (2LVs) refer to 2-tuple group evaluation data (l_i, ε_i), where l_i is the language term in the language term set $L = \{l_0, l_1, \cdots, l_{2r}\}$, and $\varepsilon_i \in (-0.5, 0.5]$ is the symbol transfer value, which indicates the error between the integrated language term and the closest original one.

Definition 1. Let $L = \{l_0, l_1, \cdots, l_{2r}\}$ be the language term set and $\widehat{L}$ be the extended language term set of L; then, the I2LVs are as follows:

$$H = \left\{ \left\langle l_{\alpha(x)}, l_{\beta(x)} \right\rangle \middle| x \in X, l_{\alpha(x)}, l_{\beta(x)} \in \widehat{L} \right\}, \tag{1}$$

Table 2: Results of the I2LV-TFAHP method.

Failure mode	E	Q	Rank
FM_1	0.681	0.126	1
FM_2	0.476	0.087	5
FM_3	0.456	0.101	6
FM_4	0.595	0.130	3
FM_5	0.363	0.109	7
FM_6	0.638	0.157	2
FM_7	0.584	0.185	4

Table 3: Priority ranks evaluated by the five FMECA methods.

Failure mode	I2LV-TFAHP	TFAHP	I2LV	I2LV-TOPSIS	Traditional method
FM_1	1	1	1	1	2
FM_2	5	6	7	6	4
FM_3	6	7	5	5	4
FM_4	3	4	3	2	5
FM_5	7	5	6	7	7
FM_6	2	3	4	3	1
FM_7	4	2	2	4	3

where the language terms $l_{\alpha(x)}$ and $l_{\beta(x)}$ indicate the membership and nonmembership degrees of element x, respectively, and satisfy $0 \leq \alpha(x) + \beta(x) \leq 2\tau$.

Definition 2. Let U and V be continuous and strictly monotonic utility functions of $\widehat{L}$. If, for any I2LV, U and V satisfy the following functions:

$$\begin{cases} U\left(l_{\alpha(x)}\right) = V\left(\text{neg}\left(l_{\alpha(x)}\right)\right), \\ V\left(l_{\beta(x)}\right) = U\left(\text{neg}\left(l_{\beta(x)}\right)\right), \\ U(l_0) = V(l_{2\tau}) = 0, \\ U(l_{2t}) = V(l_0) = 1, \end{cases} \quad (2)$$

then U and V are called the utility functions of membership degree $l_{\alpha(x)}$ and nonmembership degree $l_{\beta(x)}$, respectively.

Definition 3. Let $h_i = \langle l_{\alpha(h_i)}, l_{\beta(h_i)} \rangle (i = 1, 2, \cdots, m)$ be an I2LV and $w = (w_1, w_2, \cdots, w_n)^T$ be its weight vector, satisfying $\sum_{i=1}^{n} w_i = 1$ and $w_i \geq 0$. Then, the intuitionistic 2-tuple weighted average variables (I2WAVs) are

$$\begin{aligned} h &= I2WAV(h_1, h_2, \cdots, h_m) \\ &= \left\langle U^{-1}\left[\sum_{i=1}^{m} w_i U\left(l_{\alpha(h)}\right)\right], V^{-1}\left[\sum_{i=1}^{m} w_i V\left(l_{\beta(k)}\right)\right]\right\rangle. \end{aligned} \quad (3)$$

Definition 4. Let $h = \langle l_{\alpha(h)}, l_{\beta(h)} \rangle$ be an I2LV; then, the expected utility function of h is

$$E(h) = \frac{U\left(l_{\alpha(h)}\right) + V\left(l_{\beta(h)}\right)}{2}. \quad (4)$$

Definition 5. Let $h = \langle l_{\alpha(h)}, l_{\beta(h)} \rangle$ be an I2LV; then, the hesitation utility function of h is

$$E(h) = \frac{U\left(l_{\alpha(h)}\right) + V\left(l_{\beta(h)}\right)}{2}. \quad (5)$$

Definition 6. Let h_1 and h_2 be two I2LVs; then

(i) if $E(h_1) > E(h_2)$, then $h_1 > h_2$

(ii) if $E(h_1) = E(h_2)$ and $Q(h_1) < Q(h_2)$, then $h_1 > h_2$

(iii) if $E(h_1) = E(h_2)$ and $Q(h_1) = Q(h_2)$, then $h_1 = h_2$

2.2. TFAHP Method. The core of the analytic hierarchy process (AHP) is to construct a judgment matrix by using an integer between 1 and 9, with its inverse number used as a scale. This evaluation often does not consider the fuzzy nature of the subjective judgment. If the ratio of the weights of the two factors is not easy to determine, it is only known that the range of change is $l - u$, and the maximum possible value is m; then, the triangular fuzzy number (l, m, u) can be used in the evaluation.

