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AN INNOVATIVE APPROACH INTEGRATING 2-TUPLE AND LOWGA OPERATORS IN PROCESS FAILURE MODE AND EFFECTS ANALYSIS

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Abstract. *Process failure mode and effects analysis (FMEA) is used in the high-tech industry to assure process robustness. Traditionally, process FMEA uses the risk priority number (RPN) to evaluate the risk of failure. However, the RPN method has several main shortcomings. In order to improve the method of RPN evaluation, this paper proposes an innovative approach, integrating 2-tuple and the linguistic ordered weighted geometric averaging (LOWGA) operator in process FMEA. The main purpose of this study is to effectively resolve the main shortcomings of RPN evaluation to assure product and process robustness. In numerical verification, process FMEA of the color super-twisted nematic (CSTN) product is presented to further illustrate the proposed approach. After comparing the result that was obtained from the proposed method with both the traditional RPN method and the LOWGA method, it was found that the proposed approach provided a more accurate and reasonable ranking of the risk of failure. Moreover, the proposed method does not lose the useful information provided by the experts.*
Keywords: Process failure mode and effects analysis, Linguistic ordered weighted geometric averaging, Risk priority number, Color super-twisted nematic

1. **Introduction.** In the world of fast-improving technology, to maintain the competitive edge of an enterprise, one must guarantee that the product quality, cost and timing can all fit market demand: this is the concept of risk assessment. Many reports discuss risk assessment as a related subject, such as investment risk [13,18], operational risk, risk management [20] and risk control [21]. Most current risk assessment methods use the failure mode and effects analysis (FMEA) approach to evaluate the risk of failure. FMEA is frequently used in the high-tech industry to improve product quality and productivity. Generally, there are two types of FMEA: design FMEA and process FMEA. Design FMEA deals with design activities, such as product, machine or service design. Process FMEA is used to assess manufacturing process weaknesses and the potential effects of process failure on the product being manufactured. The main objective of FMEA is to assign the limited resources to the most serious risk items. The FMEA tool was first proposed by NASA in 1963 for their obvious reliability requirements. The American army began

using FMEA in the 1970s and in 1974 produced the army standard, "MIL-STD-1629: procedures for performing a failure mode effects and criticality analysis". In 1980, there was also a second printing of MIL-STD-1629A [30]. In 1990, the international organization for standardization (ISO) recommended the use of FMEA for design review in the ISO9000 series [29]. Currently, the FMEA technique is used extensively in ISO-9000, ISO/TS 16949 and QS-9000 quality certification levels. Today, FMEA has been adopted in many places, such as the aerospace, military, automobile, electricity, mechanical and semiconductor industries.

Traditionally, process FMEA uses the risk priority number (RPN) to rank and assess the process risk of potential failure modes. The RPN criticality calculation adopts linguistic terms to rank the severity of its failure effect (S), the chance of the failure mode occurrence (O) and the chance of the failure being undetected (D) on a numerical scale from 1 to 10. The RPN value is obtained by finding the product of these three factors. Therefore, $\text{RPN} = S \times O \times D$. 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. In the traditional RPN, though well documented and easy to apply, there is a serious shortcoming: it does not consider the ordered weight. The ordered weight is one of the most important factors to evaluate the risk of failure [4]. The concept of ordered weighted averaging (OWA) was first introduced by Yager [33] in 1988. It is a technique to get optimal weights of the attributes based on the ranks of these weighting vectors after processing aggregation. O'Hagan [25] first used the concept of entropy in the OWA equation, but the situation factor had not yet been taken into consideration in his approach. The OWA operators have been implemented extensively in the last few years. For example, Chang et al. [6] used intuitionistic fuzzy set and OWA operators to evaluate the system reliability of an aircraft propulsion system. Recently, Chiclana et al. [11] introduced the ordered weighted geometric averaging (OWGA) operator, based on the OWA operator and the geometric mean. The OWGA operator allows for the implementation of the concept of the fuzzy majority in decision-making processes with ratio-scale assessments in a similar way as OWA operators. Since its appearance, the OWGA operator has been extensively analyzed by different authors [4,10].

Many reports discuss RPN as a related subject, such as Sankar and Prabhu [26], who proposed a modified approach for prioritization of failures in a system FMEA, called risk priority rank. Their approach extended risk prioritization beyond the traditional RPN method. The ranks 1 through 1000 were used to represent the increasing risk of the 1000 possible S-O-D combinations. Braglia [2] developed a multi-attribute failure mode analysis (MAFMA) based on the analytic hierarchy process (AHP) technique, which considers four different factors – S, O, D and expected cost – as decision attributes, possible causes of failure as decision alternatives, and the selection of causes of failure as decision goals. Bowles and Pelaez [1] were the first to use fuzzy logic for working directly with linguistic terms in making criticality assessments. Xu et al. [31] proposed a fuzzy logic-based FMEA approach. It broadens the method by Bowles and Pelaez [1], from only criticality analysis to FMEA, and it constructs a fuzzy assessment system to perform it. A great deal of works in the literature [3,5,7,27,28] have been carried out using fuzzy RPN methods.

In order to meet product reliability requirements, the FMEA technique [12,24] is used in the early stage of product design or process control. However, these studies and the traditional RPN method lose some information that the experts provide, which may cause biased conclusions [8]. Recently, Herrera and Martinez [19] proposed the 2-tuple fuzzy linguistic representation model, which allows one to make processes of computing with words without the loss of information. This model is based on the concept of symbolic translation. It represents linguistic information by means of linguistic 2-tuples and defines a set of functions to facilitate computational processes over 2-tuples.

