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An Integrated Approach-Based FMECA for Risk Assessment: Application to Offshore Wind Turbine Pitch System

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Abstract: Failure mode, effects and criticality analysis (FMECA) is a well-known reliability analysis tool for recognizing, evaluating and prioritizing the known or potential failures in system, design, and process. In conventional FMECA, the failure modes are evaluated by using three risk factors, severity (*S*), occurrence (*O*) and detectability (*D*), and their risk priorities are determined by multiplying the crisp values of risk factors to obtain their risk priority numbers (RPNs). However, the conventional RPN has been considerably criticized due to its various shortcomings. Although significant efforts have been made to enhance the performance of traditional FMECA, some drawbacks still exist and need to be addressed in the real application. In this paper, a new FMECA model for risk analysis is proposed by using an integrated approach, which introduces Z-number, Rough number, the Decision-making trial and evaluation laboratory (DEMATEL) method and the VIsekriterijumska optimizacija i KOmpromisno Resenje (VIKOR) method to FMECA to overcome its deficiencies in real application. The novelty of this paper in theory is that the proposed approach integrates the strong expressive ability of *Z*-numbers to vagueness and uncertainty information, the strong point of DEMATEL method in studying the dependence among failure modes, the advantage of rough numbers for aggregating experts' diversity evaluations, and the strength of VIKOR method to flexibly model multi-criteria decision-making problems. Based on the integrated approach, the proposed risk assessment model can favorably capture and aggregate FMECA team members' diversity evaluations and prioritize failure modes under different types of uncertainties with considering the failure propagation. In terms of application, the proposed approach was applied to the risk analysis of failure modes in offshore wind turbine pitch system, and it can also be used in many industrial fields for risk assessment and safety analysis.

Keywords: failure mode; effects and criticality analysis; *Z*-number; rough number; DEMATEL method; VIKOR method

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1. Introduction

Failure mode, effects and criticality analysis (FMECA), also known as failure mode and effects analysis (FMEA) when without referring to criticality analysis, is a risk and reliability analysis tool based on multidisciplinary team cooperation [1]. The FMEA method originates from the formal design methodology by NASA and first proposed in 1960s for solving their obvious reliability and safety requirements [2]. In many fields, it can be used to enhance the reliability and safety for a system by recognizing the various failure modes and analyzing their reasons and effects in the system and process during product design and manufacturing processes. The main task of FMEA is to evaluate the likelihood of the potential failure modes and their impact and severity to identify weaknesses and key projects in the system and then provide a basis for developing improved control measures. Differing from some other reliability management approaches, FMEA emphasizes taking precautions against failures rather than finding a solution after the failures happen [3], which can greatly reduce the frequency of occurrence of failure modes and avoid serious accidents. As a widely used methodology in safety and reliability analysis, FMEA has gained a widespread attention due to its visibility and simplicity, and up to now it has been extensively used in various industries [4–11].

In traditional FMECA, each failure mode identified in a system is evaluated by three risk factors of severity (*S*), occurrence (*O*) and detectability (*D*), and their risk priorities are determined by sorting their risk priority numbers (RPNs) [12], which is obtained by multiplying the values of *S*, *O* and *D*. Generally, *S*, *O* and *D* of failure modes are scored by experts and a number ranged from 1 to 10 is given for each of the three risk factors, usually the large the number, the worse the case is. Based on the values of RPNs, the risk priorities of failure modes are determined, which can help the analyst to pinpoint system inherent vulnerabilities. A failure mode with higher RPN is regarded as more important [13], which means it has greater harm to the system and will be given a higher risk priority. Thus for guaranteeing safety and reliability, some measures of prevention and improvement should be taken preferentially to the failure modes with high risk priority to avoid their occurrence. However, the crisp value of RPN has been highly criticized for various reasons [14–19], most of which are listed as follows:

1. The relative importance of the three risk factors has not been considered or are considered as equal importance, which may not consistent with the actual situation in many cases.
2. Multiplying the values of *S*, *O* and *D* in different groups may produce the same RPN value, but the hidden risk implications of each group can be completely different, which may lead to the limited resources and time being inappropriately allocated, or worse yet, some high risk failure modes being ignored.
3. The mean of computing RPN is debatable and hypersensitive to the variation of the values of risk factors. In some cases, a subtle alteration in the value of one risk factor may have a hugely different effect on RPN when the values of other risk factors are very large.
4. The evaluations for risk factors of *S*, *O* and *D* are usually given based on discrete ordinal scales of measure, on which the calculation of multiplication is meaningless because the obtained RPNs may be not continuous with many holes and heavily distributed ranged from 1 to 1000. In this case, the ranking results of failure modes are meaningless and even misleading.
5. The three risk factors are often hard to be determined precisely. The evaluations obtained from FMECA team members are expressed by linguistic items like high, moderate or low and so on.
6. FMECA team members may provide their evaluations in different way for the same risk factor due to their different expertise and backgrounds, and some of the assessment information may be vagueness and uncertain. In conventional FMECA, there is no means to describe the group judgment more comprehensively and explore the intrinsic link between different judgments [20].