In comparison with the traditional AHP method, TFAHP uses triangular fuzzy numbers in the expert scoring process, which makes the scoring relatively reasonable and accurate [26]. Moreover, during the weight calculation, the problem of judging and adjusting the consistency of the matrix in the traditional AHP is skillfully solved by adopting a possibility matrix [27].

First of all, a set of triangular fuzzy judgment matrices is established as follows:

$$\begin{cases} A^{(k)} = \left(a_{ij}^{(k)}\right)_{n \times n} \\ a_{ij}^{(k)} = \left(l_{ij}^{(k)}, m_{ij}^{(k)}, u_{ij}^{(k)}\right) \\ \text{s.t.}, 0 \leqslant l_{ij}^{(k)} \leqslant m_{ij}^{(k)} \leqslant u_{ij}^{(k)} \leqslant 1 \end{cases} \quad (6)$$

where n is the number of factors, k is the expert serial number, K is the total number of experts (where $k = 1, 2, \cdots, K$), $a_{ij}^{(k)}$ is the ratio of the importance of factor i to factor$j$, $l_{ij}^{(k)}$ and $u_{ij}^{(k)}$ are the upper and lower bounds of the triangular fuzzy number, respectively (where $l_{ij}^{(k)} + u_{ji}^{(k)} = 1$, $u_{ij}^{(k)} + l_{ji}^{(k)} = 1$, $l_{ii}^{(k)} = 0.5$, $u_{ii}^{(k)} = 0.5$), and m_{ij} is the median of the triangular fuzzy number $m_{ij}^{(k)} + m_{ji}^{(k)} = 1$.

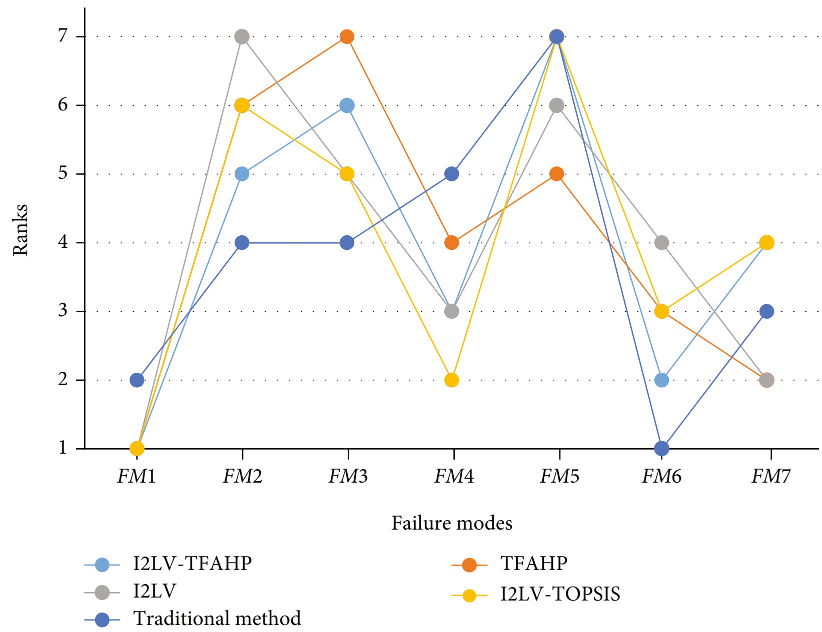

Figure 2: Comparison of the results of the five FMEA methods.

Table 4: Expert weights in different cases.