In order to effectively resolve the RPN evaluation problem mentioned above, this paper proposed an innovative approach, integrating 2-tuple and the linguistic ordered weighted geometric averaging (LOWGA) operators in process FMEA. The method is straightforward and has no loss of information. For verification of the proposed approach, a numerical example of a 1.4-inch color super-twisted nematic (CSTN) process FMEA is adopted in this paper. The result of the proposed method is compared with the traditional RPN and LOWGA operator methods.

The rest of this article is organized as follows: Section 2 reviews the relevant literature used in this study; Section 3 presents the proposed approach, which integrates 2-tuples and the LOWGA operator method for process FMEA; a real case is studied to demonstrate the feasibility of the proposed methodology in Section 4; and Section 5 concludes the article.

2. **Related Works.**

2.1. **Process FMEA.**

Process FMEA is used to assess manufacturing process weaknesses and the potential effects of process failure on the product being manufactured. Each failure mode adopts linguistic terms and will be assessed in three parameters – the severity of its failure effect (S), the chance of the failure mode occurrence (O) and the chance of the failure being undetected (D) – on a numerical scale from 1 to 10. By multiplying the values for S, O and D, the team obtains a risk priority number (RPN), which is RPN $= S \times O \times D$. These RPNs help the team to identify the processes that need priority actions for improvement. A typical set of failure index rankings and criteria are presented in Tables 1-3 [16]. Failure modes with higher RPN values are assumed to be more important and are given higher priorities than those with lower RPN values.

TABLE 1. Severity evaluation criteria [16]

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. Occurrence evaluation criteria [16]

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

Table 3. Detectability evaluation criteria [16]

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

2.2. **The linguistic 2-tuple representation method.** The linguistic 2-tuple representation method takes the symbolic aggregation model as a basis and in addition defines the concept of symbolic translation and uses it to represent the linguistic information by means of a pair of values called the linguistic 2-tuple, (s_i, α), where s_i is a linguistic term and α is a numerical value representing the symbolic translation [23].

Definition 2.1. *Let $S = \{s_0, s_1, \ldots, s_g\}$ be a linguistic term set and $\beta \in [0, g]$ be a value representing the result of a symbolic aggregation operation; then, the 2-tuple that expresses the equivalent information to β is obtained with the following function [14,19]:*

$$\Delta : [0, g] \to S \times [-0.5, 0.5) \tag{1}$$

$$\Delta(\beta) = (s_i, \alpha), \text{ with} \begin{cases} s_i, & i = \text{round}(\beta) \\ \alpha = \beta - i, & \alpha \in [-0.5, 0.5) \end{cases} \tag{2}$$

where round $(\cdot)$ is the usual round operation, s_i has the closest index label to "β", and "α" is the value of the symbolic translation.

Definition 2.2. *Let $x = \{(r_1, \alpha_1), (r_2, \alpha_2), \dots, (r_n, \alpha_n)\}$ be a set of 2-tuples; the 2-tuple arithmetic mean $\overline{x}^e$ is computed as [14,19],*

$$\overline{x}^e = \Delta\left(\sum_{i=1}^{n} \frac{1}{n}\Delta^{-1}(r_i, \alpha_i)\right) = \Delta\left(\frac{1}{n}\sum_{i=1}^{n}\beta_i\right) \tag{3}$$

The arithmetic mean for 2-tuples allows us to compute the mean of a set of linguistic values without any loss of information.

The comparison of linguistic information represented by 2-tuples is carried out according to an ordinary lexicographic order. Let (s_k, α_1) and (s_l, α_2) be 2 2-tuples, with each one representing a counting of information as follows:

- if $k < l$, then (s_k, α_1) is smaller than (s_l, α_2).
- if $k = l$, then
  (1) if $\alpha_1 = \alpha_2$, then (s_k, α_1), (s_l, α_2) represents the same information;
  (2) if $\alpha_1 < \alpha_2$, then (s_k, α_1) is smaller than (s_l, α_2);
  (3) if $\alpha_1 > \alpha_2$, then (s_k, α_1) is bigger than (s_l, α_2).

2.3. **OWGA and LOWGA operators.**

2.3.1. *Basic concept.* The OWGA operator was introduced by Chiclana et al. [10], and it reflects the fuzzy majority calculating its weighting vector by means of a fuzzy linguistic quantifier according to Yager's ideas [33]. The concept of OWGA operators is based on weighted geometric averaging (WGA) and OWA operators.

Definition 2.3. *Let WGA: $R^{+n} \to R^{+}$ [9,10], if*

$$WGA_w(a_1, a_2, \dots, a_n) = \prod\nolimits_{j=1}^{n} b_j^{w_j}, \tag{4}$$

where $w = (w_1, w_2, \dots, w_n)^T$ is the exponential weighting vector of a_j, and $w_j \in [0, 1]$, $\prod_{j=1}^{n} w_j = 1$; then WGA is called the WGA operator.

