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Integrating Spherical Fuzzy Sets and the Objective Weights Consideration of Risk Factors for Handling Risk-Ranking Issues

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Abstract: Risk assessments and risk prioritizations are crucial aspects of new product design before a product is launched into the market. Risk-ranking issues involve the information that is considered for the evaluation and objective weighting considerations of the evaluation factors that are presented by the data. However, typical risk-ranking methods cannot effectively grasp a comprehensive evaluation of this information and ignore the objective weight considerations of the risk factors, leading to inappropriate evaluation results. For a more accurate ranking result of the failure mode risk, this study proposes a novel, flexible risk-ranking approach that integrates spherical fuzzy sets and the objective weight considerations of the risk factors to process the risk-ranking issues. In the numerical case validation, a new product design risk assessment of electronic equipment was used as a numerically validated case, and the simulation results were compared with the risk priority number (RPN) method, improved risk priority number (IRPN) method, intuitionistic fuzzy weighted average (IFWA) method, and spherical weighted arithmetic average (SWAA) method. The test outcomes that were confirmed showed that the proposed novel, flexible risk-ranking approach could effectively grasp the comprehensive evaluation information and provide a more accurate ranking of the failure mode risk.

Keywords: spherical fuzzy sets; objective weights; risk ranking; risk priority number; artificial intelligence

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1. Introduction

Risk assessment and risk-ranking issues include multiple evaluation criteria, multiple failure modes, and multiple experts, which can be categorized as multi-criteria decision making (MCDM) problems. The results of the risk assessment and risk-ranking of a product or system directly affect the product quality, profit, and market competitiveness. These risk-ranking problems primarily involve two important issues: the method of evaluating the information processing and the consideration of the risk factor weights. The typical risk priority number (RPN) approach is the most widely applied method for risk assessments and has been adopted by different industry standards, such as QS9000, IATF 16949, MILSTD-1629A, ISO 9001, and IEC 60812 [1]. In the RPN method, the failure risk of the failure mode is ranked using the RPN value, which is obtained by multiplying the three risk factors, severity (*Sev*), occurrence (*Occ*), and detection (*Det*). The RPN method involves simple calculations and, in recent years, has thus been widely applied in various areas, such as hospital radiopharmacy management [2], semiconductor manufacturing [3], robot-assisted rehabilitation processes [4], photovoltaic cell manufacturing [5], power transformer equipment [6], submersible pump risk analyses [7], and high-dose-rate brachytherapy treatments [8]. However, the RPN method is not able to process the uncertainty of the evaluation information [9,10] and ignores the objective weight consideration of the risk factors [4,11], also violating the definition of the measurement scale [12,13].

To process the uncertainty of the evaluation information, Zadeh [14] first presented a fuzzy set for handling the decision making issues in everyday life. The fuzzy set (FS) method applied membership degrees (MD) and non-membership degrees (NMD) to express the content of the evaluation information. The NMD is equal to 1 minus the MD in the FS method. To solve the restriction of the FS, Atanassov [15] proposed an intuitionistic FS to increase the consideration of the indeterminacy degree (ID), which required that the sum of MD, ID, and NMD must be equal to 1. The intuitionistic FS method has the advantage of an ID consideration; therefore, the intuitionistic FS method has recently been used within many different fields, such as stock prediction [16], supplier selection [17], enterprise resource planning systems [18], medical diagnoses [19], risk assessments [20], supply chain management [21], tourist destination selection [22], and so on. Extending the concept of the intuitionistic FS, the picture fuzzy set applied the MD, ID, NMD, and refusal degree to express an expert's opinion [23], and the sum of the MD, ID, and NMD had to be less than or equal to 1. However, in the actual execution of the MCDM problems, sometimes, the sum of the MD and NMD exceeds one. To overcome the restriction of the MD and NMD of the intuitionistic FS, Yager [24] proposed a Pythagorean FS, allowing the sum of the MD and NMD to be greater than 1, but restricting the sum of squares of the MD and NMD to be less than 1. The Pythagorean FS has the advantage of being able to consider the MD, ID, and NMD simultaneously. To fully consider all the possible situations in a decision analysis, Mahmood et al. [25] used a three-dimensional FS mode to propose a spherical FS. A spherical FS allows the sum of the MD, ID, and NMD to be greater than 1, but restricts the sum of the squares of the MD, ID, and NMD to a value of less than 1. The main difference between the spherical FS and Pythagorean FS is that the spherical FS increases the consideration of the refusal degree. In a spherical FS, decision makers can specify the MD, ID, and NMD values [26]. Currently, the spherical FS is being widely used in many different areas, such as vehicle model selection [27], the construction of Fangcang shelter hospitals [28], community epidemic prevention [29], medical diagnoses [30], waste management [31], green supply chain management [32], and performance evaluation [33,34].

Another key issue in risk assessments is the objective weight consideration of the evaluation factors, which affects the accuracy of the risk assessment results. However, the traditional RPN method only considers the subjective assessment of the experts in the risk assessment process, ignoring the objectivity of the research data, which leads to incorrect assessment results [35]. Scholars have also used different calculation methods to deal with the objective weights of the MCDM problems. For example, Liang et al. [36] used the structural entropy weight approach to calculate the indicator weights of the index and then combined the fuzzy technique for order of preference with a similarity to ideal solution (TOPSIS) model, structural entropy weight approach, and cloud inference, in order to process the risk assessments of urban polyethylene gas pipelines. Likewise, Paramanik et al. [37] applied the criteria importance through an intercriteria correlation (CRITIC) approach to obtain the objective weights of the evaluation criteria, and then combined the linear programming technique for a multidimensional analysis of preference and the best–worst approach to process the web service selection problems. Earlier, Barukab et al. [38] combined the spherical FS, entropy measures, and fuzzy TOPSIS methods to process the group decision making problems for a robot selection. Recently, Chang [39] reported the use of the combined compromise solution (CoCoSo) approach and subjective–objective weights consideration to process the supplier selection problems.

To fully solve the limitations of these typical risk assessment methods, considering the information and weights, a novel flexible approach that integrates the spherical FS and objective-weight-considering factors is proposed in this study to process the risk-ranking issues. The proposed novel, flexible risk-ranking approach uses the spherical FS to fully grasp the fuzzy, intuitionistic fuzzy, and spherical fuzzy information that is provided by experts. The proposed approach also uses the preference selection index (PSI) to probe the objective weights of the evaluation factors that are presented by the data itself.