Cases	TE_1	TE_2	TE_3	TE_4
Case 0	0.2	0.35	0.15	0.3
Case 1	0.1	0.4	0.3	0.2
Case 2	0.25	0.25	0.25	0.25
Case 3	0.3	0.2	0.35	0.15
Case 4	0.4	0.1	0.4	0.1

The set of triangular fuzzy judgment matrices is merged according to the following function:

$$a_{ij} = \frac{a_{ij}^{(1)} + a_{ij}^{(2)} + \cdots + a_{ij}^{(K)}}{K}. \quad (7)$$

Secondly, the single-level triangular fuzzy weights of the judgment matrix are calculated.

$$c_i = \frac{\sum_{j=1}^{n} a_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij}} = \left(\frac{\sum_{j=1}^{n} l_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} \mu_{ij}}, \frac{\sum_{j=1}^{n} m_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} m_{ij}}, \frac{\sum_{j=1}^{n} \mu_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} l_{ij}} \right). \quad (8)$$

The single-level triangular fuzzy weights c_i are compared with each other. Let $c_{i1} = (c_{l1}, c_{m1}, c_{\mu 1})$ and $c_{i2} = (c_{l2}, c_{m2}, c_{\mu 2})$; then, the likelihood matrix $P = (p_{ij})_{n\times n}$ is solved as follows:

$$p(c_{i1} \geq c_{i2}) = 0.5 \max\left\{1 - \max\left\{\frac{c_{m2} - c_{l1}}{c_{m1} - c_{l1} + c_{m2} - c_{l2}}, 0\right\}, 0\right\} + 0.5 \max\left\{1 - \max\left\{\frac{c_{\mu 2} - c_{m1}}{c_{\mu 1} - c_{m1} + c_{\mu 2} - c_{m2}}, 0\right\}, 0\right\}. \quad (9)$$

Then, the likelihood matrix is transformed into a fuzzy matrix with consistent features.

$$r_{ij} = \frac{r_i - r_j}{2(n-1)} + 0.5, \quad (10)$$

$$r_i = \sum_{k=1}^{n} P_{ik}. \quad (11)$$

Finally, the final weights are calculated using the following formula:

$$w_i = \frac{\sum_{j=1}^{n} r_{ij} + (n/2) - 1}{n(n-1)}. \quad (12)$$

3. Methods

Supposing that there are p FMECA team experts $TE = \{TE_1, TE_2, \cdots, TE_p\}$ evaluating m failure modes $FM = \{FM_1, FM_2, \cdots, FM_m\}$ with respect to n risk factors $RF = \{RF_1, RF_2, \cdots, RF_n\}$, the expert weight vector is $w = (w^{(1)}, w^{(2)}, \cdots, w^{(p)})^T$. The expert TE_k gives an evaluation of risk factor RF_j of failure mode FM_i as a I2LV $b_{ij}^{(k)} = \langle l_{\alpha_{ij}^{(k)}}, l_{\beta_{ij}^{(k)}} \rangle$, with the I2LV matrix being $B^{(k)} = (b_{ij}^{(k)})_{m\times n}$ $(k = 1, 2, \cdots, p)$. The set of triangular fuzzy judgment matrices of risk factors is $A^{(k)} = (a_{ij}^{(k)})_{n\times n}$.

The proposed FMECA method includes the steps shown in Figure 1.

Step 1. According to I2WAV and the expert weight vector w, the I2LV matrix $B^{(k)}$ is integrated into the group I2LV

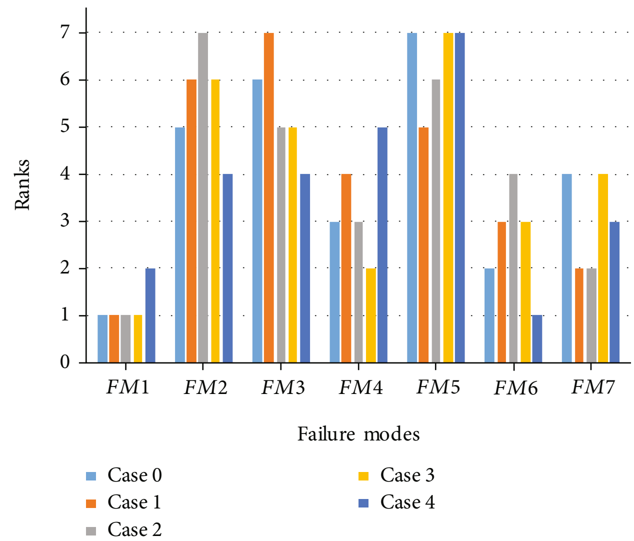

Figure 3: Sensitivity analysis for the I2LV-TFAHP method.

