information

MDPI

Article

Failure Mode and Effect Analysis (FMEA) with Extended MULTIMOORA Method Based on Interval-Valued Intuitionistic Fuzzy Set: Application in Operational Risk Evaluation for Infrastructure

Lelin Lv [1,2], Huimin Li [1,3,*], Lunyan Wang [1,3], Qing Xia [1,2] and Li Ji [1]

1 Department of Construction Engineering and Management, North China University of Water Resources and Electric Power, Zhengzhou 450046, China; lvlelin1205@163.com (L.L.); wanglunyan@ncwu.edu.cn (L.W.); xiaqingncwu@163.com (Q.X.); jili@stu.ncwu.edu.cn (L.J.)
2 Academician Workstation of Water Environment Governance and Ecological Restoration, Zhengzhou 450002, China
3 Henan Key Laboratory of Water Environment Simulation and Treatment, Zhengzhou 450045, China
* Correspondence: lihuimin3646@163.com; Tel.: +86-150-3906-3656

Received: 7 September 2019; Accepted: 11 October 2019; Published: 13 October 2019

check for updates

Abstract: Failure Mode and Effect Analysis (FMEA) is a useful risk assessment tool used to identify, evaluate, and eliminate potential failure modes in numerous fields to improve security and reliability. Risk evaluation is a crucial step in FMEA and the Risk Priority Number (RPN) is a classical method for risk evaluation. However, the traditional RPN method has deficiencies in evaluation information, risk factor weights, robustness of results, etc. To overcome these shortcomings, this paper aims to develop a new risk evaluation in FMEA method. First, this paper converts linguistic evaluation information into corresponding interval-valued intuitionistic fuzzy numbers (IVIFNs) to effectively address the uncertainty and vagueness of the information. Next, different priorities are assigned to experts using the interval-valued intuitionistic fuzzy priority weight average (IVIFPWA) operator to solve the problem of expert weight. Then, the weights of risk factors are subjectively and objectively determined using the expert evaluation method and the deviation maximization model method. Finally, the paper innovatively introduces the interval-valued intuitionistic fuzzy weighted averaging (IVIFWA) operator, Tchebycheff Metric distance, and the interval-valued intuitionistic fuzzy weighted geometric (IVIFWG) operator into the ratio system, the reference point method, and the full multiplication form of MULTIMOORA sub-methods to optimize the information aggregation process of FMEA. The extended IVIF-MULTIMOORA method is proposed to obtain the risk ranking order of failure modes, which will help in obtaining more reasonable and practical results and in improving the robustness of results. The case of the Middle Route of the South-to-North Water Diversion Project's operation risk is used to demonstrate the application and effectiveness of the proposed FMEA framework.

Keywords: failure mode and effect analysis; risk management; MULTIMOORA; interval-valued intuitionistic fuzzy sets; operational risk

1. Introduction

The Failure Mode and Effect Analysis (FMEA) method was first proposed in the 1960s [1], and it has been widely used to ensure safe and stable production and operation in the aerospace industry, electric power industry, nuclear industry, and handicraft industry, etc. [2–4]. FMEA can improve the reliability of systems by identifying and avoiding potential failures or errors [5].

Risk evaluation is a key step in FMEA, which aims to identify high-risk failure modes and improve system design to eliminate risks [6,7]. The traditional FMEA always uses the Risk Priority Number (RPN) method to represent the influence caused by failure modes, i.e., the level of risk [8,9]. By analyzing potential failure modes and their possible effects, the RPN method uses an integer scale from 1 to 10 for estimating the actual performance of different failure modes under the three risk factors of occurrence (O), severity (S), and detection (D). The RPN value is determined by multiplying the evaluation value of these three risk factors. The higher the RPN value of a failure mode, the higher the risk degree of that failure mode and the greater the possible harm to the system. Therefore, it is necessary to take appropriate actions to prevent the high-risk failure modes [10]. The risk evaluation in traditional FMEA with the RPN method is considered to be the most effective method for the prevention of risks in advance, but applying the RPN method has been widely questioned in practice [10–14]. This is mainly due to the following aspects: (1) The traditional RPN method uses exact values to express the risk level for risk factors O, S, and D, but this expression is limited by its inability to objectively reflect the complexity and uncertainty of things and the fuzziness of human thinking in processing information. (2) The weight information of risk factors is not considered in the traditional FMEA risk assessment. All risk factors are regarded as equally important, which is inconsistent with the varied importance that each factor has in actual situations. (3) Different combinations of numerical scores for O, S and D may generate exactly the same RPN value, but the risk implications may be entirely different, which is likely to lead to some high-risk failure modes going unnoticed. (4) The method of obtaining the RPN value using the numerical product calculation of risk factors O, S, and D lacks reliability because the RPN value will be highly sensitive to changes in the critical factor evaluation. (5) The robustness of a single decision-making method is relatively low. It is easy for different failure modes to have the same risk priority value, making it is difficult to determine a risk ranking order, and the unreasonable information aggregation process will cause information loss.

To resolve the defects of the traditional FMEA, scholars have put forward many improvement methods [15–18]. In particular, the integrated research and application of the FMEA method and the fuzzy theory method are widely concerned, because the fuzzy method such as the fuzzy Delphi method [19] and the fuzzy inference system [20] has the advantage of conducting risk assessment based on expert knowledge and experience [21]. Panchal et al. [22] used triangular and trapezoidal fuzzy numbers to represent FMEA information to evaluate the risk of failure modes. Ekmekcioglu et al. [23] proposed a FMEA risk assessment method based on trapezoidal fuzzy numbers. Chang [24] introduced binary semantic variables as information carriers to optimize FMEA. Vahdani et al. [25] combined a fuzzy belief structure with TOPSIS to propose a FMEA method based on a fuzzy confidence structure. Wang et al. [26] presented a new risk priority model for FMEA by using the House of Reliability—Based Rough VIKOR approach. Chen and Deng [14] proposed a new FMEA model using the Dempster-Shafer evidence theory and the grey relational projection method. Moreover, Atanassov [27,28] defined the intuitionistic fuzzy sets (IFSs) and the interval-valued intuitionistic fuzzy sets (IVIFSs) theory based on fuzzy set theory, which considers three kinds of information, namely membership degree, nonmembership degree, and hesitation degree. Therefore, IVIFSs are more flexible and practical than other theories in the expression of uncertainty, and it can be usefully applied to the FMEA method.

On the other hand, for complex risk management and investment decisions, scholars have proposed some countermeasures, such as FMEA and simulation analysis [29]. The essence of FMEA can also be regarded as a multiple criteria decision making (MCDM) problem. Together with the VIKOR [30,31], TOPSIS [32–34], AHP [35,36], and DEMATEL [37,38] methods, MCDM is widely used in FMEA research to improve the traditional ranking order method of risk priority value. However, the above MCDM methods have single decision-making modes, and the robustness of their ranking order still needs to be improved. The MULTIMOORA method is a robust and flexible MCDM technique [39]. The MOORA approach, primarily put forward by Brauers and Zavadskas [40], includes two sub-methods: the ratio system method and the reference point method. Subsequently, the MOORA method was extended, i.e., MULTIMOORA method, which was proposed by Brauers and

Zavadskas [41]. This method adds a new sub-method based on MOORA, i.e., the full multiplication form method. Brauers [42] systematically studied the robustness of MCDM methods, and proposed that a MCDM method that combines two decision-making methods is superior to a single MCDM method. Similarly, a MCDM method combining three decision-making methods is superior to a method that only combines two different decision-making methods. The MULTIMOORA method is characterized by being simple to calculate and having strong robustness [43], and it has been extended and applied in numerous fields for solving real-life MCDM problems.

In practical application of FMEA, the traditional MULTIMOORA method cannot address the uncertainty and vagueness of information. Yet, the IVIFSs can better address the expression of linguistic uncertainty, which is more flexible and practical. Hence, the motivation of this paper is to merge IVIFSs into the MULTIMOORA method of FMEA risk assessment, which can not only effectively deal with these problems, but also improve the robustness of the results [44,45]. In addition, most existing FMEA related research directly assigns weight to experts and risk factors, ignoring the importance of how weight affects the accuracy of research results. Therefore, to overcome these shortcomings, this paper aims to develop a new risk evaluation in FMEA using the MULTIMOORA method within the context of IVIFSs. First, this paper converts linguistic evaluation information into corresponding interval-valued intuitionistic fuzzy numbers (IVIFNs) to effectively address the uncertainty and vagueness of the information. Next, different priorities are assigned to experts using the interval-valued intuitionistic fuzzy priority weight average (IVIFPWA) operator to solve the problem of expert weight. Then, the weights of risk factors are subjectively and objectively determined using the expert evaluation method and the deviation maximization model method. Finally, the paper innovatively introduces the interval-valued intuitionistic fuzzy weighted averaging (IVIFWA) operator, Tchebycheff Metric distance, and the interval-valued intuitionistic fuzzy weighted geometric (IVIFWG) operator into the ratio system, the reference point method, and the full multiplication form of MULTIMOORA sub-methods to optimize the information aggregation process of FMEA. The extended IVIF-MULTIMOORA method is proposed to obtain the risk ranking order of failure modes, which will help in obtaining more reasonable and practical results and in improving the robustness of results. The case of the Middle Route of the South-to-North Water Diversion Project's operation risk is used to demonstrate the application and effectiveness of the proposed FMEA framework.

This paper is organized as follows. Section 2 introduces preliminaries about IVIFSs and the traditional MULTIMOORA method. Section 3 proposes a risk evaluation in FMEA with the extended MULTIMOORA method in an interval-valued intuitionistic fuzzy environment. Section 4 provides a case study of the Middle Route of the South-to-North Water Diversion Project's operation risk to demonstrate the application and effectiveness of the proposed method. Section 5 includes sensitivity analysis and comparison analysis. Section 6 offers conclusions and further research directions.

2. Preliminaries

2.1. Interval-Valued Intuitionistic Fuzzy Sets

Definition 1 ([28]). *Let X be a non-empty set; then an interval-valued intuitionistic fuzzy set (IVIFS) was defined as follows:*

$$\widetilde{A} = \left\{ \left\langle x, \mu_{\widetilde{A}}(x), \upsilon_{\widetilde{A}}(x) \right\rangle | x \in X \right\} \tag{1}$$

where $\mu_{\widetilde{A}}(x)$ denotes the membership degree of the element x belonging to X; $\upsilon_{\widetilde{A}}(x)$ denotes the nonmembership degree of the element x belonging to X; $\mu_{\widetilde{A}}(x) : X \to [0,1]$ and $\upsilon_{\widetilde{A}}(x) : X \to [0,1]$ with the condition $0 \leq \sup\mu_{\widetilde{A}}(x) + \sup\upsilon_{\widetilde{A}}(x) \leq 1$.