The remainder of this paper is organized as follows. In Section 2, some of the basic concepts, definitions, and algorithm rules of the RPN method, spherical weighted arithmetic average (SWAA) method, and PSI method are presented and briefly reviewed. In Section 3, a novel, flexible risk-ranking approach that integrates the SWAA and PSI methods is proposed. Section 4 presents a risk assessment numerical example of a new electronic equipment product design and compares the calculation results of the RPN, improved risk priority number (IRPN) method, intuitionistic fuzzy weighted average (IFWA) method, SWAA method, and proposed method. Section 5 presents the conclusions and future research directions.

2. Preliminaries

Here, we briefly review some of the basic definitions, concepts, and algorithm rules of the RPN method, SWAA method, and PSI method.

2.1. Risk Priority Number Method

At present, failure mode and effect analysis (FMEA) is the most commonly used risk assessment method by different industries; this method originated in the aerospace industry in the 1950s and has been widely used within different industries since [40]. The FMEA approach uses the *RPN* value to rank the possible failure risks. The *RPN* value is the product of three risk factors with equal weights: severity (*Sev*), occurrence (*Occ*), and detection (*Det*). The *RPN* value is calculated using Equation (1).

$$RPN = Sev \times Occ \times Det \tag{1}$$

The risk factor *Sev* represents the severity of the failure occurrence, *Occ* is the probability of the failure occurrence, and *Det* is the probability that a failure occurrence cannot be detected. These risk factors, *Sev*, *Occ*, and *Det*, use risk assessment ratings of 1–10. The potential failure mode (FM) has a higher RPN value, which means that this FM has a higher risk of failure, and a higher risk priority must be given to prevent the occurrence of such failures.

2.2. Spherical Fuzzy Set Method

The intuitionistic FS is the basis of the spherical FS. The basic principles related to the intuitionistic FS and the calculation rules are described as follows:

Definition 1 [41]. *Assuming that X is the universe of discourse. Then, an intuitionistic FS I in X and the IFWA are expressed as follows:*

$$I = \{x, \mu_I(x), \nu_I(x) | x \in X\} \tag{2}$$

where $\mu_I(x)$ and $\nu_I(x)$ represent the MD and NMD, respectively, and $\mu_I(x)$ and $\nu_I(x) \in [0,1]$ satisfy the condition $\mu_I(x) + \nu_I(x) \leq 1$.

$$IFWA(I_1, I_2, \ldots, I_n) = \left(1 - \prod_{g=1}^{n} (1 - \mu_g(x))^{w_g}, \prod_{g=1}^{n} \nu_g^{w_g}\right) \tag{3}$$

where w_g represents the weight of I_g, $w_g \in [0,1]$ and $\sum_{g=1}^{n} w_g = 1$.

The score value of the intuitionistic FS is defined as follows:

$$Score(I) = \mu_I(x) - \nu_I(x) \tag{4}$$

Mahmood et al. [25] used a three-dimensional FS mode by extending the concepts of the FS, intuitionistic FS, and Pythagorean FS to propose a spherical FS for processing the MCDM problems under uncertain conditions. The basic principles related to the spherical FS and the calculation rules are described as follows.

Definition 2 [42]. *Assuming that X is the universe of discourse, then, a spherical FS S in X is defined as follows:*

$$S = \{x, \mu_S(x), \pi_S(x), \nu_S(x) | x \in X\} \tag{5}$$

where the $\mu_S(x)$, $\pi_S(x)$, and $\nu_S(x)$ represent the MD, ID, and NMD, and $\mu_S(x)$, $\pi_S(x)$, and $\nu_S(x) \in [0,1]$ satisfy the condition $0 \leq (\mu_S(x))^2 + (\pi_S(x))^2 + (\nu_S(x))^2 \leq 1$.

The refusal degree $(R_S(x))$ can be expressed as follows:

$$R_S(x) = \sqrt{1 - (\mu_S(x))^2 - (\pi_S(x))^2 - (\nu_S(x))^2} \tag{6}$$

Definition 3 [42,43]. *Supposing that the $S_1 = \langle \mu_{S_1}(x), \pi_{S_1}(x), \nu_{S_1}(x) \rangle$ and $S_2 = \langle \mu_{S_2}(x), \pi_{S_2}(x), \nu_{S_2}(x) \rangle$ are any two spherical FSs, the basic algorithm rules of the spherical FSs are as follows:*

$$S_1 \oplus S_2 = \left\{ \sqrt{\mu_{S1}^2 + \mu_{S2}^2 - \mu_{S1}^2 \cdot \mu_{S2}^2}, \sqrt{(1 - \mu_{S2}^2) \cdot \pi_{S1}^2 + (1 - \mu_{S1}^2) \cdot \pi_{S2}^2 - \pi_{S1}^2 \cdot \pi_{S2}^2}, \nu_{S1} \cdot \nu_{S2} \right\} \tag{7}$$

$$S_1 \otimes S_2 = \left\{ \mu_{S1} \cdot \mu_{S2}, \sqrt{(1 - \nu_{S2}^2) \cdot \pi_{S1}^2 + (1 - \nu_{S1}^2) \cdot \pi_{S2}^2 - \pi_{S1}^2 \cdot \pi_{S2}^2}, \sqrt{\nu_{S1}^2 + \nu_{S2}^2 - \nu_{S1}^2 \cdot \nu_{S2}^2} \right\} \tag{8}$$

$$kS_1 = \left\{ \sqrt{1 - (1 - \mu_{S1}^2)^k}, \sqrt{(1 - \mu_{S1}^2)^k - (1 - \mu_{S1}^2 - \pi_{S1}^2)^k}, \nu_{S1}^k \right\}; \ k > 0 \tag{9}$$

$$S_1{}^k = \left\{ \mu_{S1}^k, \sqrt{(1 - \nu_{S1}^2)^k - (1 - \nu_{S1}^2 - \pi_{S1}^2)^k}, \sqrt{1 - (1 - \nu_{S1}^2)^k} \right\}; \ k > 0 \tag{10}$$

Definition 4 [43]. *Let $S_g = \langle \mu_S(x), \pi_S(x), \nu_S(x) \rangle$ be the spherical FS and w_g represent the weights of S_g, $w_g \in [0,1]$ and $\sum_{g=1}^n w_g = 1$. The spherical weighted arithmetic average (SWAA) is defined as:*

$$\begin{aligned} &SWAA(S_1, S_2, \ldots, S_n) = \textstyle\sum_{g=1}^n w_g S_g \\ &= \left(\sqrt{1 - \textstyle\prod_{g=1}^n \left(1 - \mu_g^2\right)^{w_g}}, \sqrt{\textstyle\prod_{g=1}^n \left(1 - \mu_g^2\right)^{w_g} - \textstyle\prod_{g=1}^n \left(1 - \mu_g^2 - \pi_g^2\right)^{w_g}}, \textstyle\prod_{g=1}^n \nu_g^{w_g} \right) \end{aligned} \tag{11}$$