Definition 2.4. *An OWGA operator of dimension n is a mapping OWGA [9,10]: $R^{+n} \to R^{+}$, which has associated with it an exponential weighting vector $w = (w_1, w_2, \dots, w_n)^T$, with $w_j \in [0, 1]$ and $\sum_{j=1}^{n} w_j = 1$, such that*

$$f(a_1, a_2, \dots, a_n) = \prod\nolimits_{j=1}^{n} b_j^{w_j}, \tag{5}$$

where b_j is the jth largest element of the collection of the n aggregated objects $a_1, a_2, \cdots, a_n$, and $b_1 \geq b_2 \geq \cdots \geq b_n$. The function value $f(a_1, a_2, \cdots, a_n)$ determines the aggregated value of arguments, $a_1, a_2, \cdots, a_n$.

The OWGA operators have only been used in situations in which the input arguments are the exact value. However, judgments of people depend on personal psychological aspects, such as experience, learning, situation and state of mind. Therefore, Xu [32] proposed the LOWGA operator concept to aggregate evaluations of experts. It is more suitable to provide their preferences by means of linguistic variables rather than numerical ones.

Definition 2.5. *A LOWGA operator of dimension n is a mapping LOWGA [32]: $\overline{S}^n \to \overline{S}$, which has associated with it an exponential weighting vector $w = (w_1, w_2, \dots, w_n)^T$,* *with* $w_j \in [0,1]$ *and* $\sum_{j=1}^{n} w_j = 1$*, such that*

$$\begin{aligned} LOWGA_w\left(s_{\alpha_1}, s_{\alpha_2}, \ldots, s_{\alpha_n}\right) &= \left(s_{\beta_1}\right)^{w_1} \otimes \left(s_{\beta_2}\right)^{w_2} \otimes \cdots \otimes \left(s_{\beta_n}\right)^{w_n} \\ &= \left(s_{\beta_1^{w_1}}\right) \otimes \left(s_{\beta_2^{w_2}}\right) \otimes \cdots \otimes \left(s_{\beta_n^{w_n}}\right) = s_\beta \end{aligned} \tag{6}$$

where $\beta = \prod_{j=1}^{n} \beta_j^{w_j}$, s_{β_j} *is the* j*th largest of the* s_{α_i}.

2.3.2. *Determination of OWGA and LOWGA weights.* Fuller and Majlender [17] used the method of Lagrange multipliers to transfer Yager's OWA equation to derive a polynomial equation, which can determine the optimal weighting vector under maximal entropy. By their method, the associated weighting vector is obtained by Equations (7)-(9).

$$\ln w_j = \frac{j-1}{n-1} \ln w_n + \frac{n-j}{n-1} \ln w_1 \Rightarrow w_j = \sqrt[n-1]{w_1^{n-j} w_n^{j-1}} \tag{7}$$

$$\text{and} \qquad w_n = \frac{((n-1)\alpha - n)\, w_1 + 1}{(n-1)\alpha + 1 - n w_1} \tag{8}$$

$$\text{then} \qquad w_1 \left[(n-1)\alpha + 1 - n w_1\right]^n = ((n-1)\alpha)^{n-1} \cdot \left[((n-1)\alpha - n)\, w_1 + 1\right] \tag{9}$$

where w is weight vector, n is the number of attributes and α is the situation parameter.

The optimal value of w_1 should satisfy Equation (9). Once w_1 is obtained, then w_n can be determined from Equation (8), and the other weights are obtained from Equation (7). Because the OWGA and LOWGA operators are based on the OWA operator, it is clear that the weighting vector w can be obtained by the same method that is used in the case of the OWA operator.

3. **Proposed Integrates of 2-tuple and the LOWGA Operator Approach.** Traditionally, the RPN method has three main shortcomings, as below: (1) it has not considered the ordered weighted of the severity, occurrence and detection; (2) it has not considered the situation parameter; and (3) it loses some valued information, which experts have to provide. Therefore, to overcome the aforementioned shortcomings, an innovative approach integrating 2-tuple and the LOWGA operator in process FMEA is proposed in this section.

3.1. **The reason for using 2-tuple and the LOWGA operator.** The traditional RPN method uses the arithmetic mean approach to deal with the S, O and D values that experts have to provide. It will cause serious drawback, which lose the useful information provided by the experts. For example, suppose that there are 4 experts to point out the severity of the failure (S) of the 2 failure modes. Failure mode 1 has an S value of 8 (each expert pointed out values of 8, 8, 9 and 8, respectively) and failure mode 2 has an S value of 8 (each expert pointed out values of 7, 8, 8 and 7, respectively). According to the traditional RPN method, they have the same S value of 8 in the 2 failure modes. However, in practice, failure mode 1 is more serious than failure mode 2. The 2-tuple method may effectively solve this problem. In the 2-tuple method, failure mode 1 has the S value (8, 0.25), and failure mode 2 has the S value $(8, -0.5)$. In this way, the experts provide all information that can be considered so that they can not lose any useful information. For this reason, using the proposed approach in assessing system risk, not the traditional RPN method, is more suitable.

In addition, most of the literature that confers on RPN-related issues does not consider the situation parameter and the ordered weight, which may cause biased conclusions. The situation parameter α and the ordered weight are two of the most important factors that are used to evaluate the risk of failure. The α value reflects a decision-maker's current degree of optimism [15]. For example, there are 2 failure modes: one (referred to as scenario 1) has an RPN value of 56 (S, O and D are 7, 4 and 2, respectively), and the other one (referred to as scenario 2) has an RPN value of 48 (S, O and D are 8, 3 and 2, respectively). In this example, it is found that D is 2 in both scenarios 1 and 2. In scenario 1, the value of O is higher than scenario 2's. In scenario 2, the value S is higher than scenario 1's. For any decision-maker, he should give higher allocation resources to defend the most dangerous scenario. He would choose the highest value of 8 in scenario 2 as a higher priority. According to the traditional RPN method, scenario 1 (RPN = 56) is assumed to be more important than scenario 2 (RPN = 48) and is given a higher priority. However, in practice, scenario 2 is more important than scenario 1. The LOWGA operator has considered the ordered weight and the situation parameter. Therefore, he uses the LOWGA operator on the process FMEA; this result is a more realistic and flexible reflection of the real situation.