Definition 2 ([28,46]). *For every $x \in X$, $\mu_{\widetilde{A}}(x)$ and $\upsilon_{\widetilde{A}}(x)$ are closed intervals whose lower and upper end points are denoted by $\mu^{-}_{\widetilde{A}}(x)$, $\mu^{+}_{\widetilde{A}}(x)$, $\upsilon^{-}_{\widetilde{A}}(x)$, and $\upsilon^{+}_{\widetilde{A}}(x)$. Then the IVIFS was denoted as follows:*

$$\widetilde{A} = \left\{ \left\langle x, \left[\mu_{\widetilde{A}}^{-}(x), \mu_{\widetilde{A}}^{+}(x) \right], \left[v_{\widetilde{A}}^{-}(x), v_{\widetilde{A}}^{+}(x) \right] \right\rangle | x \in X \right\} \quad (2)$$

where $0 \leq \mu_{\widetilde{A}}^{+}(x) + v_{\widetilde{A}}^{+}(x) \leq 1$, $\mu_{\widetilde{A}}^{-}(x), \mu_{\widetilde{A}}^{+}(x) \geq 0$.

For each $x \in X$, its hesitation interval was denoted as follows:

$$\widetilde{\pi}_{\widetilde{A}}(x) = \left[\widetilde{\pi}_{\widetilde{A}}^{-}(x), \widetilde{\pi}_{\widetilde{A}}^{+}(x) \right] = \left[1 - \mu_{\widetilde{A}}^{+}(x) - v_{\widetilde{A}}^{+}(x), 1 - \mu_{\widetilde{A}}^{-}(x) - v_{\widetilde{A}}^{-}(x) \right] \quad (3)$$

If $\mu_{\widetilde{A}}^{-}(x) = \mu_{\widetilde{A}}^{+}(x)$ and $v_{\widetilde{A}}^{-}(x) = v_{\widetilde{A}}^{+}(x)$, then an ordinary intuitionistic fuzzy set is obtained. For convenience, the IVIFS value can be denoted as $\widetilde{A} = ([a, b], [c, d])$ and it was called an interval-valued intuitionistic fuzzy number (IVIFN), where $[a, b] \subset [0, 1]$, $[c, d] \subset [0, 1]$ and $b + d \leq 1$.

Definition 3 ([46]). *The algebraic operations were extended over IVIFNs. Let* $\widetilde{A}_1 = ([a_1, b_1], [c_1, d_1])$ *and* $\widetilde{A}_2 = ([a_2, b_2], [c_2, d_2])$ *be any two IVIFSs; then some basic operations with respect to IVIFNs were defined as follows:*

$$\widetilde{A}_1 + \widetilde{A}_2 = ([a_1 + a_2 - a_1 a_2, b_1 + b_2 - b_1 b_2], [c_1 c_2, d_1 d_2]) \quad (4)$$

$$\widetilde{A}_1 \cdot \widetilde{A}_2 = ([a_1 a_2, b_1 b_2], [c_1 + c_2 - c_1 c_2, d_1 + d_2 - d_1 d_2]) \quad (5)$$

$$\lambda \widetilde{A}_1 = \left(\left[1 - (1 - a_1)^{\lambda}, 1 - (1 - b_1)^{\lambda} \right], \left[c_1^{\lambda}, d_1^{\lambda} \right] \right), \lambda \geq 0 \quad (6)$$

$$\widetilde{A}_1^{\lambda} = \left(\left[a_1^{\lambda}, b_1^{\lambda} \right], \left[1 - (1 - c_1)^{\lambda}, 1 - (1 - d_1)^{\lambda} \right] \right), \lambda \geq 0 \quad (7)$$

Definition 4 ([46]). *Let* $\widetilde{A}_1 = ([a_1, b_1], [c_1, d_1])$ *and* $\widetilde{A}_2 = ([a_2, b_2], [c_2, d_2])$ *be any two IVIFNs, the normalized Euclidean distance between* $\widetilde{A}_1$ *and* $\widetilde{A}_2$ *was defined as follows:*

$$d\left(\widetilde{A}_1, \widetilde{A}_2\right) = \frac{1}{2} \sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2 + (d_1 - d_2)^2} \quad (8)$$

Definition 5 ([46,47]). *Let* $\widetilde{A} = ([a, b], [c, d])$ *be any IVIFNs; then the score and accuracy function were denoted as follows:*

$$s\left(\widetilde{A}\right) = \frac{1}{2}(a - c + b - d) \quad (9)$$

$$h\left(\widetilde{A}\right) = \frac{1}{2}(a + c + b + d) \quad (10)$$

where $s\left(\widetilde{A}\right)$ *is the score function,* $s\left(\widetilde{A}\right) \in [-1, 1]$, *and* $h\left(\widetilde{A}\right)$ *is the accuracy function,* $h\left(\widetilde{A}\right) \in [0, 1]$.

The interval-value intuitionistic fuzzy priority weight average (IVIFPWA) operator is used to aggregate the experts' evaluation information in this study, so the score function value $s\left(\widetilde{A}\right)$ must be greater than zero. Therefore, based on the accuracy function form, the score function is modified as follows:

$$s\left(\widetilde{A}\right) = \frac{1}{2}|a - c + b - d|$$

For the two IVIFNs $\widetilde{A}_1 = ([a_1, b_1], [c_1, d_1])$ and $\widetilde{A}_2 = ([a_2, b_2], [c_2, d_2])$, a comparison was made using the score and accuracy functions as follows:

(1) If $s\left(\widetilde{A}_1\right) < s\left(\widetilde{A}_2\right)$, then $\widetilde{A}_1 < \widetilde{A}_2$;

(2) If $s\left(\widetilde{A}_1\right) = s\left(\widetilde{A}_2\right)$, and

  (a) If $h\left(\widetilde{A}_1\right) < h\left(\widetilde{A}_2\right)$, then $\widetilde{A}_1 < \widetilde{A}_2$;

  (b) If $h\left(\widetilde{A}_1\right) = h\left(\widetilde{A}_2\right)$, then $\widetilde{A}_1 = \widetilde{A}_2$;

(c) If $h\left(\widetilde{A}_1\right) > h\left(\widetilde{A}_2\right)$, then $\widetilde{A}_1 > \widetilde{A}_2$.

Definition 6 ([46]). *Let $\widetilde{A}_j = \left(\left[a_j, b_j\right], \left[c_j, d_j\right]\right), (j = 1, 2, \ldots, n)$ be a collection of IVIFNs, and let IVIFWA be $V^n \to V$, then the function for interval-valued intuitionistic fuzzy weighted averaging (IVIFWA) was defined by the IVIFWA operator as follows:*

$$\begin{aligned} \text{IVIFWA}\left(\widetilde{A}_1, \widetilde{A}_2, \cdots, \widetilde{A}_n\right) &= w_1\widetilde{A}_1 + w_2\widetilde{A}_2 + \cdots + w_n\widetilde{A}_n = \sum_{j=1}^{n} w_j\widetilde{A}_j \\ &= \left(\left[1 - \prod_{j=1}^{n}\left(1 - a_j\right)^{w_j}, 1 - \prod_{j=1}^{n}\left(1 - b_j\right)^{w_j}\right], \left[\prod_{j=1}^{n} c_j^{w_j}, \prod_{j=1}^{n} d_j^{w_j}\right]\right) \end{aligned} \tag{11}$$

where V is the interval-valued intuitionistic fuzzy set; $w = (w_1, w_2, \ldots, w_n)^T$ is the weight vector of $\widetilde{A}_j$, $w_j \geq 0, \sum_{j=1}^{n} w_j = 1$.

Definition 7 ([46]). *Let $\widetilde{A}_j = \left(\left[a_j, b_j\right], \left[c_j, d_j\right]\right), (j = 1, 2, \ldots, n)$ be a collection of IVIFNs, and let IVIFWG be $V^n \to V$, then the function interval-valued intuitionistic fuzzy weighted geometric (IVIFWG) was defined as the IVIFWG operator as follows:*

$$\begin{aligned} \text{IVIFWG}\left(\widetilde{A}_1, \widetilde{A}_2, \cdots, \widetilde{A}_n\right) &= \widetilde{A}_1^{w_1} \cdot \widetilde{A}_2^{w_2} \cdot \cdots \cdot \widetilde{A}_n^{w_n} = \prod_{j=1}^{n} \widetilde{A}_j^{w_j} \\ &= \left(\left[\prod_{j=1}^{n} a_j^{w_j}, \prod_{j=1}^{n} b_j^{w_j}\right], \left[1 - \prod_{j=1}^{n}\left(1 - c_j\right)^{w_j}, 1 - \prod_{j=1}^{n}\left(1 - d_j\right)^{w_j}\right]\right) \end{aligned} \tag{12}$$

where V is the interval-valued intuitionistic fuzzy set; $w = (w_1, w_2, \ldots, w_n)^T$ is the weight vector of $\widetilde{A}_j$, $w_j \geq 0, \sum_{j=1}^{n} w_j = 1$.

2.2. Traditional MULTIMOORA Method

Like most MCDM methods, the initial decision-making matrix is constructed as $X = \left[x_{ij}\right]_{m \times n}$, where $x_{ij} (i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$ is the evaluation value for the alternative A_i under the c_j. The alternative set is $A = (A_1, A_2, \ldots, A_i)$ and the attribute set is $C = \left(c_1, c_2, \ldots, c_j\right)$. To facilitate the comparison by normalizing the initial decision matrix $X = \left[x_{ij}\right]_{m \times n}$ into the standardized decision matrix $X^* = \left[x^*_{ij}\right]_{m \times n}$, it can be defined as the following form according to Brauers and Zavadskas [40]:

$$x^*_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{13}$$

where x_{ij} is the initial evaluation value, that is, the evaluation of the alternative A_i under the attribute c_j; $i = 1, 2, \ldots, m$, $j = 1, 2, \ldots, n$; m is the number of alternatives and n is the number of attributes; and x^*_{ij} is the dimensionless evaluation value of the decision matrix.

The traditional MULTIMOORA method comprises three sub-methods: the ratio system method, the reference point method, and the full multiplicative form method. The final ranking of each alternative can be determined based on the results of the three sub-methods.

2.2.1. The Ratio System Method

The ration system method is the first part of the MULTIMOORA method. After standardization, the evaluation value of all alternatives under the ratio system method can be obtained as follows:

$$y_i = \sum_{j=1}^{g} x_{ij}^* - \sum_{j=g+1}^{n} x_{ij}^* \quad (14)$$

where g and $n-g$ respectively indicate the number of benefit-type and cost-type attributes. y_i represents the evaluation value of the alternative A_i; The higher the value of y_i, the better the corresponding alternative. Therefore, the optimal alternative A_{rs}^* according to the ratio system method can be obtained as follows [40]:

$$A_{RS}^* = \left(A_i \middle| \max_i y_i\right) \quad (15)$$

2.2.2. The Reference Point Method

The reference point method is the second part of the MULTIMOORA method. The first step of the reference point method is to determine the optimal reference point of each attribute. The optimal reference point of all attributes can be conceived as the following form:

$$r_j = \begin{cases} \max_i x_{ij}^*, & j \le g \\ \min_i x_{ij}^*, & j > g \end{cases} \quad (16)$$

After determining the optimal reference point, the deviation degree between all attribute values x_{ij}^* and the corresponding optimal reference point r_j can be obtained, that is $\left|r_j - x_{ij}^*\right|$. Therefore, the maximum deviation of each alternative, i.e., the evaluation value of each alternative according to the reference point method, can be expressed as follows:

$$z_i = \max_j \left|r_j - x_{ij}^*\right| \quad (17)$$

The smaller the value of z_i, the better the corresponding alternative. Finally, the optimal alternative A_{RP}^* according to the reference point method can be obtained as follows [40]:

$$A_{RP}^* = \left\{A_i \middle| \min_i z_i\right\} \quad (18)$$

2.2.3. The Full Multiplicative Form Method

The full multiplicative form method is the third part of the MULTIMOORA method. It embodies the minimization and maximization problems of the purely multiplicative utility function [41]. Based on this, the evaluation values of all alternatives under the full multiplicative form method can be expressed as follows:

$$U_i = \frac{\prod_{j=1}^{g} x_{ij}^*}{\prod_{j=g+1}^{n} x_{ij}^*} \quad (19)$$

where $\prod_{j=1}^{g} x_{ij}^*$ represents the product of the evaluation values of all the benefit-type attributes; similarly, $\prod_{j=g+1}^{n} x_{ij}^*$ represents the product of the evaluation values of all the cost-type attributes.