Definition 5 [43]. *Let $S_g = \langle \mu_S(x), \pi_S(x), \nu_S(x) \rangle$ be the spherical FS and w_g represent the weight of S_g, $w_g \in [0,1]$ and $\sum_{g=1}^n w_g = 1$. The spherical weighted geometric average (SWGA) is defined as:*

$$\begin{aligned} &SWGA(S_1, S_2, \ldots, S_n) = \textstyle\prod_{g=1}^n S_g{}^{w_g} \\ &= \left(\textstyle\prod_{g=1}^n \mu_g^{w_g}, \sqrt{\textstyle\prod_{g=1}^n \left(1 - \nu_g^2\right)^{w_g} - \textstyle\prod_{g=1}^n \left(1 - \nu_g^2 - \pi_g^2\right)^{w_g}}, \sqrt{1 - \textstyle\prod_{g=1}^n \left(1 - \nu_g^2\right)^{w_g}} \right) \end{aligned} \tag{12}$$

Definition 6 [28,43]. *Let $S_g = \langle \mu_S(x), \pi_S(x), \nu_S(x) \rangle$* be the spherical FS, *$\mu_S(x)$, $\pi_S(x)$, and $\nu_S(x) \in [0,1]$, then the score and accuracy values are defined as follows:*

$$Score(S) = (\mu_S - \pi_S)^2 - (\nu_S - \pi_S)^2 \tag{13}$$

$$Accuracy(S) = \mu_S^2 + \pi_S^2 + \nu_S^2 \tag{14}$$

Definition 7 [1,28]**.** *The comparison rules of the two spherical FSs,* $S_1 = \langle \mu_{S1}(x), \pi_{S1}(x), \nu_{S1}(x) \rangle$ and $S_2 = \langle \mu_{S2}(x), \pi_{S2}(x), \nu_{S2}(x) \rangle$, *are defined as follows.*

(1) If $Score(S_1) > Score(S_2)$, then $S_1 > S_2$;
(2) if $Score(S_1) = Score(S_2)$, and $Accuracy(S_1) > Accuracy(S_2)$, then $S_1 > S_2$;
(3) if $Score(S_1) = Score(S_2)$, and $Accuracy(S_1) = Accuracy(S_2)$, then $S_1 = S_2$.

2.3. The Preference Selection Index (PSI) Method

The PSI approach was first introduced by Maniya and Bhatt [44]; in this approach, statistical concepts are used to calculate the overall preference value of the assessment factors and then process the material selection issues. The algorithm program of the PSI approach is as follows:

(1) Create an initial decision matrix, x_{ij}:

The x_{ij} values represent the values of the ith alternative and jth decision criterion. $i = 1, 2, \ldots, m$, and $j = 1, 2, \ldots, n$.

$$x_{ij} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{15}$$

(2) The decision matrix is normalized as, N_{ij}:

$$N_{ij} = \frac{x_{ij}}{x_j^{max}}, \text{ for the profit decision criteria} \tag{16}$$

$$N_{ij} = \frac{x_j^{min}}{x_{ij}}, \text{ for the cost decision criteria} \tag{17}$$

(3) The preference variation value PV_j is calculated as:

$$PV_j = \sum\nolimits_{i=1}^{m} \left(N_{ij} - \bar{N}_j\right)^2, \ \bar{N}_j = \frac{1}{m}\sum\nolimits_{i=1}^{m} N_{ij} \tag{18}$$

(4) The overall preference value OP_j is calculated as:

$$OP_j = \frac{1 - PV_j}{n - \sum_{j=1}^{n} PV_j} \tag{19}$$

(5) The preference selection value PS_i is calculated as:

$$PS_i = \sum\nolimits_{j=1}^{n} N_{ij} \times OP_j \tag{20}$$

3. Proposed Novel Flexible Risk-Ranking Approach

Failure risk analysis is a crucial factor in product design and manufacturing processes. FMEA is the most commonly and widely used risk assessment method and is used as a different industry standard. It is a systematic, structured approach to risk assessment and uses RPN values to rank the risks of the FM. In product or system failure risk assessment, two main factors need to be considered: the information for the evaluation and the objective weighting considerations of the risk factors that are presented by the data themselves. However, the RPN method cannot process intuitionistic and spherical fuzzy information, nor does it consider the objective weighting of the risk factors that are presented by the data. Moreover, the calculation mode of an RPN method violates the definition of the measurement scale. To solve the restrictions of the RPN method, this study integrated the spherical FS and an objective weight consideration of the risk factors to process these risk-ranking issues. The proposed method uses the MD, ID, and NMD of the spherical FS to represent the assessment information of the risk factors. Thus, the proposed novel, flexible risk-ranking approach can process fuzzy, intuitionistic fuzzy, and spherical fuzzy information simultaneously and can fully consider various types of information. The proposed novel, flexible risk-ranking approach used the PSI approach to calculate the objective weights of the risk factors and the SWAA method to obtain the aggregation values of the risk factors, which solves the problem of the RPN method violating the definition of the measurement scale.

The proposed method can be broadly divided into eight steps (as shown in Figure 1), as follows.

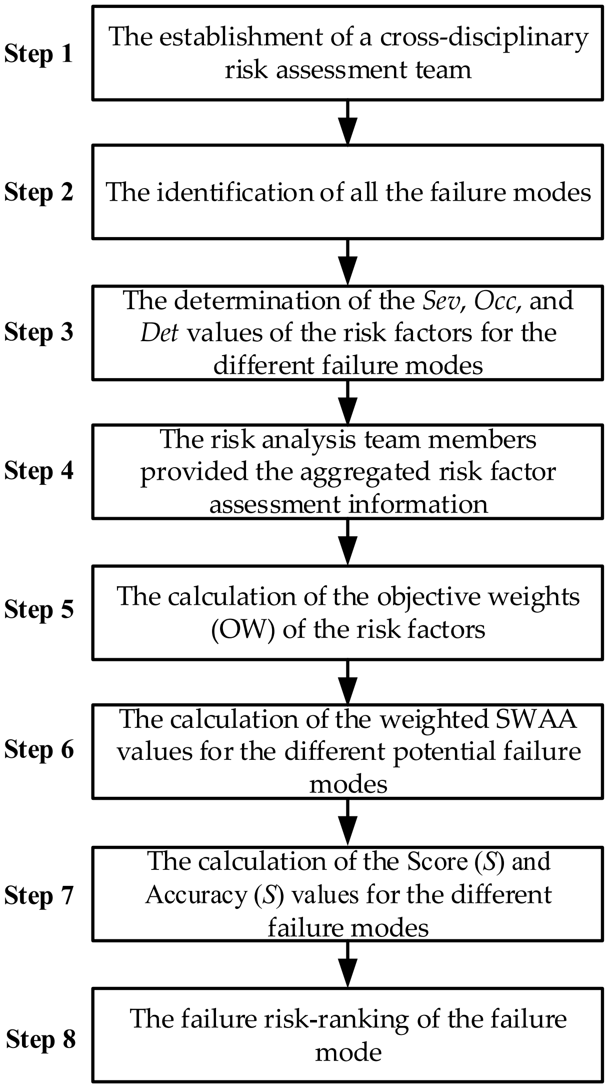

Figure 1. The flowchart of the proposed method.