3.2. **The procedure of the proposed approach.** The procedure of the proposed approach is organized into seven steps and explained as follows:

Step 1. List potential failure modes.

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

Step 2. List potential effects of failure modes.

Arrange failure mode content in a process FMEA table. List the reasons of failure mode occurrence.

Step 3. Define the scales for S, O and D, respectively.

For each failure mode, each process FMEA member points out the severity of the failure (S), the probability of failure (O) and the probability of not detecting the failure (D) individually to establish the corresponding linguistic value.

Step 4. Calculate the LOWGA weights.

From Section 2.3.2, use Equations (7)-(9) to calculate the LOWGA weights.

Step 5. Calculate the aggregated value by LOWGA weights.

In this step, the experts must decide the prerequisite situation parameter (α). According to Step 3 and Step 4, use Equation (6) to calculate the aggregated value by LOWGA weights.

Step 6. Rank the priority for assessing failure risk.

According to the results of Step 6, the comparison of linguistic information represented by 2-tuples is carried out according to an ordinary lexicographic order, which takes the cause of failure out of the risk prioritization ranking.

Step 7. Analyze the results and provide suggestions.

4. **Numerical Verification and Comparison.** In this section, this study uses a real case of a color super-twisted nematic (CSTN) liquid crystal display (LCD) product that was drawn from a professional LCD manufacturer in Taiwan to demonstrate our proposed approach.

4.1. **Overview.**

4.1.1. *Brief description of CSTN products.* In recent years, the market for the new portable electronic products has grown explosively. In these applications – e.g., mobile phones, mp3 players, PDAs and other consumer electronics – LCD technologies have played an important role owing to the requirements of light weight, small size, low power and durable reliability. Basically, there are 2 main streams in LCD technologies. They are CSTN LCD and thin film transistor (TFT) LCD. TFT LCD provides more vivid colors and sharper images. However, they are expensive, due to low fabrication yield due to the large panel size. On the other hand, CSTN LCDs are more cost-attractive due to the much simpler process in manufacturing [22].

The structure of CSTN LCDs is including a color filter, retardation film and STN-LCD panel. A grayscale scheme is applied to control the transmittance of red, green and blue pixels on the color filter. By the different proportions of red, green and blue elements, it can get many kinds of colors. Additionally, it can get higher contrasts and wider viewing angles on the display due to the optical compensation properties of the retardation film.

The manufacturing of CSTN LCDs includes a front-end process, back-end process and module assembly process. The CSTN module assembly processes can be shown in Figure 1.