The higher the value of U_i, the better the corresponding alternative. Therefore, the optimal alternative A_{RP}^* according to the full multiplicative form method can be obtained as follows [41]:

$$A_{FM}^* = \left\{A_i \middle| \max_i U_i\right\} \quad (20)$$

2.2.4. The Final Ranking of Alternatives Based on Dominance Theory

Based on the fundamental idea of dominance theory, the ranking results obtained in Sections 2.2.1–2.2.3 are integrated to get the final ranking result [48,49], which is called the MULTIMOORA ranking.

3. Risk Evaluation in FMEA with IVIF-MULTIMOORA

In this section, a novel FMEA framework with an extended MULTIMOORA method for risk evaluation is proposed under an interval-valued intuitionistic fuzzy environment. The flow chart for risk evaluation in Figure 1 shows the proposed ranking method of failure modes in the FMEA process.

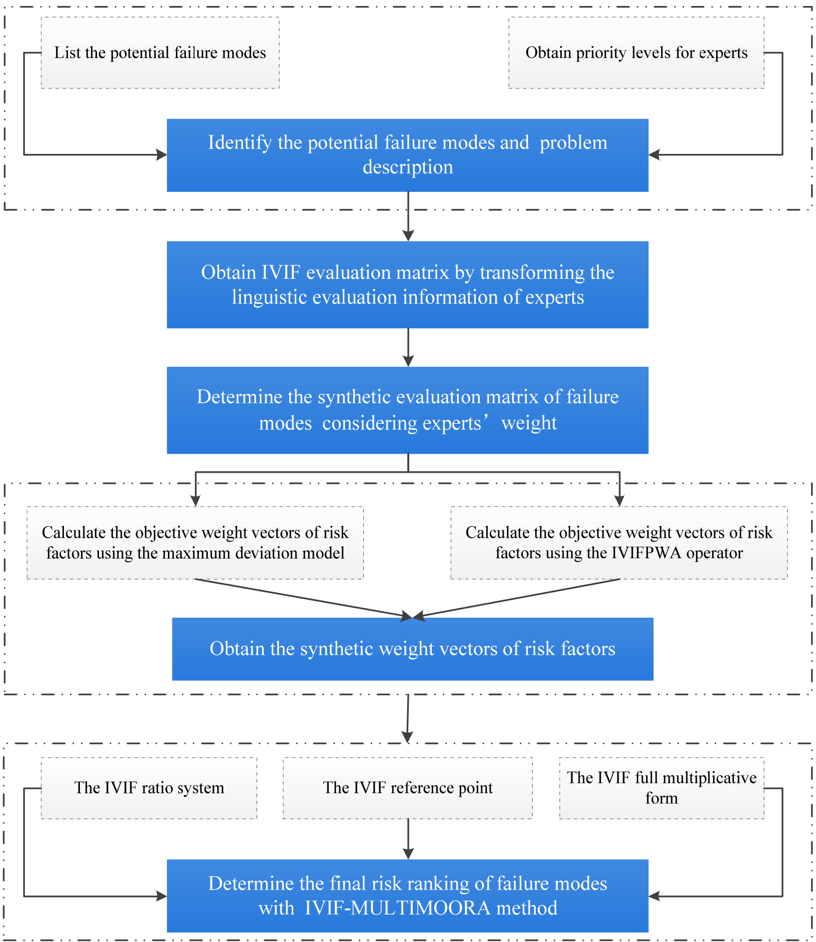

Figure 1. Risk evaluation in Failure Mode and Effect Analysis (FMEA) with interval-valued intuitionistic fuzzy (IVIF)-MULTIMOORA method flow chart.

3.1. Identify the Potential Failure Modes and Problem Description

The FMEA expert team is responsible for the evaluation of m failure modes $FM_i(i = 1, 2, \cdots, m)$ with respect to n risk factor $RF_j(j = 1, 2, \cdots, n)$, and assessment of the importance of risk factors using linguistic variables. Then, the linguistic assessment results are transformed into relative interval-valued intuitionistic fuzzy numbers. Where the $\widetilde{A}_k = \left(\widetilde{A}_{ij}^k\right)_{m\times n}$ denotes an IVIF assessment matrix for the failure mode given by the expert DM_k, suppose the FMEA team consists of s experts $DM_k(k = 1, 2, \cdots, s)$. According to their different knowledge structure and domain experience, the experts are divided into s priority levels. The knowledge structure of DM_1 is closer to the evaluation objects of FMEA and the domain experience is more extensive. Thus, the evaluation information of DM_1 has the highest priority level. Conversely, the priority level of DM_s is the lowest. $\widetilde{A}_{ij}^k = \left(\mu_{ij}^k, \upsilon_{ij}^k\right) = \left(\left[\mu_{ij}^{k-}, \mu_{ij}^{k+}\right], \left[\upsilon_{ij}^{k-}, \upsilon_{ij}^{k+}\right]\right)$ denotes an IVIFN of failure mode FM_i with respect to the risk factor RF_j. $\widetilde{W}_k = \left(\widetilde{A}_j^k\right)_{1\times n}$ is an IVIF assessment matrix for the weight of risk factors given by DM_k. $\widetilde{A}_j^k = \left(\mu_j^k, \upsilon_j^k\right)$ is an IVIFN for importance with respect to risk factor RF_j given by DM_k. $w_j^O(j = 1, 2, \cdots, n)$ and $w_j^S(j = 1, 2, \cdots, n)$ denote the objective and subjective weight vector of risk factor, respectively.

3.2. Obtain IVIF Evaluation Matrix by Transforming the Linguistic Evaluation Information of Experts

The FMEA experts team conducts risk assessment and management by collecting historical data such as occurrence frequency, consequence severity, and detection rate of failure mode, etc. However, most existing accident data are incomplete, so this section adopts the method of expert reference historical data to evaluate failure mode in order to obtain risk assessment information.

Uncertainty and incomplete information exist in practice, and it is difficult for experts to accurately assess information using real numbers. Therefore, experts tend to use linguistic variables to evaluate the actual performance of failure modes from all aspects of risk factors. Linguistic variables can be converted into the corresponding IVIFNs according to certain rules (Table 1) [10], and it is possible to obtain an IVIF evaluation matrix of the failure modes $\widetilde{A}_k = \left(\widetilde{A}_{ij}^k\right)_{m\times n}$. The traditional FMEA method comprises three types of risk factors: Occurrence (O), severity (S), and detection (D), where occurrence denotes the frequency of the failure, severity denotes the seriousness of the failure, and detection denotes the likelihood of the failure not being detected.

Table 1. Linguistic variables for rating failure mode.

Linguistic Variables	Benefit-Type for IVIFNs	Cost-Type for IVIFNs
Extremely low (EL)	([0.00,0.05], [0.90,0.90])	([0.90,0.90], [0.00,0.05])
Very low (VL)	([0.05,0.10], [0.80,0.90])	([0.80,0.90], [0.05,0.10])
Low (L)	([0.10,0.20], [0.70,0.80])	([0.70,0.80], [0.10,0.20])
Medium low (ML)	([0.30,0.40], [0.50,0.60])	([0.50,0.60], [0.30,0.40])
Medium (M)	([0.50,0.50], [0.50,0.50])	([0.50,0.50], [0.50,0.50])
Medium high (MH)	([0.50,0.60], [0.30,0.40])	([0.30,0.40], [0.50,0.60])
High (H)	([0.70,0.80], [0.10,0.20])	([0.10,0.20], [0.70,0.80])
Very high (VH)	([0.80,0.90], [0.05,0.10])	([0.05,0.10], [0.80,0.90])
Extremely high (EH)	([0.90,0.90], [0.00,0.05])	([0.00,0.05], [0.90,0.90])

The IVIF-MULTIMOORA ranking method needs to subtract and divide the assessment information according to the types of risk factors, but the corresponding operation rules of IVIFNs have not been unified. To enhance the universality of the method, the $\widetilde{A}_{ij}^k = \left(\mu_{ij}^k, \upsilon_{ij}^k\right)$ is transformed as follows:

$$\hat{A}_{ij}^k = \begin{cases} \widetilde{A}_{ij}^k = \left(\mu_{ij}^k, \upsilon_{ij}^k\right), & j \in B \\ Neg\widetilde{A}_{ij}^k = \left(\upsilon_{ij}^k, \mu_{ij}^k\right), & j \in C \end{cases} \tag{21}$$

Then $\hat{A}_{ij}^k = \left(\hat{\mu}_{ij}^k, \hat{\upsilon}_{ij}^k\right)$ is obtained, where B is the benefit-type risk factor subset, and C is the cost-type risk factor subset.

3.3. Determine the Synthetic Evaluation Matrix of Failure Modes Considering Experts' Weight

Most existing FMEA related research directly gives weight to experts, which has a certain impact on the accuracy of research results. It is difficult to accurately determine the weight of experts using a subjective weighting method, but it is simple and feasible to determine the priority levels of experts according to the difference of their knowledge structures and experience. Yu [50] defined the interval-valued intuitionistic fuzzy priority weight average (IVIFPWA) operator based on the priority average operator constructed by Yager [51] as follows:

Definition 8 *Let $\hat{A}_{ij}^{k} = \left(\left[\hat{a}_{ij}^{k}, \hat{b}_{ij}^{k}\right], \left[\hat{c}_{ij}^{k}, \hat{d}_{ij}^{k}\right]\right)$, $(k = 1, 2, \cdots, s)$ be a collection of evaluation information of IVIFNs for failure modes given by s experts, and let IVIFPWA be $V^n \to V$, then the function for interval-valued intuitionistic fuzzy priority weight average (IVIFPWA) is defined by the IVIFPWA operator as follows:*

$$\mathrm{IVIFPWA}\left(\hat{A}_{ij}^{1}, \hat{A}_{ij}^{2}, \cdots, \hat{A}_{ij}^{s}\right) = \hat{A}_{ij}$$
$$\left(\left[1 - \prod_{k=1}^{s}\left(1 - \hat{a}_j\right)^{T_k / \sum_{k=1}^{s} T_k}, 1 - \prod_{k=1}^{s}\left(1 - \hat{b}_j\right)^{T_k / \sum_{k=1}^{s} T_k}\right], \left[\prod_{k=1}^{s} \hat{c}_j^{\,T_k / \sum_{k=1}^{s} T_k}, \prod_{k=1}^{s} \hat{d}_j^{\,T_k / \sum_{k=1}^{s} T_k}\right]\right) \tag{22}$$

where $T_k = \prod_{t=1}^{k-1} s\left(\hat{A}_{ij}^{t}\right)$, $T_1 = 1$, in the process of information aggregation, the expert weight information is determined according to the score function value of the information itself, and the IVIF comprehensive evaluation matrix for failure modes is obtained by $\widetilde{A} = \left(\hat{A}_{ij}\right)_{m \times n}$.