Step 1. The establishment of a cross-disciplinary risk assessment team.

This was achieved based on their respective professional backgrounds.

Step 2. The identification of all the failure modes.

The risk analysis team members had a discussion to identify all the possible potential FMs based on the risk topic being evaluated.

Step 3. The determination of the *Sev*, *Occ*, and *Det* values of the risk factors for the different failure modes.

The risk analysis team members, according to their professional experience and background, determined the *Sev*, *Occ*, and *Det* values of the risk factors for the different FMs.

Step 4. The risk analysis team members provided the aggregated risk factor assessment information.

Based on the data from Step 3, Equation (11) was used to aggregate the assessment information of the risk factors that were provided by the risk analysis team members.

Step 5. The calculation of the objective weights (OW) of the risk factors.

Based on the data from Step 4, Equations (15)–(18) were used to calculate the preference variation value (PV_j). Then, Equation (19) was used to calculate the overall preference value (OP_j).

Based on the overall preference value (OP_j), Equation (21) was used to calculate the objective weights (OW_j) of the risk factors.

$$OW_j = \frac{(\mu_j - \pi_j)^2 - (v_j - \pi_j)^2}{\sum_{j=1}^{3}\left((\mu_j - \pi_j)^2 - (v_j - \pi_j)^2\right)} \tag{21}$$

Step 6. The calculation of the weighted SWAA values for the different potential failure modes.

Based on the data from Steps 4 and 5, Equation (11) was used to calculate the weighted SWAA values of the different FMs.

Step 7. The calculation of the $Score(S)$ and $Accuracy(S)$ values for the different failure modes.

Based on the data from Step 6, Equations (13) and (14) were used to calculate the $Score(S)$ and $Accuracy(S)$ values of the different FMs, respectively.

Step 8. The failure risk-ranking of the failure mode.

The failure risk of the FM was ranked according to the $Score(S)$ and $Accuracy(S)$ values.

4. Numerical Example

4.1. Case Overview

The completeness of the information considerations and the rationality of the evaluation results of the proposed novel, flexible risk-ranking approach were verified in this study by using the new product design of electronic equipment as a numerically validated case (adapted from [45]). The new product design for electronic equipment requires a risk assessment, avoiding a product failure with limited resources and instantly completing the system design within the specification constraints specified by the customer. The risk analysis assessment team for electronic equipment includes three domain experts (DE1, DE2, and DE3) in engineering and electronic design. The main goal of the risk analysis assessment team is to confirm the possible failure risk items in the product design process of the electronic equipment, correctly sort the risk-ranking of the potential FM, and allocate resources under the limited resources in the best possible way to prevent the occurrence of risks. The relationship between the linguistic terms and spherical fuzzy numbers within the new product design of an electronic equipment case is shown in Table 1, according to which, the domain experts are given these linguistic terms based on the different potential FMs, the results of which are shown in Table 2.

Table 1. Relationship between the linguistic terms and spherical fuzzy numbers.

Linguistic Terms	μ_S	π_S	ν_S
Extremely high impact (EH)	0.95	0.10	0.20
Very high impact (VH)	0.85	0.20	0.30
High impact (HI)	0.75	0.30	0.40
Slightly high impact (SH)	0.65	0.40	0.50
Medium impact (MI)	0.55	0.50	0.60
Slightly low impact (SL)	0.45	0.40	0.70
Low impact (LI)	0.35	0.30	0.80
Very low impact (VL)	0.25	0.20	0.85
Extremely low impact (EL)	0.15	0.10	0.90
Extremely very low impact (EV)	0.10	0.10	0.95

Table 2. Linguistic values of potential failure items given by experts. (FM: failure mode).

Items	**Potential Failure Mode**	*Sev*			*Occ*			*Det*		
		DE1	**DE2**	**DE3**	**DE1**	**DE2**	**DE3**	**DE1**	**DE2**	**DE3**
1	Extremely limited launch time (FM1)	MI	SL	SL	SL	SL	LI	SH	SL	SL
2	Customer request changes (FM2)	SL	SL	LI	SL	SL	LI	EH	EH	VH
3	Lack of aesthetic consideration (FM3)	MI	SL	MI	MI	MI	SL	SH	MI	MI
4	Product technical failure (FM4)	HI	SH	HI	VL	VL	SL	VL	SL	VL
5	Design changes at the last minute (FM5)	VH	EH	EH	SL	SL	SL	SL	SL	SL
6	Poor product performance (FM6)	VH	HI	VH	MI	MI	SL	SH	MI	MI
7	Manufacturing is not ready to start (FM7)	SL	SL	LI	SL	LI	LI	SL	SL	LI
8	Insufficient manufacturing capacity (FM8)	MI	SL	MI	LI	VL	VL	MI	SL	MI
9	Long lead times for materials (FM9)	SL	SL	LI	SL	SL	LI	LI	LI	LI
10	Potential market saturation (FM10)	VL	VL	LI	SH	MI	MI	MI	LI	MI
11	Failed test run (FM11)	SL	LI	SL	LI	SL	LI	LI	SL	LI
12	Customer sample failed (FM12)	MI	SH	MI	MI	LI	MI	SH	MI	MI
13	Insufficient stock to start (FM13)	LI	LI	LI	SL	LI	SL	SL	SL	SL
14	Incorrect market analysis (FM14)	VH	HI	VH	MI	MI	SL	VH	HI	VH
15	Unavailability of any new technology for development (FM15)	LI	LI	SL	SL	SL	SL	SL	LI	LI
16	Environmental compliance not considered (FM16)	LI	SL	LI	SL	LI	LI	LI	LI	SL
17	New technologies in the manufacturing process (FM17)	SH	SL	SL	SL	SL	LI	SL	LI	SL
18	Lack of experts to develop products (FM18)	SL	LI	SL	SL	SL	LI	LI	SL	SL
19	Poor quality raw materials (FM19)	EL	VL	EL	EL	EL	LI	VL	EL	EL

4.2. Solution with the Risk Priority Number Approach

The RPN approach [2] uses the RPN value to rank the possible failure risks. The RPN value is the product of the three equal weighted risk factors: *Sev*, *Occ*, and *Det*. The higher the RPN value that is represented, the higher the risk level of the FM, and it must be given a higher risk prevention priority to prevent the occurrence of this FM. However, the RPN method can only handle the MD information of the FM. As shown in Tables 1 and 2, Equation (1) was used to calculate the RPN value of the electronic equipment new product design failure, and the results are expressed in Table 3.