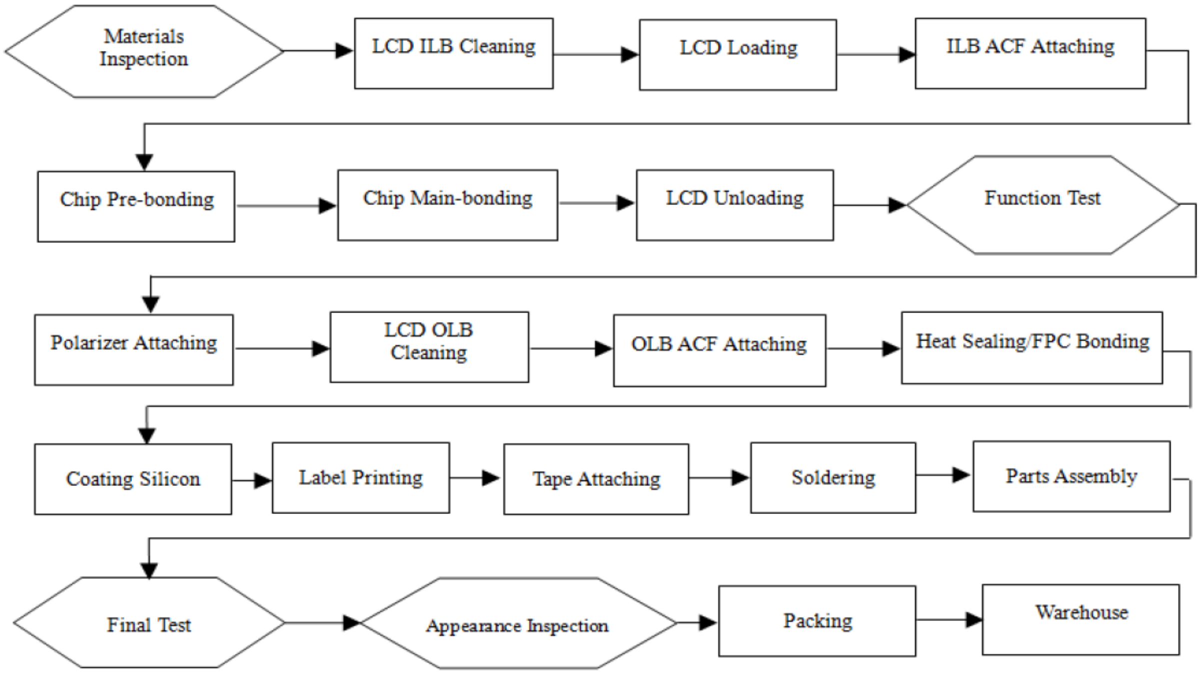

FIGURE 1. CSTN module assembly process

4.1.2. *Introduction of case company.* A professional LCD manufacturer's data in Taiwan will be taken as an example to demonstrate the procedure proposed in this paper. W corporation, founded in 1990, with various quality certifications of ISO 9001, ISO 9002, ISO 14001, QS 9000 and TS 16949, is a world-leading manufacturer of small-to-medium LCDs and touch panels. Headquartered in the Taichung export processing zone, the corporation is a Taiwan-based company with a growing international presence. W corporation is a company dedicated to the development, design, manufacture, and sale of ITO glass, touch panels, light guides, TN, STN, CSTN and TFT LCD/LCM. The displays manufactured by W corporation are primarily used in handheld electronic devices, such as mobile phones, communication products, digital still cameras, portable navigation devices, MP3/MP4 and digital photo frames. W corporation's production of a 1.4-inch CSTN product is shown in Figure 2. The process FMEA of this 1.4-inch CSTN is shown in Table 4. This process FMEA team has 4 experts; the S, O and D of the possible range of the failures are defined and organized in Table 5.

4.2. **Solution based on the traditional RPN method [16].** The traditional RPN method uses three parameters (S, O and D) that are utilized to describe each failure mode by rating on a 1-10 scale. The RPN value is the product of the S, O and D ratings.

TABLE 4. The process FMEA of 1.4-inch CSTN

No.	Process Description	Potential Failure Mode	Potential Failure Effect	Potential Failure Cause
1	Component Inspection Aim: Checking of incoming material specification.	Non-conformance of specification	Creating assembly inconvenience, increasing rework possibility.	Operator production error
2	LCD Cleaning Aim: To attain the best assembly result in Hot-Press process of LCD & FPC.	Short circuit	Picture display not even, horizontal line during electrical test	Due to foreign particles causing short circuit at the circuit line. During test, missing line results will occur.
3	ILB Bonding Aim: IC and LCD Assembly Process	ACF adherence N.G.	Affect product's function	Incorrect adjustment of ACF FEED or ACF ROLLER weight not satisfactory
4	ILB Bonding Aim: IC and LCD Assembly Process	Combining location offset	Abnormal display of picture during test	Incorrect machine setting
5	ILB Bonding Aim: IC and LCD Assembly Process	Conductive particle damage (N.G.)	Electrical characteristic N.G. or electrical characteristic test N.G. after dependability characteristic	Foreign Particles
6	ILB Bonding Aim: IC and LCD Assembly Process	Conductive particle damage (N.G.)	Electrical characteristic N.G. or electrical characteristic test N.G. after dependability characteristic	Over setting of Press head pressure
7	Function test Aim: Test product electrical characteristics, whether picture is normal or not	Short Circuit	Picture display not even, horizontal line during electrical test	Due to short circuit of internal glass etching process, test resulting in unevenness and horizontal line
8	Function test Aim: Test product electrical characteristics, whether picture is normal or not	PI Black/White Spots	Obvious appearance N.G. during LED test	Incoming LCD material N.G.
9	OLB Bonding Aim: Get ACF and use LCD & FPC temperature, time, pressure and other process condition to attain setting	FPC Combining location offset	No picture or picture abnormality during electrical test	FPC hot press offset
10	OLB Bonding Aim: Get ACF and use LCD & FPC temperature, time, pressure and other process condition to attain setting	ACF adherence N.G.	Affect product's functions	Incorrect ACF FEED adjustment or ACF ROLLER weight not satisfactory
11	OLB Bonding Aim: Get ACF and use LCD & FPC temperature, time, pressure and other process condition to attain setting	Conductive particle damage (N.G.)	Electrical characteristic N.G. or electrical characteristic test N.G. after dependability characteristic	Over setting of Press head pressure
12	Final Testing Aim: To test product's electrical characteristic, check picture whether normal or not	PI Black/White Spots	Obvious appearance N.G. during LED test	Incoming LCD material N.G.
13	Appearance Inspection Aim: Inspect all items totally after assembly.	Crack	Customer cannot assemble	Product N.G. due to no designated area to put during processing

FIGURE 2. 1.4-inch CSTN

TABLE 5. S, O and D of the possible range of failures

No.	S				O				D			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
1	8	8	9	8	3	2	2	2	2	2	2	3
2	7	8	8	7	3	2	1	2	3	2	2	2
3	7	8	8	7	2	2	1	2	3	3	2	2
4	9	8	8	7	4	3	3	3	3	2	2	2
5	8	8	7	8	4	3	3	2	2	3	4	4
6	8	8	9	8	4	3	2	3	2	2	3	2
7	8	8	7	8	5	4	3	4	2	2	2	3
8	8	8	7	7	5	6	7	7	2	2	3	2
9	8	7	6	8	4	4	3	4	2	2	3	2
10	8	8	7	8	2	2	3	2	2	3	3	2
11	9	8	7	8	3	3	4	3	3	2	2	2
12	8	8	7	7	5	6	7	7	2	2	3	2
13	7	8	9	8	3	2	2	2	1	1	2	1

Failure modes having a higher RPN are assumed to be more important and are given a higher priority for corrective action than those having a lower RPN. The resulting RPN values of the 1.4-inch CSTN are shown in Table 6.