Table 5: Failure mode priority ranks under various cases.

Failure mode	Case 0	Case 1	Case 2	Case 3	Case 4
FM_1	1	1	1	1	2
FM_2	5	6	7	6	4
FM_3	6	7	5	5	4
FM_4	3	4	3	2	5
FM_5	7	5	6	7	7
FM_6	2	3	4	3	1
FM_7	4	2	2	4	3

matrix $B=(b_{ij})_{m\times n}=(\langle l_{\alpha_{ij}}, l_{\beta_{ij}}\rangle)_{m\times n}$.

$$b_{ij}=\mathrm{I2WAV}\left(b_{ij}^{(1)}, b_{ij}^{(2)},\cdots,b_{ij}^{(p)}\right)=\left\langle U^{-1}\left[\sum_{k=1}^{p} w^{(k)}U\left(l_{\alpha_i^{(k)}}\right)\right], V^{-1}\left[\sum_{k=1}^{p} w^{(k)}V\left(l_{\beta_{ij}^{(k)}}\right)\right]\right\rangle. \quad (13)$$

Step 2. The TFAHP method is adopted to assess the weight vector of risk elements $\varpi=(\varpi_1,\varpi_2,\cdots,\varpi_n)^T$.

Step 3. According to the group I2WAV and the weight vector of risk elements, the group I2WAV for every risk element of failure modes A_i is integrated to obtain the comprehensive I2WAV $b_i=\langle l_a, l_b\rangle$.

$$b_i=I2WAV(b_{i1},b_{i2},\cdots,b_{in})=\left\langle U^{-1}\left[\sum_{j=1}^{n}\varpi_j U\left(l_{\alpha_{ij}}\right)\right], V^{-1}\left[\sum_{j=1}^{n}\varpi_j V\left(l_{\beta_{ij}}\right)\right]\right\rangle. \quad (14)$$

Step 4. According to Definitions 4 and 5, the expected utility value $E(b_i)$ and the hesitation utility value $Q(b_i)$ of the comprehensive I2WAV b_i are calculated.

Step 5. According to Definition 6, the expected utility value and the hesitation utility value are sorted to acquire the failure mode's risk priorities.

4. Case Study

The section uses the new FMEA method according to I2LV and TFAHP (I2LV-TFAHP method) to assess the failure modes of a crimp-type insulated-gate bipolar transistor (IGBT).

Step 1. The FMECA team consists of four experts, $\{TE_1, TE_2, TE_3, TE_4\}$. The risk elements are detection (D), severity (S), and occurrence (O). The weight of the experts in each risk factor is $w=(0.2,0.35,0.15,0.3)^T$, and the linguistic term set is $L=\{l_0,l_1,l_2,l_3,l_4,l_5,l_6\}=\{$extremely low, very low, low, moderate, high, very high, extremely high$\}$. Through detailed analysis of the IGBT, the FMECA team identifies seven potential failure modes: fretting wear (FM_1), short circuit (FM_2), open circuit (FM_3), microcorrosion (FM_4), boundary warpage (FM_5), gate oxide-layer destruction (FM_6), and spring failure (FM_7).

Step 2. The experts use I2LV to evaluate the failure modes. The I2LV matrices $B^{(k)}=(b_{ij}^{(k)})_{m\times n}(k=1,2,3,4; i=1,2,3; j=1,2,3,4,5,6,7)$ are provided.

Step 3. According to I2WAV and the experts' weight vector w, the group I2LV matrix is obtained.

Step 4. Experts use triangular fuzzy numbers to score and average the risk factors to obtain a judgment matrix (Table 1). The risk element weights calculated by the TFAHP method are $\varpi=(0.319,0.485,0.196)^T$.