Table 3. The RPN value of the electronic equipment new product design failure.

Items	*Sev*	*Occ*	*Det*	RPN	Rank
1	0.483	0.417	0.517	0.104	7
2	0.417	0.417	0.917	0.159	5
3	0.517	0.517	0.583	0.156	6
4	0.717	0.317	0.317	0.072	12
5	0.917	0.450	0.450	0.186	3
6	0.817	0.517	0.583	0.246	2
7	0.417	0.383	0.417	0.067	13
8	0.517	0.283	0.517	0.076	10
9	0.417	0.417	0.350	0.061	17
10	0.283	0.583	0.483	0.080	9
11	0.417	0.383	0.383	0.061	16
12	0.583	0.483	0.583	0.164	4
13	0.350	0.417	0.450	0.066	15
14	0.817	0.517	0.817	0.345	1
15	0.383	0.450	0.383	0.066	14
16	0.383	0.383	0.383	0.056	18
17	0.517	0.417	0.417	0.090	8
18	0.417	0.417	0.417	0.072	11
19	0.183	0.217	0.183	0.007	19

4.3. Solution with the Improved Risk Priority Number Method

To solve the problem of the RPN method violating the definition of the measurement scale, the improved risk priority number (IRPN) [46] is used as the sum of the *Sev*, *Occ*, and *Det* risk factors to estimate the IRPN value. The IRPN method is the same as the RPN approach and can only process the MD information of the FM. According to Tables 1 and 2, the sum of *Sev*, *Occ*, and *Det* risk factors was used to calculate the IRPN value for the electronic equipment new product design failure, and the results are expressed in Table 4.

Table 4. The IRPN value of the electronic equipment new product design failure.

Items	*Sev*	*Occ*	*Det*	IRPN	Rank
1	0.483	0.417	0.517	1.417	7
2	0.417	0.417	0.917	1.750	4
3	0.517	0.517	0.583	1.617	6
4	0.717	0.317	0.317	1.350	8
5	0.917	0.450	0.450	1.817	3
6	0.817	0.517	0.583	1.917	2
7	0.417	0.383	0.417	1.217	13
8	0.517	0.283	0.517	1.317	11
9	0.417	0.417	0.350	1.183	16
10	0.283	0.583	0.483	1.350	8
11	0.417	0.383	0.383	1.183	16
12	0.583	0.483	0.583	1.650	5
13	0.350	0.417	0.450	1.217	13
14	0.817	0.517	0.817	2.150	1
15	0.383	0.450	0.383	1.217	13
16	0.383	0.383	0.383	1.150	18
17	0.517	0.417	0.417	1.350	8
18	0.417	0.417	0.417	1.250	12
19	0.183	0.217	0.183	0.583	19

4.4. Solution with the Intuitionistic Fuzzy Weighted Average Method

The intuitionistic fuzzy weighted average (IFWA) method [41] can simultaneously consider the MD and NMD in the risk assessment problem of the new product design of the electronic equipment. According to Tables 1 and 2, Equations (3) and (4) were used to calculate the IFWA and score values for the electronic equipment new product design failure, and results are expressed in Table 5.

Table 5. The IFWA value of the electronic equipment new product design failure.

Items	*Sev*	*Occ*	*Det*	IFWA	$Score(I)$	Rank
1	(0.486, 0.514)	(0.419, 0.581)	(0.527, 0.473)	(0.479, 0.521)	−0.042	8
2	(0.419, 0.581)	(0.419, 0.581)	(0.928, 0.072)	(0.710, 0.290)	0.420	3
3	(0.519, 0.481)	(0.519, 0.481)	(0.586, 0.414)	(0.542, 0.458)	0.085	6
4	(0.720, 0.280)	(0.324, 0.676)	(0.324, 0.676)	(0.496, 0.504)	−0.008	7
5	(0.928, 0.072)	(0.450, 0.550)	(0.450, 0.550)	(0.721, 0.279)	0.441	2
6	(0.822, 0.178)	(0.519, 0.481)	(0.586, 0.414)	(0.672, 0.328)	0.343	4
7	(0.419, 0.581)	(0.385, 0.615)	(0.419, 0.581)	(0.408, 0.592)	−0.185	13
8	(0.519, 0.481)	(0.285, 0.715)	(0.519, 0.481)	(0.451, 0.549)	−0.098	11
9	(0.419, 0.581)	(0.419, 0.581)	(0.350, 0.650)	(0.397, 0.603)	−0.207	16
10	(0.285, 0.715)	(0.586, 0.414)	(0.491, 0.509)	(0.468, 0.532)	−0.064	9
11	(0.419, 0.581)	(0.385, 0.615)	(0.385, 0.615)	(0.397, 0.603)	−0.207	16
12	(0.586, 0.414)	(0.491, 0.509)	(0.586, 0.414)	(0.557, 0.443)	0.113	5
13	(0.350, 0.650)	(0.419, 0.581)	(0.450, 0.550)	(0.408, 0.582)	−0.185	13
14	(0.822, 0.172)	(0.519, 0.481)	(0.822, 0.178)	(0.752, 0.248)	0.504	1
15	(0.385, 0.615)	(0.450, 0.550)	(0.385, 0.615)	(0.408, 0.592)	−0.185	13
16	(0.385, 0.615)	(0.385, 0.615)	(0.385, 0.615)	(0.385, 0.615)	−0.230	18
17	(0.527, 0.473)	(0.419, 0.581)	(0.419, 0.581)	(0.457, 0.543)	−0.086	10
18	(0.419, 0.581)	(0.419, 0.581)	(0.419, 0.581)	(0.419, 0.581)	−0.163	12
19	(0.185, 0.815)	(0.223, 0.777)	(0.185, 0.815)	(0.198, 0.802)	−0.605	19

4.5. Solution with the Spherical Weighted Arithmetic Average Method

The spherical weighted arithmetic average (SWAA) method [43] can simultaneously consider the MD, ID, and NMD of the new product design of the electronic equipment. As mentioned in Tables 1 and 2, Equation (11) was used to aggregate the evaluation opinions of the different domain experts on the risk factors *Sev*, *Occ*, and *Det*. Then, Equations (11), (13) and (14) were used to calculate the SWAA, score, and accuracy values for the electronic equipment new product design failure, and the results are expressed in Table 6.