3.4. Obtain the Synthetic Weight Vectors of Risk Factors

In the traditional FMEA risk assessment, weight information of risk factors is not considered. So, occurrence (O), severity (S), and detection (D) are regarded as equally important, which is obviously inconsistent with practice and leads to inaccurate risk ranking of the final failure modes. Approaches to determine the weight of risk factors mainly include the subjective weighting method, the objective weighting method, and the comprehensive weighting method. The comprehensive weighting method has been adopted by numerous scholars because it can consider both subjective and objective factors, and overcome the limitation of only considering unilateral methods. This subsection will determine the weight of risk factors from both subjective and objective aspects by using the comprehensive weight method and combining the expert evaluation method and deviation maximization model method in order to overcome the gap that exists in traditional FMEA risk assessment when the weight of risk factors is not considered.

Determine the subjective weight. First, s experts evaluate the importance of the three risk factors for occurrence (O), severity (S), and detection (D) with Table 1, and the IVIF evaluation matrix for risk factor weights $\widetilde{W}_k = \left(\widetilde{A}_j^k\right)_{1 \times n}$ is obtained. Then, the IVIF evaluation matrix of risk factor weights $\widetilde{W} = \left(\widetilde{A}_j\right)_{1 \times n}$ is obtained by aggregating the weight information of s experts using the IVIFPWA operator. Finally, the subjective weight of risk factors is determined according to the score function of the weight information. The greater the score function value of risk factor weight information, the greater the impact of the risk factor on the risk ranking, and the greater the weight. On the contrary, the less that the risk factor influences the ranking, the less the weight. According to Equation (9), the score function value $s\left(\widetilde{A}_j\right)$ of the risk factor weight information is obtained, and then the subjective weight of the risk factor can be determined as follows:

$$w_j^S = \frac{s\left(\widetilde{A}_j\right)}{\sum_{j=1}^{n} s\left(\widetilde{A}_j\right)} \tag{23}$$

Determine the objective weight. According to the information theory, under the circumstance that the attribute weight is completely unknown in MCDM problems, if all alternatives have similar attribute values with respect to an attribute. Then, a small weight should be assigned to the attribute. This is due to the fact that such an attribute does not help in differentiating alternatives [52]. An IVIF evaluation matrix $\widetilde{A} = \left(\hat{A}_{ij}\right)_{m \times n}$ can be obtained based on the above principles and failure modes. Let the deviation between FM_i and other failure modes with respect to the risk factor RF_j be $d_{ij}(w) = \sum_{h=1}^{m} d\left(\hat{A}_{ij}, \hat{A}_{hj}\right) \; w_j^O$, where $d\left(\hat{A}_{ij}, \hat{A}_{hj}\right)$ is the Euclidean distance between $\hat{A}_{ij}$ and $\hat{A}_{hj}$. Then, the total deviation for the evaluation information of failure modes denotes $d(w) = \sum_{j=1}^{n} \sum_{i=1}^{m} \sum_{h \neq i} d\left(\hat{A}_{ij}, \hat{A}_{hj}\right) \; w_j^O$. The deviation maximization model is constructed as follows [53]:

$$\begin{aligned} &\max \sum_{j=1}^{n} \sum_{i=1}^{m} \sum_{h \neq i} d\left(\hat{A}_{ij}, \hat{A}_{hj}\right) \; w_j^O \\ &s.t. \;\; \sum_{j=1}^{n} \left(w_j^O\right)^2 = 1, w_j^O \geq 0, j = 1, 2, \cdots, n \end{aligned} \tag{24}$$

To solve this optimization model, we constructed the Lagrange function as follows:

$$L(w, \lambda) = d(w) + \frac{\lambda}{2}\left(\sum_{j=1}^{n}\left(w_j^O\right)^2 - 1\right) \tag{25}$$

where λ is the Lagrange multiplier.

The partial derivatives of Equation (25) are calculated with respect to w_j^O and λ, respectively, and their partial derivatives are set to equal zero as follows:

$$\begin{cases} \frac{\partial L(w,\lambda)}{\partial w_j^O} = \sum_{i=1}^{m} \sum_{h \neq i} d\left(\hat{A}_{ij}, \hat{A}_{hj}\right) \; w_j^O + \lambda w_j^O = 0 \\ \frac{\partial L(w,\lambda)}{\partial \lambda} = \sum_{j=1}^{n} w_j^O \; - 1 = 0 \end{cases} \tag{26}$$

The optimal solution of the objective weight of the risk factor can be found by solving Equation (26), and then can be normalized as follows:

$$w_j^O = \frac{\sum_{i=1}^{m} \sum_{h \neq i} d\left(\hat{A}_{ij}, \hat{A}_{hj}\right)}{\sum_{j=1}^{n} \sum_{i=1}^{m} \sum_{h \neq i} d\left(\hat{A}_{ij}, \hat{A}_{hj}\right)}, j = 1, 2, \cdots, n \tag{27}$$

Determine the comprehensive weight. Aggregate subjective weight $w_j^S = \left(w_1^s, w_2^s, \ldots, w_n^s\right)$ and objective weight $w_j^O = \left(w_1^o, w_2^o, \ldots, w_n^o\right)$, and then determine the comprehensive weight $w_j = (w_1, w_2, \ldots, w_n)$ of risk factor as follows:

$$w_j = \delta_1 w_j^S + \delta_2 w_j^O \tag{28}$$

where δ_1 and δ_2 are the relative importance for the subjective and objective weight, respectively, where $0 \leq \delta_1, \delta_2 \leq 1, \quad \delta_1 + \delta_2 = 1, \quad j = 1, 2, \ldots, n$.

3.5. Determine the Final Risk Ranking of Failure Modes with IVIF-MULTIMOORA Method

The IVIFWA operator and IVIFGA operator are introduced into the ratio system and the full multiplicative form model respectively, to avoid the information loss. Calculate the improved Euclidean distance between the evaluation information and the reference point in the reference point method. In this subsection, the IVIF-MULTIMOORA method is constructed to determine the final risk ranking based on dominance theory.

3.5.1. The IVIF-Ratio System is Used to Determine the Risk Ranking Order of Failure Modes

For each IVIFN $\widetilde{A} = ([a,b],[c,d])$, satisfying $[a,b] \subset [0,1]$, $[c,d] \subset [0,1]$, and $b + d \leq 1$, there is no need to standardize the evaluation information. According to Definition 6, the comprehensive utility value of FM_i is obtained by using the IVIF evaluation matrix $\widetilde{A} = \left(\hat{A}_{ij}\right)_{m\times n}$ of failure mode and the weight vector $w_j = (w_1, w_2, \ldots, w_n)$ of the risk factor as follows:

$$\begin{aligned} y_i &= \text{IVIFWA}\left(\hat{A}_{i1}, \hat{A}_{i2}, \cdots, \hat{A}_{in}\right) = \mathop{\oplus}_{j=1}^{n} w_j \hat{A}_{ij} \\ &= \left(\left[1 - \prod_{j=1}^{n} w_j\left(1 - a_{ij}\right), 1 - \prod_{j=1}^{n} w_j\left(1 - b_{ij}\right)\right], \left[\prod_{j=1}^{n} w_j c_{ij}, \prod_{j=1}^{n} w_j d_{ij}\right]\right) \end{aligned} \tag{29}$$

where y_i denotes the comprehensive utility value under all risk factors of FM_i. According to Definition 5 and Equations (9) and (10), the score function value $s\left(\widetilde{A}\right)$ and accuracy function value $h\left(\widetilde{A}\right)$ of the comprehensive utility value of different failure modes are obtained. Then, the risk of failure mode is ranked based on the comprehensive utility value y_i. The smaller the y_i value is, the higher the risk rank.

3.5.2. The IVIF-Reference Point is Used to Determine the Risk Ranking Order of Failure Modes

There are two kinds of reference points: (1) the maximum or minimum value of the failure mode evaluation information under different risk factors, and (2) positive and negative ideal reference points. This study adopted positive ideal reference points, that is $\hat{\phi}_j = ([1,1],[0,0])$. Then, the distances between failure mode FM_i and the reference point under different risk factors was calculated using the Minkowski Metric [54] method [55]:

$$d\left(\hat{\phi}_j, FM_i\right) = \left\{\sum_{j=1}^{n}\left[d\left(\hat{\phi}_j, \hat{A}_{ij}\right)\right]^{\gamma}\right\}^{1/\gamma}, \quad \gamma \in N^{+} \tag{30}$$

The robustness of the optimal ranking problem based on the Minkowski Metric method increases with the increase of the γ value [42], so set $\gamma \to \infty$. The distance was called the Tchebycheff Metric, and it was calculated as follows:

$$d\left(\hat{\phi}_j, FM_i\right) = \max_{1\leq j\leq n} d\left(\hat{\phi}_j, \hat{A}_{ij}\right) \tag{31}$$

Combined with Equation (8), the risk factor weight vector $w_j = (w_1, w_2, \ldots, w_n)$ is introduced as the significance coefficient. The Minkowski Metric is calculated between failure mode FM_i and the reference point under different risk factors, which can be obtained as follows:

$$d\left(\hat{\phi}_j, FM_i\right) = \max_{1\leq j\leq n} d\left(\hat{\phi}_j, \hat{A}_{ij}\right) = \max_{1\leq j\leq n} \frac{w_j}{2}\sqrt{\left(a_{ij}-1\right)^2 + \left(b_{ij}-1\right)^2 + \left(c_{ij}\right)^2 + \left(d_{ij}\right)^2} \tag{32}$$

where $d\left(\hat{\phi}_j, FM_i\right)$ denotes the Minkowski Metric distance. The higher the $d\left(\hat{\phi}_j, FM_i\right)$ value is, the higher the risk ranking order is.

3.5.3. The IVIF-Full Multiplicative Form is Used to Determine the Risk Ranking Order of Failure Modes

According to Definition 7, the multiplicative utility value of FM_i was obtained using the IVIF evaluation matrix $\widetilde{A} = \left(\hat{A}_{ij}\right)_{m\times n}$ of failure mode, and weight vector $w_j = (w_1, w_2, \ldots, w_n)$ of risk factor as follows:

$$\begin{aligned} U_i &= \text{IVIFWG}\left(\hat{A}_{i1}, \hat{A}_{i2}, \cdots, \hat{A}_{in}\right) = \mathop{\otimes}_{j=1}^{n} \hat{A}_{ij}^{\,w_j} \\ &= \left(\left[\prod_{j=1}^{n} a_{ij}^{\,w_j}, \prod_{j=1}^{n} b_{ij}^{\,w_j}\right], \left[1 - \prod_{j=1}^{n}\left(1 - c_{ij}\right)^{w_j}, 1 - \prod_{j=1}^{n}\left(1 - d_{ij}\right)^{w_j}\right]\right) \end{aligned} \tag{33}$$

where U_i denotes the multiplicative utility value under all risk factors of failure modes. The scoring function value and accuracy function value of the multiplication utility value can be obtained and the failure mode risk ranking order can be determined. The smaller the U_i value is, the higher the risk ranking order is.