TABLE 6. The RPN of the 1.4-inch CSTN

No.	1	2	3	4	5	6	7	8	9	10	11	12	13
S	8	8	8	8	8	8	8	8	7	8	8	8	8
O	2	2	2	3	3	3	4	6	4	2	3	6	2
D	2	2	3	2	3	2	2	2	2	3	2	2	1
RPN	32	32	48	48	72	48	64	96	56	48	48	96	16

4.3. **Solution based on the LOWGA method [32].** The LOWGA is based on the OWGA operator, defined by Chiclana et al. [10]. The method offers a computationally feasible method for aggregating linguistic information of the corresponding linguistic labels. According to integrated experts' knowledge and experience, the decided prerequisite situation parameter α value of the 1.4-inch CSTN is 0.7. The collective values of the 1.4-inch CSTN by the LOWGA method are shown in Table 7.

TABLE 7. The collective values of the 1.4-inch CSTN by the LOWGA method

No.	S	O	D	LOWGA method					
				$\alpha = 0.5$	$\alpha = 0.6$	$\alpha = 0.7$	$\alpha = 0.8$	$\alpha = 0.9$	$\alpha = 1.0$
1	s_8	s_2	s_2	$s_{3.171}$	$s_{3.668}$	$s_{4.311}$	$s_{5.148}$	$s_{6.281}$	$s_{8.000}$
2	s_8	s_2	s_2	$s_{3.171}$	$s_{3.668}$	$s_{4.311}$	$s_{5.148}$	$s_{6.281}$	$s_{8.000}$
3	s_8	s_2	s_3	$s_{3.630}$	$s_{4.181}$	$s_{4.853}$	$s_{5.665}$	$s_{6.667}$	$s_{8.000}$
4	s_8	s_3	s_2	$s_{3.630}$	$s_{4.181}$	$s_{4.853}$	$s_{5.665}$	$s_{6.667}$	$s_{8.000}$
5	s_8	s_3	s_3	$s_{4.154}$	$s_{4.605}$	$s_{5.165}$	$s_{5.856}$	$s_{6.737}$	$s_{8.000}$
6	s_8	s_3	s_2	$s_{3.630}$	$s_{4.181}$	$s_{4.853}$	$s_{5.665}$	$s_{6.667}$	$s_{8.000}$
7	s_8	s_4	s_2	$s_{3.994}$	$s_{4.588}$	$s_{5.278}$	$s_{6.063}$	$s_{6.955}$	$s_{8.000}$
8	s_8	s_6	s_2	$s_{4.572}$	$s_{5.230}$	$s_{5.941}$	$s_{6.672}$	$s_{7.382}$	$s_{8.000}$
9	s_7	s_4	s_2	$s_{3.821}$	$s_{4.328}$	$s_{4.902}$	$s_{5.535}$	$s_{6.228}$	$s_{7.000}$
10	s_8	s_2	s_3	$s_{3.630}$	$s_{4.181}$	$s_{4.853}$	$s_{5.665}$	$s_{6.667}$	$s_{8.000}$
11	s_8	s_3	s_2	$s_{3.630}$	$s_{4.181}$	$s_{4.853}$	$s_{5.665}$	$s_{6.667}$	$s_{8.000}$
12	s_8	s_6	s_2	$s_{4.572}$	$s_{5.230}$	$s_{5.941}$	$s_{6.672}$	$s_{7.382}$	$s_{8.000}$
13	s_8	s_2	s_1	$s_{2.518}$	$s_{3.110}$	$s_{3.874}$	$s_{4.864}$	$s_{6.169}$	$s_{8.000}$

This part uses No. 3 (situation parameter $\alpha = 0.7$), whose collective value rank is $s_{4.853}$ by the LOWGA method in this example; the calculation flow is as follows:

In this example, the initial weighting vector is $[0.554, 0.292, 0.154]$ $(\alpha = 0.7)$.

$$\begin{aligned} \text{LOWGA}_w(s_8, s_2, s_3) &= (s_8)^{0.554} \otimes (s_3)^{0.292} \otimes (s_2)^{0.154} \\ &= (s_{8^{0.554}}) \otimes (s_{3^{0.292}}) \otimes (s_{2^{0.154}}) = s_{4.853} \end{aligned}$$

4.4. **Solution based on the proposed method.** According to Equations (7)-(9), the optimal weighting vector under the maximal entropy for $n = 3$ is calculated and organized in Table 8.

TABLE 8. The optimal weighting vector under the maximal entropy $(n = 3)$

alpha	w_1	w_2	w_3
0.5	0.333333	0.333333	0.333333
0.6	0.438355	0.323242	0.238392
0.7	0.553955	0.291992	0.153999
0.8	0.681854	0.235840	0.081892
0.9	0.826294	0.146973	0.026306
1	1	0	0

Based on Tables 5 and 8, Equations (3) and (6), the aggregate of the LOWGA value of the 1.4-inch CSTN is calculated and shown in Table 9. The following example is made to further explain the calculating process.