Table 6. The SWAA, score, and accuracy values of the electronic equipment new product design failure.

Items	*Sev*	*Occ*	*Det*	SWAA	$Score(S)$	$Accuracy(S)$	Rank
1	(0.487, 0.443, 0.665)	(0.420, 0.373, 0.732)	(0.533, 0.403, 0.626)	(0.484, 0.409, 0.673)	−0.064	0.854	8
2	(0.420, 0.373, 0.732)	(0.420, 0.373, 0.732)	(0.928, 0.127, 0.229)	(0.739, 0.263, 0.497)	0.172	0.862	3
3	(0.520, 0.475, 0.632)	(0.520, 0.475, 0.632)	(0.587, 0.467, 0.565)	(0.544, 0.473, 0.608)	−0.013	0.890	6
4	(0.721, 0.332, 0.431)	(0.334, 0.296, 0.797)	(0.334, 0.296, 0.797)	(0.526, 0.324, 0.649)	−0.065	0.803	9
5	(0.928, 0.127, 0.229)	(0.450, 0.400, 0.700)	(0.450, 0.400, 0.700)	(0.745, 0.278, 0.482)	0.177	0.865	2
6	(0.823, 0.231, 0.330)	(0.520, 0.475, 0.632)	(0.587, 0.467, 0.565)	(0.681, 0.382, 0.490)	0.078	0.850	4
7	(0.420, 0.373, 0.732)	(0.387, 0.341, 0.765)	(0.420, 0.373, 0.732)	(0.410, 0.363, 0.743)	−0.142	0.851	13
8	(0.520, 0.475, 0.632)	(0.288, 0.240, 0.833)	(0.520, 0.475, 0.632)	(0.461, 0.431, 0.693)	−0.068	0.878	10
9	(0.420, 0.373, 0.732)	(0.420, 0.373, 0.732)	(0.350, 0.300, 0.800)	(0.399, 0.352, 0.754)	−0.159	0.851	16
10	(0.288, 0.240, 0.833)	(0.587, 0.467, 0.565)	(0.497, 0.461, 0.660)	(0.482, 0.424, 0.677)	−0.061	0.871	7
11	(0.420, 0.373, 0.732)	(0.387, 0.341, 0.765)	(0.387, 0.341, 0.765)	(0.399, 0.352, 0.754)	−0.159	0.851	16
12	(0.587, 0.467, 0.565)	(0.497, 0.461, 0.660)	(0.587, 0.467, 0.565)	(0.560, 0.466, 0.595)	−0.008	0.885	5
13	(0.350, 0.300, 0.800)	(0.420, 0.373, 0.732)	(0.450, 0.400, 0.700)	(0.410, 0.363, 0.743)	−0.142	0.851	13
14	(0.823, 0.231, 0.330)	(0.520, 0.475, 0.632)	(0.823, 0.231, 0.330)	(0.759, 0.303, 0.410)	0.197	0.836	1
15	(0.387, 0.341, 0.765)	(0.450, 0.400, 0.700)	(0.387, 0.341, 0.765)	(0.410, 0.363, 0.743)	−0.142	0.851	13
16	(0.387, 0.341, 0.765)	(0.387, 0.341, 0.765)	(0.387, 0.341, 0.765)	(0.387, 0.341, 0.765)	−0.178	0.852	18
17	(0.533, 0.403, 0.626)	(0.420, 0.373, 0.732)	(0.420, 0.373, 0.732)	(0.463, 0.385, 0.695)	−0.090	0.845	11
18	(0.420, 0.373, 0.732)	(0.420, 0.373, 0.732)	(0.420, 0.373, 0.732)	(0.420, 0.373, 0.732)	−0.126	0.852	12
19	(0.190, 0.143, 0.883)	(0.239, 0.199, 0.865)	(0.190, 0.143, 0.883)	(0.208, 0.164, 0.877)	−0.506	0.839	19

4.6. Solution with the Proposed Novel Flexible Risk-Ranking Approach

To solve the restrictions of the typical risk assessment approach in its information processing and objective weighting considerations, the proposed method integrates the spherical FS and considers the objective weights of the risk factors to process the risk-ranking issues. The proposed novel, flexible approach is implemented in eight distinct steps, as described below. The process first must establish a cross-disciplinary risk assessment team, identify all the potential FMs, and determine the *Ser*, *Occ*, and *Det* values of the risk factors for the different potential FMs (Steps 1–3).

Step 4. The risk analysis team members provided the aggregated risk factor assessment information.

Based on Tables 1 and 2, Equation (11) was used to aggregate the evaluation opinions of the different domain experts on the risk factors *Sev*, *Occ*, and *Det*, and the results are expressed in Table 7.

Table 7. The weighted SWAA, score, and accuracy values of the proposed method.