3.5.4. Determine the Final Risk Ranking Order of Failure Modes Based on Dominance Theory

The IVIF-MULTIMOORA method comprises the IVIF-ratio system, the IVIF-reference point, and the IVIF-full multiplicative method, that is, three kinds of risk ranking of failure modes exist, and have equal importance. According to dominance theory, the final risk ranking of the failure modes is determined based on the three kinds of risk ranking in each of the fault modes.

4. Case Study on Middle Route of the South-to-North Water Diversion Project

The Middle Route of the South-to-North Water Diversion Project contains many types of hydraulic structures, such as open channel, aqueduct, inverted siphon, closed conduit, tunnel, Prestressed Concrete Cylinder Pipe (PCCP) pipeline, and concrete gravity dam. For the abovementioned hydraulic structures, Xiong et al. [56] determined eleven common potential failure modes for the Middle Route of the South-to-North Water Diversion Project though the systematic analysis of the following risks: Capsizing (FM_1), Slippage (FM_2), Crack (FM_3), Leakage (FM_4), Geological Disaster (FM_5), Overtopping (FM_6), Pipeline Bursting (FM_7), Ice Damage (FM_8), Pollution (FM_9), Power Failure of Electromechanical Equipment (FM_{10}), and Terrorist Attack (FM_{11}). In this section, an extended MULTIMOORA approach based on IVIF is proposed to evaluate the risk prioritization of the eleven failure modes.

Step 1: Determine the IVIF comprehensive evaluation matrix. Suppose the team of experts for FMEA comprises three members with different knowledge structures and domain experience. The experts are divided into three priority levels, i.e., DM_1, DM_2 and DM_3. First, the actual performance of the failure modes under the three risk factors (O, S, D) and the importance of the risk factors were evaluated by the three experts, as shown in Table 2. Second, the evaluation information of linguistic variables is converted into the corresponding IVIFNs, and then the IVIF evaluation matrix $\widetilde{A}_k = \left(\widetilde{A}_{ij}^k\right)_{m\times n}$ is constructed. Third, since O, S, and D are cost-type risk factors, the evaluation matrix was transformed according to Equation (21), as shown in Table 3. Finally, according to Definition 8, the three experts' evaluation information is aggregated by using the IVIFPWA operator, and then the IVIF comprehensive evaluation matrix $\widetilde{A} = \left(\hat{A}_{ij}\right)_{m\times n}$ for failure modes is obtained in Table 4.

Table 2. Evaluation information from experts using linguistic variables.

Risk Factors	*O*			*S*			*D*		
Experts	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
Importance of Risk Factors	H	VH	VH	EH	VH	EH	H	H	VH
FM_1	EL	VL	VL	EH	VH	VH	VL	L	L
FM_2	ML	M	L	VH	H	VH	ML	M	M
FM_3	H	MH	H	H	H	MH	MH	H	H
FM_4	VH	VH	H	MH	H	MH	H	VH	VH
FM_5	M	M	ML	H	EH	VH	H	L	H
FM_6	ML	ML	L	H	H	MH	L	VL	EL
FM_7	VL	L	L	VH	EH	H	VL	EL	VL
FM_8	H	MH	H	H	MH	MH	M	H	MH
FM_9	ML	L	ML	EH	VH	EH	MH	H	L
FM_{10}	M	M	ML	M	L	ML	ML	L	L
FM_{11}	EL	EL	VL	EH	EH	EH	L	VL	VL

Table 3. Interval-valued intuitionistic fuzzy evaluation matrix.

Risk Factors	***O***			***S***			***D***		
Experts. / **Failure Modes**	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
FM_1	([0.90,0.90], [0.00,0.05])	([0.80,0.90], [0.05,0.10])	([0.80,0.90], [0.05,0.10])	([0.00,0.05], [0.90,0.90])	([0.05,0.10], [0.80,0.90])	([0.05,0.10], [0.80,0.90])	([0.80,0.90], [0.05,0.10])	([0.70,0.80], [0.10,0.20])	([0.70,0.80], [0.10,0.20])
FM_2	([0.50,0.60], [0.30,0.40])	([0.50,0.50], [0.50,0.50])	([0.70,0.80], [0.10,0.20])	([0.05,0.10], [0.80,0.90])	([0.10,0.20], [0.70,0.80])	([0.05,0.10], [0.80,0.90])	([0.50,0.60], [0.30,0.40])	([0.50,0.50], [0.50,0.50])	([0.50,0.50], [0.50,0.50])
FM_3	([0.10,0.20], [0.70,0.80])	([0.30,0.40], [0.50,0.60])	([0.10,0.20], [0.70,0.80])	([0.10,0.20], [0.70,0.80])	([0.10,0.20], [0.70,0.80])	([0.30,0.40], [0.50,0.60])	([0.30,0.40], [0.50,0.60])	([0.10,0.20], [0.70,0.80])	([0.10,0.20], [0.70,0.80])
FM_4	([0.05,0.10], [0.80,0.90])	([0.05,0.10], [0.80,0.90])	([0.10,0.20], [0.70,0.80])	([0.30,0.40], [0.50,0.60])	([0.10,0.20], [0.70,0.80])	([0.30,0.40], [0.50,0.60])	([0.10,0.20], [0.70,0.80])	([0.05,0.10], [0.80,0.90])	([0.05,0.10], [0.80,0.90])
FM_5	([0.50,0.50], [0.50,0.50])	([0.50,0.50], [0.50,0.50])	([0.50,0.60], [0.30,0.40])	([0.10,0.20], [0.70,0.80])	([0.00,0.05], [0.90,0.90])	([0.05,0.10], [0.80,0.90])	([0.10,0.20], [0.70,0.80])	([0.70,0.80], [0.10,0.20])	([0.10,0.20], [0.70,0.80])
FM_6	([0.50,0.60], [0.30,0.40])	([0.50,0.60], [0.30,0.40])	([0.70,0.80], [0.10,0.20])	([0.10,0.20], [0.70,0.80])	([0.10,0.20], [0.70,0.80])	([0.30,0.40], [0.50,0.60])	([0.70,0.80], [0.10,0.20])	([0.80,0.90], [0.05,0.10])	([0.90,0.90], [0.00,0.05])
FM_7	([0.80,0.90], [0.05,0.10])	([0.70,0.80], [0.10,0.20])	([0.70,0.80], [0.10,0.20])	([0.05,0.10], [0.80,0.90])	([0.00,0.05], [0.90,0.90])	([0.10,0.20], [0.70,0.80])	([0.80,0.90], [0.05,0.10])	([0.90,0.90], [0.00,0.05])	([0.80,0.90], [0.05,0.10])
FM_8	([0.10,0.20], [0.70,0.80])	([0.30,0.40], [0.50,0.60])	([0.10,0.20], [0.70,0.80])	([0.10,0.20], [0.70,0.80])	([0.30,0.40], [0.50,0.60])	([0.30,0.40], [0.50,0.60])	([0.50,0.50], [0.50,0.50])	([0.10,0.20], [0.70,0.80])	([0.30,0.40], [0.50,0.60])
FM_9	([0.50,0.60], [0.30,0.40])	([0.70,0.80], [0.10,0.20])	([0.50,0.60], [0.30,0.40])	([0.00,0.05], [0.90,0.90])	([0.05,0.10], [0.80,0.90])	([0.00,0.05], [0.90,0.90])	([0.00,0.05], [0.90,0.90])	([0.10,0.20], [0.70,0.80])	([0.70,0.80], [0.10,0.20])
FM_{10}	([0.50,0.50], [0.50,0.50])	([0.50,0.50], [0.50,0.50])	([0.50,0.60], [0.30,0.40])	([0.50,0.50], [0.50,0.50])	([0.70,0.80], [0.10,0.20])	([0.50,0.60], [0.30,0.40])	([0.50,0.60], [0.30,0.40])	([0.70,0.80], [0.10,0.20])	([0.70,0.80], [0.10,0.20])
FM_{11}	([0.90,0.90], [0.00,0.05])	([0.90,0.90], [0.00,0.05])	([0.80,0.90], [0.05,0.10])	([0.00,0.05], [0.90,0.90])	([0.00,0.05], [0.90,0.90])	([0.00,0.05], [0.90,0.90])	([0.70,0.80], [0.10,0.20])	([0.80,0.90], [0.05,0.10])	([0.80,0.90], [0.05,0.10])

Table 4. Interval-valued intuitionistic fuzzy comprehensive evaluation matrix.

Failure Modes	O	S	D
FM_1	([0.839,0.900], [0.030,0.080])	([0.030,0.080], [0.839,0.900)	([0.745,0.845], [0.078,0.155])
FM_2	([0.500,0.583], [0.333,0.417])	([0.067,0.135], [0.765,0.865])	([0.500,0.583], [0.333,0.417])
FM_3	([0.170,0.270], [0.630,0.730])	([0.137,0.237], [0.663,0.763])	([0.252,0.352], [0.548,0.648])
FM_4	([0.063,0.125], [0.775,0.875])	([0.270,0.370], [0.530,0.630])	([0.074,0.148], [0.752,0.852])
FM_5	([0.500,0.500], [0.500,0.500])	([0.059,0.133], [0.781,0.853])	([0.284,0.384], [0.516,0.616])
FM_6	([0.506,0.606], [0.294,0.394])	([0.137,0.237], [0.663,0.763])	([0.774,0.852], [0.063,0.137])
FM_7	([0.745,0.845], [0.078,0.155])	([0.048,0.112], [0.804,0.872)	([0.832,0.900], [0.034,0.084])
FM_8	([0.170,0.270], [0.630,0.730])	([0.184,0.284], [0.616,0.716])	([0.500,0.500], [0.500,0.500])
FM_9	([0.530,0.630], [0.270,0.370])	([0.017,0.067], [0.866,0.900])	([0.190,0.269], [0.652,0.710])
FM_{10}	([0.500,0.500], [0.500,0.500)	([0.500,0.800], [0.500,0.500])	([0.548,0.648], [0.252,0.352])
FM_{11}	([0.871,0.900], [0.014,0.064])	([0.000,0.050], [0.900,0900])	([0.752,0.852], [0.074,0.148])

Step 2: Determine the Weight of Risk Factors. First, the IVIF comprehensive evaluation matrix $\widetilde{W}_k = \left(\widetilde{A}_j^k\right)_{1\times n}$ of risk factor weight can be determined from Tables 1 and 2. Second, the weight evaluation information for risk factors given by the three experts in Table 2 can be aggregated using Equation (22). The IVIF comprehensive evaluation matrix $\widetilde{W} = \left(\widetilde{A}_j\right)_{1\times n}$ of risk factor weight and the corresponding score function value $s\left(\widetilde{A}_j\right)$ are obtained in Table 5. Then, the subjective weight vector of risk factors is obtained using Equation (23), i.e., $w_j^S = (0.319, 0.389, 0.292)$. Third, according to the IVIF comprehensive evaluation matrix of failure modes in Table 4, the deviations between evaluation information of different failure modes can be obtained as shown in Table 6. Then, the objective weight vector of risk factors is obtained as $w_j^O = (0.385, 0.310, 0.305)$ by solving the deviation maximization optimization model using Equation (24). Finally, supposing that the $\delta_1 = \delta_2 = 0.5$, i.e., subjective and objective weights are equally important, then the comprehensive weights of risk factors were determined, $w_j = \delta_1 w_j^S + \delta_2 w_j^O = (0.352, 0.350, 0.298)$.