Step 5. According to Equation (14), the comprehensive I2WAV is calculated.

$$\begin{cases} b_1=\langle l_{0.68}, l_{0.48}\rangle, b_2=\langle l_{2.59}, l_{2.89}\rangle, b_3=\langle l_{2.43}, l_{2.96}\rangle, \\ b_4=\langle l_{3.18}, l_{2.04}\rangle, b_5=\langle l_{1.85}, l_{3.49}\rangle, b_6=\langle l_{3.36}, l_{1.70}\rangle, \\ b_7=\langle l_{2.95}, l_{1.94}\rangle. \end{cases} \quad (15)$$

Step 6. The expected utility value and hesitation utility value of the comprehensive I2WAV $b_i (i=1,2,3,4,5,6,7)$ are calculated according to Equations (4) and (5).

Step 7. The failure mode risk priority ranks are determined based on $E(b_i)$ and $Q(b_i)$, as shown in the last column of Table 2.

Table 3 shows that FM_1 has the highest expected utility degree in fretting wear failure and, therefore, should be offered a top risk priority. The order of the risk priorities of the seven failure modes is $FM_1 > FM_6 > FM_4 > FM_7 > FM_2 > FM_3 > FM_5$.

By comparing TFAHP, I2LV, I2LV-TOPSIS, and the traditional method, the rationality of the I2LV-TFAHP method is verified. The evaluation outcomes are displayed in Table 3 and Figure 2.

Table 4 and Figure 2 demonstrate the following facts.

TFAHP, I2LV, and I2LV-TOPSIS all indicate that the failure mode with the highest risk priority is FM_1 (fretting wear), which is consistent with the conclusion of I2LV-TFAHP.

I2LV-TFAHP ranks FM_6 (gate oxide-layer destruction) in second place, while TFAHP and I2LV rank FM_7 (spring failure) in second place and the I2LV-TOPSIS method ranks FM_4 (microcorrosion) in second place. The TFAHP, I2LV, and I2LV-TOPSIS methods rank FM_6 in fifth, fourth, and third places, respectively. Using engineering knowledge during the operation of IGBT, the failure frequency of the gate oxide-layer destruction is higher than that of the spring failure as well as microcorrosion, as shown in the risk element *O*. Thus, in the I2LV-TFAHP method, it is reasonable to rank the FM_6 risk priority in second place.

The I2LV-TFAHP ranks FM_5 (boundary warpage) in seventh place, while the TFAHP and I2LV methods rank FM_3 (open circuit) and FM_2 (short circuit) in seventh place. The open circuit and short circuit of the IGBT make it unable to work, and the effect of boundary warpage on the IGBT function is small, as reflected in the risk factors. Therefore, it is also reasonable for the I2LV-TFAHP method to rank FM_5 in seventh place.

The first four failure modes with the highest risk, as evaluated by typical methods, are not the same as those of the four other methods, particularly when all of the new methods select FM_1 as the highest-risk failure mode. Moreover, the traditional method ranks FM_2 and FM_3 in equal fourth place, meaning that it cannot distinguish between their risks.

The above information indicates that the proposed I2LV-TFAHP method is more reasonable and accurate than other methods.

Sensitivity analysis is performed by changing the expert weights, as shown in Table 4, where case 0 demonstrates the previously mentioned application, and cases 1 to 4 indicate cases with different weights.

The ranking outcomes of the failure mode risk priorities in various cases are displayed in Figure 3 and Table 5. They show that a change in expert weight has a very slight influence on the risk priority rank, which means that the suggested method is sufficiently robust in ranking the risk priorities of the failure modes identified in the FMECA.

5. Conclusions

In this study, an advanced FMECA method based on I2LV and TFAHP is proposed to deal with the shortcomings and limitations of the conventional FMECA method. It also suggests a different way to prioritize the risks of different failure modes. I2LV can effectively deal with the fuzzy nature of linguistic variables, while TFAHP is adopted to evaluate the risk element weights and the comprehensive ranking of the failure mode risk priorities. An application example is provided to demonstrate the failure mode risk priorities in the FMECA provided by the IGBT. Compared with TFAHP, I2LV, I2LV-TOPSIS, and the traditional method, the proposed I2LV-TFAHP method is more accurate and reasonable and has greater robustness when analysing risk priority ranks.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest in publishing this article.

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