Items	*Sev*	*Occ*	*Det*	Weighted SWAA	$Score(S)$	$Accuracy(S)$	Rank
1	(0.487, 0.443, 0.665)	(0.420, 0.373, 0.732)	(0.533, 0.403, 0.626)	(0.450, 0.403, 0.704)	−0.088	0.860	9
2	(0.420, 0.373, 0.732)	(0.420, 0.373, 0.732)	(0.928, 0.127, 0.229)	(0.476, 0.360, 0.703)	−0.104	0.850	10
3	(0.520, 0.475, 0.632)	(0.520, 0.475, 0.632)	(0.587, 0.467, 0.565)	(0.523, 0.475, 0.629)	−0.021	0.895	5
4	(0.721, 0.332, 0.431)	(0.334, 0.296, 0.797)	(0.334, 0.296, 0.797)	(0.534, 0.325, 0.641)	−0.056	0.802	7
5	(0.928, 0.127, 0.229)	(0.450, 0.400, 0.700)	(0.450, 0.400, 0.700)	(0.755, 0.272, 0.472)	0.194	0.867	1
6	(0.823, 0.231, 0.330)	(0.520, 0.475, 0.632)	(0.587, 0.467, 0.565)	(0.675, 0.378, 0.500)	0.073	0.849	3
7	(0.420, 0.373, 0.732)	(0.387, 0.341, 0.765)	(0.420, 0.373, 0.732)	(0.401, 0.354, 0.752)	−0.156	0.851	15
8	(0.520, 0.475, 0.632)	(0.288, 0.240, 0.833)	(0.520, 0.475, 0.632)	(0.401, 0.375, 0.748)	−0.138	0.861	14
9	(0.420, 0.373, 0.732)	(0.420, 0.373, 0.732)	(0.350, 0.300, 0.800)	(0.418, 0.371, 0.734)	−0.130	0.852	13
10	(0.288, 0.240, 0.833)	(0.587, 0.467, 0.565)	(0.497, 0.461, 0.660)	(0.509, 0.427, 0.651)	−0.044	0.865	6
11	(0.420, 0.373, 0.732)	(0.387, 0.341, 0.765)	(0.387, 0.341, 0.765)	(0.399, 0.353, 0.753)	−0.158	0.851	16
12	(0.587, 0.467, 0.565)	(0.497, 0.461, 0.660)	(0.587, 0.467, 0.565)	(0.535, 0.464, 0.621)	−0.020	0.888	4
13	(0.350, 0.300, 0.800)	(0.420, 0.373, 0.732)	(0.450, 0.400, 0.700)	(0.399, 0.352, 0.754)	−0.159	0.851	17
14	(0.823, 0.231, 0.330)	(0.520, 0.475, 0.632)	(0.823, 0.231, 0.330)	(0.684, 0.370, 0.491)	0.084	0.846	2
15	(0.387, 0.341, 0.765)	(0.450, 0.400, 0.700)	(0.387, 0.341, 0.765)	(0.427, 0.380, 0.725)	−0.117	0.852	11
16	(0.387, 0.341, 0.765)	(0.387, 0.341, 0.765)	(0.387, 0.341, 0.765)	(0.387, 0.341, 0.765)	−0.178	0.852	18
17	(0.533, 0.403, 0.626)	(0.420, 0.373, 0.732)	(0.420, 0.373, 0.732)	(0.465, 0.386, 0.692)	−0.088	0.845	8
18	(0.420, 0.373, 0.732)	(0.420, 0.373, 0.732)	(0.420, 0.373, 0.732)	(0.420, 0.373, 0.732)	−0.126	0.852	12
19	(0.190, 0.143, 0.883)	(0.239, 0.199, 0.865)	(0.190, 0.143, 0.883)	(0.221, 0.180, 0.872)	−0.478	0.842	19

Step 5. The calculation of the objective weights (OW) of the risk factors.

Based on the data from Step 4, Equations (15)–(18) were used to calculate the preference variation value (PV_j), as given below:

$$PV_{Sev} = (0.670, 0.192, 0.607);\ PV_{Occ} = (0.126, 0.106, 0.099);\ PV_{Det} = (0.517, 0.190, 0.464)$$

According to the preference variation value (PV_j), Equation (19) was used to calculate the overall preference value (OP_j), as given below:

$$OP_{Sev} = (0.196, 0.322, 0.215);\ OP_{Occ} = (0.518, 0.356, 0.492);\ OP_{Det} = (0.286, 0.322, 0.293)$$

According to the overall preference value (OP_j), Equation (21) was used to calculate the objective weights (OW_j) of the risk factors, as given below:

$$OW_{Sev} = 0.353;\ OW_{Occ} = 0.612;\ OW_{Det} = 0.035$$

Step 6. The weighted SWAA values for the different potential failure modes were calculated.

Based on the data from Steps 4 and 5, Equation (11) was used to calculate the weighted SWAA values of the different potential FMs; the results are expressed in Table 7.

Step 7. The calculation of the $Score(S)$ and $Accuracy(S)$ values for the different failure modes.

Based on the data from Step 6, Equations (13) and (14) were used to calculate the $Score(S)$ and $Accuracy(S)$ values of the different potential FMs, respectively, and the results are expressed in Table 7.

Step 8. The failure risk-ranking of the failure mode.

According to the $Score(S)$ and $Accuracy(S)$ values, the comparison rules of the spherical FS (Definition 7) were applied to the failure risk-ranking of the potential FM, and the results are expressed in Table 7.

4.7. Comparison between Different Methods

In order to verify the comprehensiveness and effectiveness of the proposed novel, flexible risk-ranking approach in the information processing and weight processing of the risk-ranking problem, Section 4 adopts a risk assessment case of the new product design of electronic equipment to verify and compare its calculation results with the RPN method, IRPN method, IFWA method, and SWAA method. These five calculation methods were calculated using the same input data (Tables 1 and 2). After the calculation, the risk-ranking results of the different calculation methods for the potential FMs are expressed in Table 8 and Figure 2. The main differences in the factors considered by the five different calculation approaches are expressed in Table 9.

Table 8. The risk-ranking results of different calculation methods for potential failure mode.

Items	**RPN Method [2]**		**IRPN Method [46]**		**IFWA Method [41]**		**SWAA Method [43]**			**Proposed Method**		
	RPN	**Rank**	**IRPN**	**Rank**	$Score(I)$	**Rank**	$Score(S)$	$Accuracy(S)$	**Rank**	$Score(S)$	$Accuracy(S)$	**Rank**
1	0.104	7	1.417	7	−0.042	8	−0.064	0.854	8	−0.088	0.860	9
2	0.159	5	1.750	4	0.420	3	0.172	0.862	3	−0.104	0.850	10
3	0.156	6	1.617	6	0.085	6	−0.013	0.890	6	−0.021	0.895	5
4	0.072	12	1.350	8	−0.008	7	−0.065	0.803	9	−0.056	0.802	7
5	0.186	3	1.817	3	0.441	2	0.177	0.865	2	0.194	0.867	1
6	0.246	2	1.917	2	0.343	4	0.078	0.850	4	0.073	0.849	3
7	0.067	13	1.217	13	−0.185	13	−0.142	0.851	13	−0.156	0.851	15
8	0.076	10	1.317	11	−0.098	11	−0.068	0.878	10	−0.138	0.861	14
9	0.061	17	1.183	16	−0.207	16	−0.159	0.851	16	−0.130	0.852	13
10	0.080	9	1.350	8	−0.064	9	−0.061	0.871	7	−0.044	0.865	6
11	0.061	16	1.183	16	−0.207	16	−0.159	0.851	16	−0.158	0.851	16
12	0.164	4	1.650	5	0.113	5	−0.008	0.885	5	−0.020	0.888	4
13	0.066	15	1.217	13	−0.185	13	−0.142	0.851	13	−0.159	0.851	17
14	0.345	1	2.150	1	0.504	1	0.197	0.836	1	0.084	0.846	2
15	0.066	14	1.217	13	−0.185	13	−0.142	0.851	13	−0.117	0.852	11
16	0.056	18	1.150	18	−0.230	18	−0.178	0.852	18	−0.178	0.852	18
17	0.090	8	1.350	8	−0.086	10	−0.090	0.845	11	−0.088	0.845	8
18	0.072	11	1.250	12	−0.163	12	−0.126	0.852	12	−0.126	0.852	12
19	0.007	19	0.583	19	−0.605	19	−0.506	0.839	19	−0.478	0.842	19