Table 5. Relevant parameters of subjective weight.

Risk Factors	$\widetilde{A}_j^1$	$\widetilde{A}_j^2$	$\widetilde{A}_j^3$	$\widetilde{A}_j$	$s(\widetilde{A}_j)$
O	([0.70,0.80], [0.10,0.20])	([0.80,0.90], [0.05,0.10])	([0.80,0.90], [0.05,0.10])	([0.690,0.841], [0.070,0.150])	0.690
S	([0.90,0.90], [0.00,0.05])	([0.80,0.90], [0.05,0.10])	([0.90,0.90], [0.00,0.05])	([0.870,0.900], [0.020,0.070])	0.841
D	([0.70,0.80], [0.10,0.20])	([0.70,0.80], [0.10,0.20])	([0.80,0.90], [0.05,0.10])	([0.720,0.820], [0.090,0.180])	0.632

Step 3: Determine the Final Risk Ranking Order of Potential Failure Modes. The comprehensive utility value y_i, the Tchebycheff Metric distance $d_{\max}$, and the multiplicative utility value U_i of potential failure modes are obtained using Equations (29), (32), and (33) in Table 7. Then, the risk ranking of potential failure mode is obtained, as expressed in Table 8, by the IVIF-ratio system, the IVIF-reference point, and the IVIF-full multiplicative form method. Finally, the final risk ranking of potential failure modes is determined based on dominance theory as seen in the last column of Table 8. Therefore,

Leakage (FM_4) has the highest risk degree among the failure modes. Power Failure of Electromechanical Equipment (FM_{10}) has the lowest risk degree among the failure modes. The risk ranking order for the remaining failure modes is as follows: Pollution (FM_9), Crack (FM_3), Geological Disaster (FM_5), Terrorist Attack (FM_{11}), Slippage (FM_2), Ice Damage (FM_8), Capsizing (FM_1), Pipeline Bursting (FM_7), and Overtopping (FM_6). From the results, we can determine that the risk ranking order of failure modes is acceptable for practical applications.

Table 6. Relevant parameters of objective weight.

Failure Modes	$d(\hat{A}_{iO},\hat{A}_{hO})$	$d(\hat{A}_{iS},\hat{A}_{hS})$	$d(\hat{A}_{iD},\hat{A}_{hD})$
FM_1	3.851	1.355	3.076
FM_2	2.275	1.988	1.843
FM_3	3.423	2.853	2.429
FM_4	4.589	3.929	3.288
FM_5	2.399	2.912	2.010
FM_6	2.265	1.967	1.810
FM_7	3.452	3.035	2.622
FM_8	3.472	2.092	2.507
FM_9	2.387	2.098	1.987
FM_{10}	2.358	2.047	2.740
FM_{11}	4.207	3.613	3.175

Table 7. Relevant parameters of the IVIF-MULTIMOORA method.

Failure Modes	y_i	$d_{\max}$	U_i
FM_1	([0.528,0.597], [0.328,0.390])	0.320	([0.254,0.379], [0.491,0.588])
FM_2	([0.349,0.426], [0.485,0.574])	0.302	([0.248,0.349], [0.537,0.588])
FM_3	([0.183,0.283], [0.617,0.717])	0.270	([0.177,0.279], [0.620,0.721])
FM_4	([0.139,0.218], [0.628,0.782])	0.305	([0.110,0.192], [0.700,0.808])
FM_5	([0.281,0.337], [0.603,0.658])	0.304	([0.200,0.291], [0.629,0.699])
FM_6	([0.457,0.550], [0.354,0.447])	0.271	([0.363,0.483], [0.407,0.515])
FM_7	([0.527,0.605], [0.319,0.385])	0.310	([0.295,0.424], [0.456,0.553])
FM_8	([0.273,0.343], [0.587,0.657])	0.258	([0.241,0.330], [0.590,0.670])
FM_9	([0.249,0.325], [0.592,0.657])	0.324	([0.117,0.223], [0.676,0.738])
FM_{10}	([0.514,0.544], [0.426,0.456])	0.176	([0.514,0.540], [0.436,0.460])
FM_{11}	([0.531,0.588], [0.342,0.382])	0.330	([0.000,0.322], [0.566,0.584])

Table 8. The final risk ranking order of failure modes with the IVIF-MULTIMOORA method.

Failure Modes	IVIF-Ratio System	IVIF-Reference Point	IVIF-Full Multiplicative Form	IVIF-MULTIMOORA
FM_1	10	3	8	8
FM_2	6	7	7	6
FM_3	2	9	3	3
FM_4	1	5	1	1
FM_5	4	6	4	4
FM_6	8	8	10	10
FM_7	11	4	9	9
FM_8	5	10	6	7
FM_9	3	2	2	2
FM_{10}	7	11	11	11
FM_{11}	9	1	5	5

5. Sensitivity Analysis and Comparison Analysis

5.1. Sensitivity Analysis

The sensitivity analysis of the risk evaluation results of the FMEA with the proposed IVIF-MULTIMOORA method is conducted in this section according to the five cases of weighting risk factors shown in Table 9. Among them, Case 1 is the result of this study, and Case 2–5 are the weight of other risk factors that may occur. The risk ranking order of five cases for the 11 failure modes of Middle Route of the South-to-North Water Diversion Project is obtained as shown in Figure 2. As can be seen from Figure 2, the change of risk factor weight has a certain impact on the final risk ranking order of failure modes. For example, under the circumstances of occurrence (O) and severity (S) with high weight and detection (D) with low weight, Slippage (FM_2) is ranked low in the risk order. This indicates that the frequency of Slippage in the Middle Route of the South-to-North Water Diversion Project is relatively low. If the focus is on frequency, the risk ranking of FM_2 would be reduced. Similarly, for the failure mode Leakage (FM_4), the excessive leakage of channels not only affects the benefit of irrigation and water supply, but also damages the banks of channels by infiltration, causing problems such as Capsizing (FM_1) and Slippage (FM_2) [57]. In Case 3, the weight of risk factor S changed to extremely low, which decreased the risk degree. The Leakage (FM_4) risk ranking order changed from first to third. Therefore, it is particularly important to select appropriate methods to determine the weight information of risk factors. The proposed comprehensive weighting method in this paper gives full consideration to experts' opinions and to the assessment information itself in weight determination, which makes the risk ranking order closer to what it is in practice.

Table 9. Risk factor weights in sensitivity analysis.

Risk Factors	Case 1	Case 2	Case 3	Case 4	Case 5
O	0.352	0.4	0.4	0.4	0.5
S	0.350	0.4	0.2	0.3	0.3
D	0.298	0.2	0.4	0.3	0.2

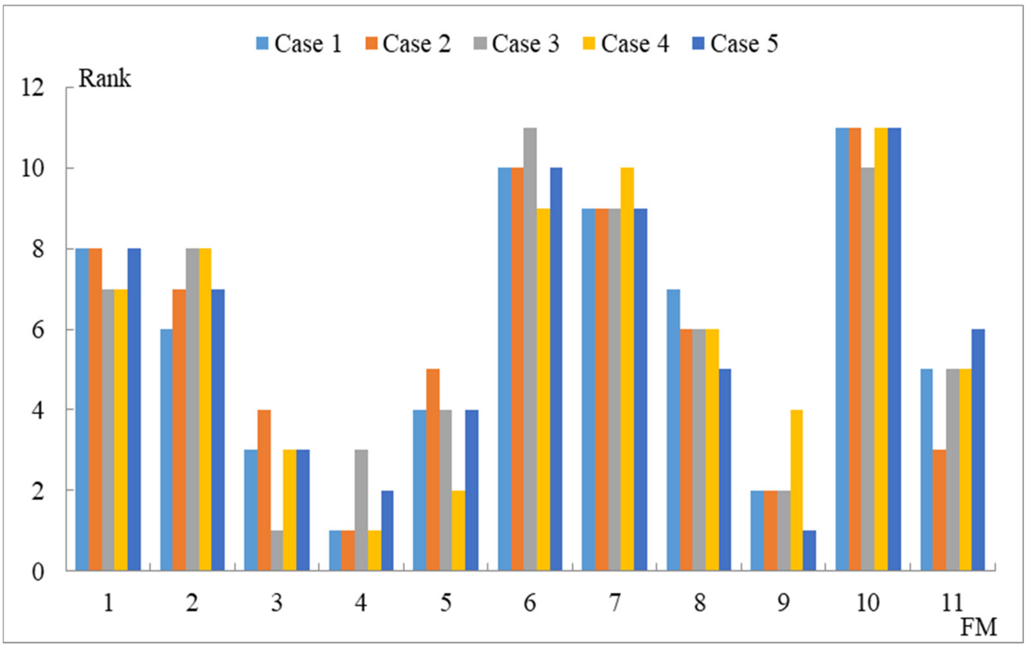

Figure 2. Results of sensitivity analysis for different risk factor weights.

5.2. Comparison Analysis

To verify the feasibility and effectiveness of the method proposed in this paper, the risk ranking results for failure modes using the IVIF-MULTIMOORA method are compared with the traditional MULTIMOORA method and the RPN method, as shown in Figure 3.

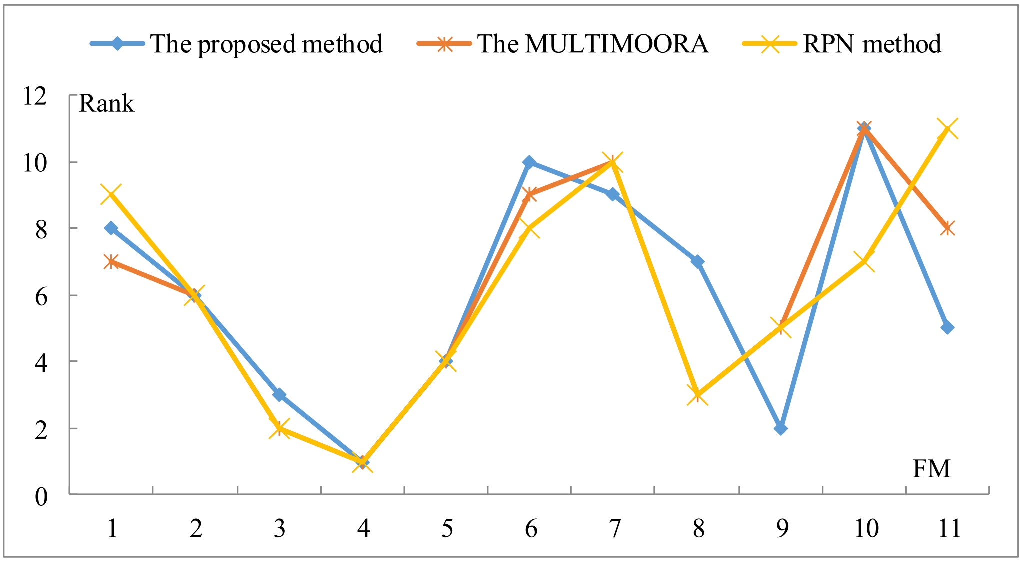

Figure 3. Results of comparison analysis.