This part uses No. 3 (situation parameter $\alpha = 0.7$), whose collective value rank is $(s_4, 0.349)$, by the proposed method in this example; the calculation flow is as follows:

In this example, the initial weighting vector is $[0.554, 0.292, 0.154]$ ($\alpha = 0.7$).

$$\begin{aligned} &\text{LOWGA}_w\left((s_8, -0.5), (s_2, -0.25), (s_3, -0.5)\right) \\ &= (s_8, -0.5)^{0.554} \otimes (s_3, -0.5)^{0.292} \otimes (s_2, -0.25)^{0.154} = (s_4, 0.349) \end{aligned}$$

TABLE 9. The aggregate of the LOWGA value of the 1.4-inch CSTN

No.	S	O	D	Integrate 2-tuple and LOWGA method					
				$\alpha = 0.54$	$\alpha = 0.6$	$\alpha = 0.7$	$\alpha = 0.8$	$\alpha = 0.9$	$\alpha = 1.0$
1	$(s_8, 0.25)$	$(s_2, 0.25)$	$(s_2, 0.25)$	$(s_3, 0.465)$	$(s_4, -0.028)$	$(s_5, -0.378)$	$(s_5, 0.458)$	$(s_7, -0.425)$	$(s_8, 0.25)$
2	$(s_8, -0.5)$	$(s_2, 0)$	$(s_2, 0.25)$	$(s_3, 0.228)$	$(s_4, -0.296)$	$(s_4, 0.305)$	$(s_5, 0.065)$	$(s_6, 0.059)$	$(s_8, -0.5)$
3	$(s_8, -0.5)$	$(s_2, -0.25)$	$(s_3, -0.5)$	$(s_3, 0.198)$	$(s_4, -0.288)$	$(s_4, 0.349)$	$(s_5, 0.136)$	$(s_6, 0.132)$	$(s_8, -0.5)$
4	$(s_8, 0)$	$(s_3, 0.25)$	$(s_2, 0.25)$	$(s_4, -0.123)$	$(s_4, 0.413)$	$(s_5, 0.058)$	$(s_6, -0.171)$	$(s_7, -0.234)$	$(s_8, 0)$
5	$(s_8, -0.25)$	$(s_3, 0)$	$(s_3, 0.25)$	$(s_4, 0.222)$	$(s_5, -0.340)$	$(s_5, 0.195)$	$(s_6, -0.160)$	$(s_7, -0.359)$	$(s_8, -0.25)$
6	$(s_8, 0.25)$	$(s_3, 0)$	$(s_2, 0.25)$	$(s_4, -0.186)$	$(s_4, 0.358)$	$(s_5, 0.027)$	$(s_6, -0.159)$	$(s_7, -0.141)$	$(s_8, 0.25)$
7	$(s_8, -0.25)$	$(s_4, 0)$	$(s_2, 0.25)$	$(s_4, 0.111)$	$(s_5, -0.346)$	$(s_5, 0.281)$	$(s_6, -0.009)$	$(s_7, -0.204)$	$(s_8, -0.25)$
8	$(s_8, -0.5)$	$(s_6, 0.25)$	$(s_2, 0.25)$	$(s_5, -0.283)$	$(s_5, 0.299)$	$(s_6, -0.092)$	$(s_7, -0.491)$	$(s_7, 0.062)$	$(s_8, -0.5)$
9	$(s_7, 0.25)$	$(s_4, -0.25)$	$(s_2, 0.25)$	$(s_4, -0.065)$	$(s_4, 0.426)$	$(s_5, -0.006)$	$(s_6, -0.362)$	$(s_6, 0.371)$	$(s_7, 0.25)$
10	$(s_8, -0.25)$	$(s_2, 0.25)$	$(s_3, -0.5)$	$(s_4, -0.485)$	$(s_4, -0.002)$	$(s_5, -0.396)$	$(s_5, 0.362)$	$(s_6, 0.342)$	$(s_8, -0.25)$
11	$(s_8, 0)$	$(s_3, 0.25)$	$(s_2, 0.25)$	$(s_4, -0.123)$	$(s_4, 0.413)$	$(s_5, 0.058)$	$(s_6, -0.171)$	$(s_7, -0.234)$	$(s_8, 0)$
12	$(s_8, -0.5)$	$(s_6, 0.25)$	$(s_2, 0.25)$	$(s_5, -0.283)$	$(s_5, 0.299)$	$(s_6, -0.092)$	$(s_7, -0.491)$	$(s_7, 0.062)$	$(s_8, -0.5)$
13	$(s_8, 0)$	$(s_2, 0.25)$	$(s_1, 0.25)$	$(s_3, -0.180)$	$(s_3, 0.407)$	$(s_4, 0.150)$	$(s_5, 0.093)$	$(s_6, 0.313)$	$(s_8, 0)$

4.5. **Comparisons and discussion.** In order to evaluate the proposed method, a numerical verification is performed in Section 4, which compares the proposed approach (integrates 2-tuple and the LOWGA method) with the traditional RPN method and LOWGA method. The input data are shown in Tables 4 and 5. In the comparison of the results of the 3 methods, the differences between the proposed method and the other methods can be clearly shown in Table 10. These main differences of special attributes that are considered between the 3 methods are shown in Table 11. From Tables 6, 7 and 9, this paper has discovered the following findings.

(1) The proposed approach is convenient for the user to differentiate the risk representations in the failures having the same RPN and the same collective value (LOWGA method).

Nos. 3, 4, 6, 10 and 11 have the same RPN of 48 and the same collective value ($\alpha = 0.7$, LOWGA method) of $s_{4.853}$. Regarding the traditional RPN method and LOWGA method, Nos. 3, 4, 6, 10 and 11 have the same priority. However, the different rating combinations might imply different risks. In the proposed method, using an integration of the 2-tuple and LOWGA approach, the rankings of Nos. 3, 4, 6, 10 and 11 are 11, 5, 7, 10 and 5, respectively.