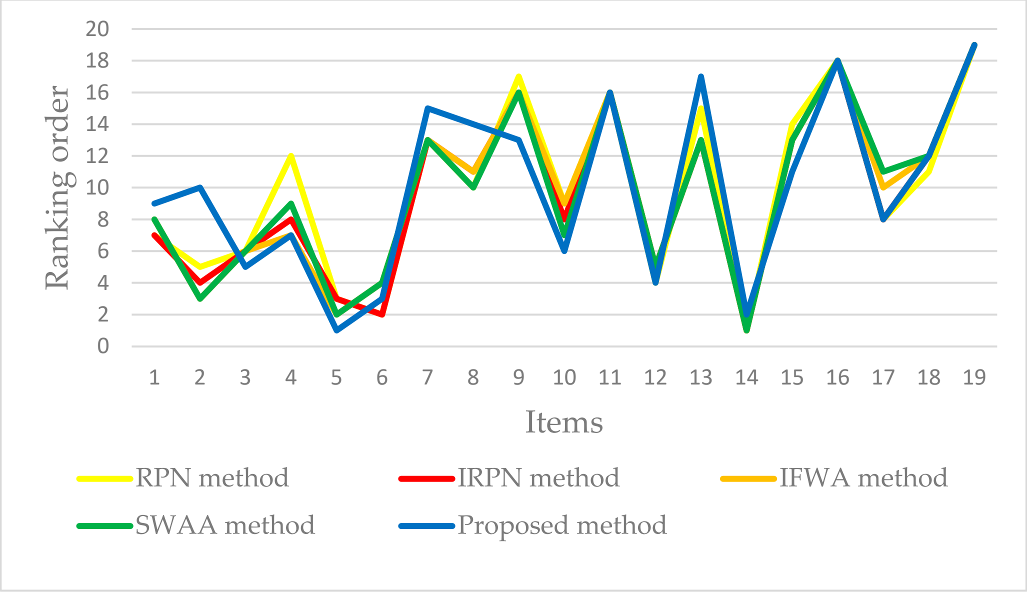

Figure 2. The risk-ranking results of different calculation methods.

Table 9. The main differences in factors considered by different calculation methods.

	Information Consideration		Measurement Scale Consideration	Objective Weight Consideration
	Intuitionistic Fuzzy Information	Spherical Fuzzy Information		
RPN method [2]	No	No	No	No
IRPN method [46]	No	No	Yes	No
IFWA method [41]	Yes	No	Yes	No
SWAA method [43]	Yes	Yes	Yes	No
Proposed method	Yes	Yes	Yes	Yes

According to the contents of Tables 3–9, the primary advantages of the proposed novel, flexible risk-ranking approach over the other calculation methods are as follows. Firstly, its information consideration is an advantage; both the RPN method and IRPN method can only process the MD information of a potential FM, and cannot handle the ID and refusal degree information, while the IFWA method can effectively grasp the intuitionistic fuzzy information that is provided by the experts on the risk factors (MD, ID, and NMD information of a potential FM). However, the IFWA method still cannot effectively deal with the spherical fuzzy information (MD, ID, NMD, and refusal degree information of a potential FM) that is provided by the experts on the risk factors. The SWAA method and the proposed method can simultaneously process the MD, ID, NMD, and refusal degree information of a potential FM and can fully consider various types of information.

Secondly, its measurement scale consideration is also advantageous. The attributes of the data distinguish the different measurement scales. The measurement scale includes the nominal scale, ordinal scale, interval scale, and ratio scale. The data attributes of the risk factors belong to the ordinal scale, and the geometric mean cannot be used for calculation. The RPN method uses the concept of the Ser, Occ, and Det risk factor products for its calculation; this violates the definition of the measurement scale and leads to biased risk-ranking results. The IRPN, IFWA, SWAA, and the proposed novel, flexible risk-ranking approach can fully consider the definition of the data attribute measurement scale and apply a more reasonable calculation mode.

The other advantage is its objective weight consideration. The RPN, IRPN, IFWA, and SWAA methods ignore the objective weighting considerations of the risk factors that are presented by the data, which may lead to distortion of the risk-ranking results. The proposed novel approach used the PSI technique to calculate the objective weights of the different risk factors to truly reflect the significance of the data.

5. Conclusions

For any industry, risk analysis and risk prioritization are key issues. Maximizing the yield rate of products under limited resources will ensure the profitability of the company and the overall customer satisfaction. Risk analysis and risk ranking must be considered as the processing modes of the information evaluation and the relative weight of the risk factors. The lack of a comprehensive evaluation information consideration or ignoring the objective weighting of the risk factors can lead to incorrect evaluation results. However, most of the risk-ranking methods cannot simultaneously handle the comprehensive evaluation information consideration, measurement scale consideration, and relative weight of the risk factors, which causes biased risk-ranking results. This study proposed a novel, flexible risk-ranking approach to obtain rigorous and correct risk-ranking results; here, the spherical FS and objective weight considerations of the risk factors are integrated to process the risk-ranking issues.

The contributions of the proposed novel, flexible risk-ranking method are as follows:

(1) The proposed novel, flexible risk-ranking method can grasp the information on the intuitionistic fuzzy evaluation of the risk factors,

(2) The proposed novel, flexible risk-ranking method can grasp the information on the spherical fuzzy evaluation of the risk factors,

(3) The proposed novel, flexible risk-ranking method considers the measurement scale of the data,

(4) The proposed novel, flexible risk-ranking method considers the relative weights of the risk factors,

(5) The IRPN, IFWA, and SWAA methods are special examples of the proposed novel, flexible risk-ranking method.

In the future, researchers can extend the concept of the proposed method to process different decision making problems such as performance evaluation, supplier selection, reliability evaluation, green energy planning, resource allocation, big data processing, and project management. In addition, future researchers can probe the impact of different subjective and objective weight combinations on their risk-ranking results.

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