The method proposed in this paper is compared with the traditional MULTIMOORA method and the RPN method, and much of the risk ranking order for failure modes is unchanged or only slightly changed, while a few failure modes show dramatic changes, such as Ice Damage (FM_8), Pollution (FM_9), and Terrorist Attack (FM_{11}). The Middle Route of the South-to-North Water Diversion Project is long and spans extensive latitudes [58]. There is a risk of ice jams and ice dams during water transmission in winter [59,60]. The appearance of ice jams and ice dams will reduce the water-carrying capacity of the channel, cause the water level upstream to rise, threaten the dykes, and interrupt the water supply in serious cases. However, after several years of operation, a variety of effective prevention and control measures have been implemented to address these problems [61,62], such as setting up an electric heating system or a water disturbance system, and enhancing inspections. Moreover, Ice Damage (FM_8) occurs only in winter. Therefore, the risk ranking order of FM_8 is seventh consistent with the actual situation. For the failure mode Pollution (FM_9), it must be noted that the Middle Route of the South-to-North Water Diversion Project is a long, open channel susceptible to pollution, which is difficult to prevent. Once a water pollution accident occurs, the hazard is large and involves a wide area [63]. Therefore, it is reasonable to have a high-risk ranking order for failure mode FM_9. In China, the probability of a Terrorist Attack (FM_{11}) is almost zero. However, if an attack happens, the severity would be extremely serious and the harm would be immeasurable. Therefore, it is practical that the risk is ranked as moderate.

The causes of the differences among these methods are as follow: (1) Real numbers have insufficient utility in depicting the uncertainty of assessment information using these methods, i.e., the traditional MULTIMOORA method and the RPN method have certain limitations for they cannot objectively reflect the complexity and uncertainty of things. (2) The proposed method in the paper introduces IVIFWA operator, improved Euclidean distance, and IVIFWG operator into the traditional MULTIMOORA method to optimize the information aggregation process and to highlight the effect of risk factor weight on risk ranking order. However, risk factors are regarded as equally important in the traditional MULTIMOORA method and the RPN method. (3) Brauers and Zavadskas [43] proposed conditions to measure the robustness of MCDM methods, and concluded that the robustness of MCDM methods, when combined with multiple decision-making methods, are better than that of the MCDM method combined with a single decision-making method. The IVIF-MULTIMOORA method comprises three decision making methods, which improves the robustness of the results to some extent. The comparison analysis presents that the risk ranking order for FMEA with the proposed method is more reasonable and robust. Therefore, the ranking results obtained by the IVIF-MULTIMOORA method are more scientific and applicable than those obtained by the MULTIMOORA and the RPN methods.

To conclude, although the results appear to have a slight difference in risk ranking among the IVIF-MULTIMOORA method, the traditional MULTIMOORA method, and the RPN method, the highest risk ranking of failure mode is completely the same with these three methods, that is, Leakage (FM_4) is at the first rank. Moreover, both the proposed method and the traditional MULTIMOORA method reveal failure mode of Power Failure of Electromechanical Equipment (FM_{10}) with the lowest risk. From the comparative results shown in Figure 3, the ranking results of the three methods are basically the same, but Ice Damage (FM_8), Pollution (FM_9), and Terrorist Attack (FM_{11}) have obvious differences in risk ranking. As previously discussed, compared with the other two methods, the calculation results of the proposed method in this paper are more consistent with the actual situation of the project, thus verifying that the proposed method has more reference value than the above two traditional methods. In addition, the proposed method in this paper has been optimized in every step of the FMEA process, and the results can provide decision-makers with more accurate reference basis for risk management, thus confirming the feasibility and effectiveness of the proposed method.

6. Conclusions

The traditional FMEA risk evaluation method has been widely used in the aerospace industry, the electric power industry, the nuclear industry, and the handicraft industry, etc., but some deficiencies still exist. This paper proposed a risk evaluation with the IVIF-MULTIMOORA method to improve the accuracy and scientificity of the FMEA process. First, to solve the uncertainty and vagueness of evaluation information, this paper converted the linguistic evaluation information of experts into corresponding interval-valued intuitionistic fuzzy numbers. Second, priority to experts was assigned with the interval-value intuitionistic fuzzy priority weight average operator to solve the problem of determining expert weight, and information loss was avoided in information aggregation. Third, the weights of risk factors were determined based on the full consideration of the experts' opinions and assessment information itself by using the expert evaluation method and deviation maximization model method, respectively. Finally, the ratio system, the reference point method, and the full multiplication model of MULTIMOORA sub-methods were improved by using the interval-value intuitionistic fuzzy weighted averaging operator, Tchebycheff Metric distance, and interval-value intuitionistic fuzzy weighted geometric operator, respectively, which optimized information aggregation process. The IVIF-MULTIMOORA method is proposed to obtain the reasonable and practical risk ranking order for failure modes. The feasibility and effectiveness of the proposed method were testified by carrying out the operational risk evaluation of the Middle Route of the South-to-North Water Diversion Project. Moreover, sensitivity analysis and comparative analysis were conducted. Compared with the existing methods of FMEA, the proposed approach is superior in the following ways:

(1) Linguistic variables are used to represent the evaluation information, which is more in line with the practical thinking habits than traditional methods that use real numbers. Converting linguistic evaluation information into corresponding interval-valued intuitionistic fuzzy numbers effectively deals with the uncertainty of experts' evaluation information and retains the integrality of the information.

(2) Different priority levels are assigned to experts according to differences in experts' knowledge structures and domain experience. Experts' evaluation information is aggregated using the IVIFPWA operator, which solves the problem of determining expert weight and improves the accuracy of results.

(3) The comprehensive weighting method, which is composed of the expert evaluation method and the deviation maximization model method, is proposed to determine the weight information of risk factors. The comprehensive weighting method in this paper gives full consideration to the experts' opinions and the assessment information itself in the weight determination, which makes the risk ranking order more accurate and closer to what it is in practice.
(4) By innovatively introducing the IVIFWA operator, Tchebycheff Metric distance, and the IVIFWG operator into the ratio system, the reference point method, and the full multiplication model of MULTIMOORA sub-methods, respectively, the information aggregation of the FMEA process is optimized. The extended IVIF-MULTIMOORA method can effectively obtain a more feasible and practical result and can improve the robustness of the result.

This paper analyzes the operational risk of the Middle Route of the South-to-North Water Diversion Project using the IVIF-MULTIMOORA method. It has a certain guiding significance and provides reference for the practical popularization and application of risk management strategies in the operation of other infrastructure projects, such as highways, waterworks, and sewage treatment plants. Throughout the process of the research and in practice, we realized that precise evaluation results are important for risk management of infrastructure, but we lacked actual accident data in the course of the project. Thus, important questions arise: How can relevant research be conducted in the absence of accident data and experts' evaluation information? Furthermore, how can available accident data be converted to the corresponding evaluation information form? These questions will be the research focus of risk assessment in the future.

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

Author Contributions: L.L. gave the idea of this paper, wrote and revised the paper; H.L. presented the framework of this paper, and gave many suggestions; L.W. gave many suggestions to improve paper; Q.X. calculated practical examples; L.J. spelled and checked this paper.

Funding: National Key R&D Program of China (No. 2018YFC0406905); National Natural Science Foundation of China (No. 71974056, No. 71302191); and the Foundation for Distinguished Young Talents in Higher Education of Henan (Humanities & Social Sciences), China (No.2017-cxrc-023).

Acknowledgments: This study was supported by the National Key R&D Program of China (No.2018YFC0406905), MOE (Ministry of Education in China) Project of Humanities and Social Sciences (No.19YJC630078), National Natural Science Foundation of China (No.71302191), the Foundation for Distinguished Young Talents in Higher Education of Henan (Humanities & Social Sciences) (No.2017-cxrc-023), Training Program for Young Backbone Teachers in Institutions of Higher Learning of Henan (No.2018GGJS080), and the 10th Graduate Student Innovation Project of North China University of Water Resources and Electric Power (No.YK2018-04).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bowles, J.B.; Peláez, C.E. Fuzzy logic prioritization of failures in a system failure mode, effects and criticality analysis. *Reliab. Eng. Syst. Saf.* **1995**, *50*, 203–213. [CrossRef]
2. Liu, H.C.; Liu, L.; Li, P. Failure mode and effects analysis using intuitionistic fuzzy hybrid weighted Euclidean distance operator. *Int. J. Syst. Sci.* **2014**, *45*, 2012–2030. [CrossRef]
3. Song, W.Y.; Ming, X.G.; Wu, Z.Y.; Zhu, B. A rough TOPSIS approach for failure mode and effects analysis in uncertain environments. *Qual. Reliab. Eng. Int.* **2014**, *30*, 473–486. [CrossRef]
4. Liu, H.C.; Liu, L.; Liu, N. Risk evaluation approaches in failure mode and effects analysis: A literature review. *Expert Syst. Appl.* **2013**, *40*, 828–838. [CrossRef]
5. Deng, X.Y.; Jiang, W. Fuzzy risk evaluation in failure mode and effects analysis using a D numbers based multi-sensor information fusion method. *Sensors* **2017**, *17*, 2086. [CrossRef] [PubMed]
6. Wang, Y.M.; Chin, K.S.; Poon, G.K.K.; Yang, J.B. Risk evaluation in failure mode and effects analysis using fuzzy weighted geometric mean. *Expert Syst. Appl.* **2009**, *36*, 1195–1207. [CrossRef]
7. Franceschini, F.; Galetto, M. A new approach for evaluation of risk priorities of failure modes in FMEA. *Int. J. Prod. Res.* **2001**, *39*, 2991–3002. [CrossRef]