(2) The proposed approach achieved a more accurate risk ranking.

Table 6 clearly show that No. 5 has an RPN value of 72 (S, O and D are 8, 3 and 3, respectively). No. 7 has an RPN value of 64 (S, O and D are 8, 4 and 2, respectively). In this example, it is found that S is 8 for both No. 5 and No. 7. In No. 5, the value of D is higher than No. 7. In No. 7, the value of O is higher than No. 5. For any decision-maker, he should give high allocation resources to defend the most dangerous scenario. He would choose the highest value of 4 in No. 7 as a higher priority. According to the traditional RPN method, No. 5 (RPN = 72) is assumed to be more important than No. 7 (RPN = 64) and is given a higher priority. That is because the traditional RPN method does not consider the ordered weight and obtains biased conclusions. In practice, No. 7 is more important than No. 5. The results of our proposed method show that No. 7 has a higher priority compared with No. 5.

This shows that a more accurate ranking can be achieved by integrating 2-tuple and the LOWGA operator method to evaluate the orders of risk for failure problems.

(3) The proposed method does not lose the useful information provided by the experts.

The traditional RPN method and LOWGA method have the same serious drawback, the "loss of information", which implies a lack of precision in the final results. In this CSTN case, this research can find that the severity of the failure (S) values of No. 1 and No. 2 have the same S value, 8 (based on the traditional RPN method) and the same collective value, s_8 (based on the LOWGA method); thus, they have the same priority based on these 2 approaches. However, in practice, No. 1 is more serious than No. 2. In the proposed method, the 2-tuple linguistic variable (s_i, α) is used to represent the collective value of S. The No. 1 collective value is (s_8, 0.25) and the No. 2 collective value is (s_8, -0.5) for S. The results show that the proposed method is without loss of information, which the experts have to provide.

(4) The proposed approach can reduce the occurrence of duplicated RPN numbers.

From Table 10, the traditional RPN method yielded 4 unique RPN values among 13 items when ranking the risk of failure in the 1.4-inch CSTN product. These elements are formed by the product of the rankings of S, O and D. We then find that the LOWGA method resulted in 4 unique collective values ($\alpha = 0.7$, LOWGA method) among 13 items when ranking the risk of failure in the 1.4-inch CSTN product. The proposed method, using an integrated 2-tuple and LOWGA approach, yielded 9 unique aggregate values ($\alpha = 0.7$, integrates 2-tuple and LOWGA) among 13 items. For this reason, using the proposed approach in assessing system risk, not the traditional RPN and LOWGA methods, is more suitable.

Table 10. The ranking comparison of the traditional RPN method, LOWGA method and the proposed method

No.	RPN	Collective value (LOWGA method)	Aggregate value (integrates 2-tuple and LOWGA)	Ranking RPN	Ranking LOWGA ($\alpha = 0.7$)	Ranking integrates 2-tuple and LOWGA ($\alpha = 0.7$)
1	32	$s_{4.311}$	(s_5, -0.378)	11	11	9
2	32	$s_{4.311}$	(s_4, 0.305)	11	11	12
3	48	$s_{4.853}$	(s_4, 0.349)	6	6	11
4	48	$s_{4.853}$	(s_5, 0.058)	6	6	5
5	72	$s_{5.165}$	(s_5, 0.195)	3	4	4
6	48	$s_{4.853}$	(s_5, 0.027)	6	6	7
7	64	$s_{5.278}$	(s_5, 0.281)	4	3	3
8	96	$s_{5.941}$	(s_6, -0.092)	1	1	1
9	56	$s_{4.902}$	(s_5, -0.006)	5	5	8
10	48	$s_{4.853}$	(s_5, -0.396)	6	6	10
11	48	$s_{4.853}$	(s_5, 0.058)	6	6	5
12	96	$s_{5.941}$	(s_6, -0.092)	1	1	1
13	16	$s_{3.874}$	(s_4, 0.150)	13	13	13

Table 11. The three methods' special attributes and main differences

Method selection	Consider factor		
	Situation parameter	Complete information consideration	Order weight
Traditional RPN method	No	Partial	No
LOWGA method	Yes	Partial	Yes
Proposed method	Yes	Yes	Yes

5. **Conclusions.** This paper proposed an innovative approach, integrating 2-tuple and the LOWGA operator in process FMEA. The main advantage of this study is straightforward and has no loss of information. In addition, this approach has no limitation on the number of risk factors and is applicable to any number of risk factors. In order to further illustrate the proposed method and compare it with the listed techniques of RPN methods, the 1.4-inch CSTN is adopted as a simulation example. This study also compared the simulation results with the traditional RPN method and LOWGA method. The results showed that the proposed approach can effectively solve traditional RPN method shortcomings. It is more convenient to differentiate the risk representations between the failure modes having the same RPN. The analysis results can help managers and engineers to determine which failure modes pose a hazard that must be designed out of the product, which ones can be handled by appropriate corrective actions and mitigation procedures, and which ones can be safely ignored.

The advantages of the proposed approach are summarized as follows.

(1) The proposed method does not lose the useful information provided by the experts.
(2) The proposed method considers the ordered weight of severity, occurrence and detection parameters.
(3) The proposed method provides more accurate and effective information to assist the decision-making process.
(4) The proposed method can reduce the occurrence of duplicate RPN numbers.
(5) The failure information in FMEA is described as linguistic variables; this result is more realistic and is a flexible reflection of the real situation.

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