8. Zammori, F.; Gabbrielli, R. ANP/RPN: A multi criteria evaluation of the risk priority number. *Qual. Reliab. Eng. Int.* **2012**, *28*, 85–104. [CrossRef]
9. Xiao, N.; Huang, H.Z.; Li, Y.; He, L.; Jin, T. Multiple failure modes analysis and weighted risk priority number evaluation in FMEA. *Eng. Fail. Anal.* **2011**, *18*, 1162–1170. [CrossRef]
10. Zhao, H.; You, J.X.; Liu, H.C. Failure mode and effect analysis using MULTIMOORA method with continuous weighted entropy under interval-valued intuitionistic fuzzy environment. *Soft Comput.* **2017**, *21*, 5355–5367. [CrossRef]
11. Kahraman, C.; Kaya, I.; Senvar, Ö. Healthcare failure mode and effects analysis under fuzziness. *Hum. Ecol. Risk Assess.* **2012**, *19*, 538–552. [CrossRef]
12. Liu, H.C.; Fan, X.J.; Li, P.; Chen, Y.Z. Evaluating the risk of failure modes with extended MULTIMOORA method under fuzzy environment. *Eng. Appl. Artif. Intell.* **2014**, *34*, 168–177. [CrossRef]
13. Liu, H.C.; Li, P.; You, J.X.; Chen, Y.Z. A novel approach for FMEA: Combination of interval 2-tuple linguistic variables and gray relational analysis. *Qual. Reliab. Eng. Int.* **2014**, *31*, 761–772. [CrossRef]
14. Chen, L.Y.; Deng, Y. A new failure mode and effects analysis model using Dempster-Shafer evidence theory and grey relational projection method. *Eng. Appl. Artif. Intell.* **2018**, *76*, 13–20. [CrossRef]
15. Selim, H.; Yunusoglu, M.G.; Balaman, S.Y. A Dynamic maintenance planning framework based on fuzzy TOPSIS and FMEA: Application in an International Food Company. *Qual. Reliab. Eng. Int.* **2016**, *32*, 795–804. [CrossRef]
16. Du, Y.; Lu, X.; Su, X.; Hu, Y.; Deng, Y. New failure mode and effects analysis: An evidential downscaling method. *Qual. Reliab. Eng. Int.* **2016**, *32*, 737–746. [CrossRef]
17. Mandal, S.; Maiti, J. Risk analysis using FMEA: Fuzzy similarity value and possibility theory based approach. *Expert Syst. Appl.* **2014**, *41*, 3527–3537. [CrossRef]
18. Safari, H.; Faraji, Z.; Majidian, S. Identifying and evaluating enterprise architecture risks using FMEA and fuzzy VIKOR. *J. Intell. Manuf.* **2016**, *27*, 475–486. [CrossRef]
19. Constantino, N.; d'Amato, M.; Pellegrino, R. A real options and fuzzy Delphi-based approach for appraising the effect of an urban infrastructure on surrounding lands. *Fuzzy Econ. Rev.* **2009**, *2*, 3–16.
20. Kozlova, M.; Collan, M.; Luukka, P. New investment decision-making tool that combines a fuzzy inference system with real option analysis. *Fuzzy Econ. Rev.* **2018**, *23*, 63–92. [CrossRef]
21. Zhang, H.J.; Dong, Y.C.; Palomares-Carrascosa, I.; Zhou, H.W. Failure mode and effect analysis in a linguistic context: A consensus-based multiattribute group decision-making approach. *IEEE Trans. Reliab.* **2019**, *68*, 566–582. [CrossRef]
22. Panchal, D.; Singh, A.K.; Chatterjee, P.; Zavadskas, E.K.; Keshavarz-Ghorabaee, M. A new fuzzy methodology-based structured framework for RAM and risk analysis. *Appl. Soft Comput.* **2019**, *74*, 242–254. [CrossRef]
23. Ekmekcioglu, M.; Kutlu, A.C. A fuzzy hybrid approach for fuzzy process FMEA: An application to a spindle manufacturing process. *Int. J. Comput. Int. Syst.* **2012**, *5*, 611–626. [CrossRef]
24. Chang, K.H. A more general risk assessment methodology using a soft set-based ranking technique. *Soft Comput.* **2014**, *18*, 169–183. [CrossRef]
25. Vahdani, B.; Salimi, M.; Charkhchian, M. A new FMEA method by integrating fuzzy belief structure and TOPSIS to improve risk evaluation process. *Int. J. Adv. Manuf. Technol.* **2015**, *77*, 357–368. [CrossRef]
26. Wang, Z.; Gao, J.M.; Wang, R.X.; Chen, K.; Gao, Z.Y.; Zheng, W. Failure mode and effects analysis by using the house of reliability-based rough VIKOR approach. *IEEE Trans. Reliab.* **2018**, *67*, 230–248. [CrossRef]
27. Atanassov, K.T. Intuitionistic fuzzy sets. *Fuzzy Sets Syst.* **1986**, *20*, 87–96. [CrossRef]
28. Atanassov, K.T.; Gargov, G. Interval-valued intuitionistic fuzzy sets. *Fuzzy Sets Syst.* **1989**, *31*, 343–349. [CrossRef]
29. Kozlova, M.; Collan, M.; Luukka, P. Simulation decomposition: New approach for better simulation analysis of multi-variable investment projects. *Fuzzy Econ. Rev.* **2016**, *21*, 3–18. [CrossRef]
30. Tian, Z.P.; Wang, J.Q.; Zhang, H.Y. An integrated approach for failure mode and effects analysis based on fuzzy best-worst, relative entropy, and VIKOR methods. *Appl. Soft Comput.* **2018**, *72*, 636–646. [CrossRef]
31. Liu, H.C.; Liu, L.; Liu, N.; Mao, L.X. Risk evaluation in failure mode and effects analysis with extended VIKOR method under fuzzy environment. *Expert Syst. Appl.* **2012**, *39*, 12926–12934. [CrossRef]
32. Bian, T.; Zheng, H.; Yin, L.; Deng, Y. Failure mode and effects analysis based on D numbers and TOPSIS. *Qual. Reliab. Eng. Int.* **2018**, *34*, 501–515. [CrossRef]

33. Liu, H.C.; Wang, L.E.; Li, Z.; Hu, Y.P. Improving risk evaluation in FMEA with cloud model and hierarchical TOPSIS method. *IEEE Trans. Fuzzy Syst.* **2019**, *27*, 84–95. [CrossRef]
34. Tekez, E.K. Failure Modes and Effects Analysis using fuzzy TOPSIS in knitting process. *Tekst. Konfeksiyon* **2018**, *28*, 21–26.
35. Abdelgawad, M.; Fayek, A.R. Risk Management in the construction industry using combined fuzzy FMEA and fuzzy AHP. *J. Constr. Eng. Manag.* **2010**, *136*, 1028–1036. [CrossRef]
36. Bao, J.; Johansson, J.; Zhang, J. An occupational disease assessment of the mining industry's occupational health and safety management system based on FMEA and an improved AHP model. *Sustainability* **2017**, *9*, 94. [CrossRef]
37. Tsai, S.B.; Yu, J.; Ma, L.; Luo, F.; Zhou, J.; Chen, Q.; Xu, L. A study on solving the production process problems of the photovoltaic cell industry. *Renew. Sustain. Energy Rev.* **2018**, *82*, 3546–3553. [CrossRef]
38. Tsai, S.B.; Zhou, J.; Gao, Y.; Wang, J.; Li, G.; Zheng, Y.; Ren, P.; Xu, W. Combining FMEA with DEMATEL models to solve production process problems. *PLoS ONE* **2017**, *12*, e0183634. [CrossRef]
39. Wu, S.M.; You, X.Y.; Liu, H.C.; Wang, L.E. Improving quality function deployment analysis with the cloud MULTIMOORA method. *Int. Trans. Oper. Res.* **2018**, in press. [CrossRef]
40. Brauers, W.K.M.; Zavadskas, E.K. The MOORA method and its application to privatization in a transition economy. *Control Cybern.* **2006**, *35*, 445–469.
41. Brauers, W.K.M.; Zavadskas, E.K. Project management by MULTIMOORA as an instrument for transition economies. *Technol. Econ. Dev. Econ.* **2010**, *16*, 5–24. [CrossRef]
42. Brauers, W.K.M. Project management for a country with multiple objectives. *Czech Econ. Rev.* **2012**, *6*, 80–101.
43. Brauers, W.K.M.; Zavadskas, E.K. Robustness of MULTIMOORA: A method for multi-objective optimization. *Informatica* **2012**, *1*, 1–25.
44. Tomas, B.; Alvydas, B. A survey on development and applications of the multi-criteria decision making method MULTIMOORA. *J. Multi Criteria Decis. Anal.* **2014**, *21*, 209–222.
45. Zavadskas, E.K.; Antucheviciene, J.; Hajiagha, S.H.R.; Hashemi, S.S. The interval-valued intuitionistic fuzzy MULTIMOORA method for group decision making in engineering. *Math Probl. Eng.* **2015**, *2015*, 560690. [CrossRef]
46. Xu, Z.S. Methods for aggregating interval-valued intuitionistic fuzzy information and their application to decision making. *Control Decis.* **2007**, *22*, 215–219.
47. Ye, J. Multi-criteria fuzzy decision making method based on a novel accuracy function under interval-valued intuitionistic fuzzy environment. *Expert Syst. Appl.* **2009**, *36*, 6899–6902. [CrossRef]
48. Brauers, W.K.M.; Zavadskas, E.K. MULTIMOORA optimization used to decide on a bank loan to buy property. *Technol. Econ. Dev. Econ.* **2011**, *17*, 174–188. [CrossRef]
49. Brauers, W.K.M.; Balezentis, A.; Balezentis, T. MULTIMOORA for the EU Member States updated with fuzzy number theory. *Technol. Econ. Dev. Econ.* **2011**, *17*, 259–290. [CrossRef]
50. Yu, D.J. Intuitionistic fuzzy prioritized operators and their application in multi-criteria group decision making. *Technol. Econ. Dev. Econ.* **2013**, *19*, 1–21. [CrossRef]
51. Yager, R.R. Prioritized aggregation operators. *Int. J. Approx. Reason.* **2008**, *48*, 263–274. [CrossRef]
52. Zeleny, M.; Cochrane, J.L. *Multiple Criteria Decision Making*; McGraw-Hill: New York, NY, USA, 1982.
53. Xu, Z. A deviation-based approach to intuitionistic fuzzy multiple attribute group decision making. *Group Decis. Negot.* **2010**, *19*, 57–76. [CrossRef]
54. Minkowski, H. Gesammelte Abhandlungen. *Monatsh. Math. Phys.* **1911**, *25*, 30–31.
55. Zhang, X.; Jin, F.; Liu, P. A grey relational projection method for multi-attribute decision making based on intuitionistic trapezoidal fuzzy number. *Appl. Math. Model.* **2013**, *37*, 3467–3477. [CrossRef]
56. Xiong, Y.H.; Qi, W.G.; Wang, Z.J. Operation risk of the Middle Route of the South-to-North Water Diversion Project—Risk identification in the Middle Route of the South-to-North Water Diversion Project. *South North Water Transf. Water Sci. Technol.* **2010**, *8*, 1–5.
57. Hu, H.Z.; Mao, X.M.; Yang, Q. Impacts of Yongding River Ecological Restoration on the Groundwater Environment: Scenario Prediction. *Vadose Zone J.* **2018**, *17*, 1–15. [CrossRef]
58. Liu, Z.P.; Wu, Y.H.; Chen, W.X.; Cui, W.; Mu, X.P.; Guo, X.C. *Hydraulics Research on the Middle Route of South to North Water Diversion Project*; China Water and Power Press: Beijing, China, 2010; pp. 20–46.
59. Fu, H.; Yang, K.L.; Guo, X.L.; Guo, Y.X.; Wang, T. Safe operation of inverted siphon during ice period. *J. Hydrodyn.* **2015**, *27*, 204–209. [CrossRef]

60. Fu, H.; Guo, X.L.; Yang, K.L.; Wang, T.; Guo, Y.X. Ice accumulation and thickness distribution before inverted siphon. *J. Hydrodyn.* **2017**, *29*, 61–67. [CrossRef]
61. Guo, X.L.; Yang, K.L.; Fu, H.; Wang, T. Numerical simulation of ice regime in the water conveyance system during winter in Middle Route of South-to-North Water Transfer Project. *Shuili Xuebao* **2011**, *42*, 1268–1276.
62. Lian, J.J.; Zhao, X. Research on layout distance between net-style ice boom with two axes. *South North Water Transf. Water Sci. Technol.* **2012**, *10*, 1–3.
63. Tang, C.H.; Yi, Y.J.; Yang, Z.F.; Cheng, X. Water pollution risk simulation and prediction in the main canal of the South-to-North Water Transfer Project. *J. Hydrol.* **2014**, *519*, 2111–2120. [CrossRef]