In order to conquer the shortcomings mentioned above and enhance the applicability of traditional FMECA to real cases [3], much attention have been paid to its improvements and a variety of theories and methods have been introduced to FMECA. For example, fuzzy set has been introduced to FMECA for transforming the vagueness of experts' evaluation into a mathematical formula; information fusion method like Dempster–Shafer Theory and rough number, etc., are introduced to FMECA for aggregating different evaluations; multi-criteria decision making methods like the VIsekriterijumska optimizacija i KOmpromisno Resenje (VIKOR) method and Technique for Ordering Preference by Similarity to Ideal Solution (TOPSIS) method, etc., are introduced to FMECA for ranking failure modes. Some of the main theories and methods are presented in Table 1.

In studies of FMECA in wind turbines, some experts take the structures of different wind turbines, economic factors, costs and climatic regions into consideration. For example, Mahmood et al. [21] developed a mathematical tool for risk and failure mode analysis of wind turbine systems (both onshore and offshore) by integrating the aspects of traditional FMEA and some economic considerations such as power production losses, and the costs of logistics and transportation. Samet et al. [22] proposed a FMECA methodology with considering different weather conditions or climatic regions and different wind turbine design types such as direct-drive model and geared-drive model. Nacef et al. [23] developed a hybrid cost-FMEA by integrating cost factors to assess the criticality, these costs vary from replacement costs to expected failure costs.

Table 1. Some of the theories and methods used in FMECA.

Categories	Theories and Methods	Roles in FMECA
Artificial intelligence techniques	Fuzzy rule-base system [24]	It can be used to deal with the drawback 5. in FMECA by transforming the vagueness of the evaluation of failure modes into a mathematical formula, which has the decision making ability by ranking the failure modes using fuzzy rules.
	Evidential reasoning method (ER) [25]	It can be used to deal with the drawbacks 5. and 6. in FMECA by modeling the diversity and uncertainty of experts' evaluations, which enables experts to evaluate failure modes in an independent way and aggregating their evaluations in a rigorous yet nonlinear rather than simple addition or multiplication manner.
	Rough number [26]	It can be used to deal with the drawback 6. in FMECA by aggregating the vague and uncertain evaluations of failure modes, which can reduce the subjectively of experts' opinion in aggregation process and make the decision-making more objective.
	Dempster–Shafer Theory (DST) [27]	It can be used to deal with the drawbacks 5. and 6. in FMECA by aggregating different types of subjective and uncertain evaluations using Dempster's rule, which has the ability of representing and handling various uncertainty information using belief structure.
	D number [28]	It can be used to deal with the drawbacks 5. and 6. in FMECA by representing and aggregating the experts' evaluations with cognitive uncertainty and imprecision for failure modes, which is capable of efficiently expressing various types of uncertainty.
Multi-criteria decision making (MCDM)	Analytic hierarchy process (AHP) method [29]	It can be used to deal with the drawbacks 2., 3. and 4. in FMECA, which determines the risk priorities of failure modes by using eigen vectors for synthesizing a series of paired comparison evaluations based on the evaluation of failure modes in a hierarchical way.
	TOPSIS method [30]	It can be used to deal with the drawbacks 2., 3. and 4. in FMECA, which determines the risk priorities of failure modes by comparing the Euclid distances simultaneously from the best evaluation value and from the worst evaluation value.
	VIKOR method [16]	It can be used to deal with the drawbacks 2., 3. and 4. in FMECA, which determines the risk priorities of failure modes by using a compromise solution of maximizing the group utility of the majority, and meanwhile minimizing the individual regret of the opponent.
	Decision making trial and evaluation laboratory (DEMATEL) method [31]	It can be used to deal with the drawbacks 2., 3., 4. and 7. in FMECA, which determines the risk priorities of failure modes by studying the dependence among failure modes in FMECA process using the graph theory and matrix tools.
	Grey theory method [32]	It can be used to deal with the drawbacks 2., 3. and 4. in FMECA, which determines the risk priorities of failure modes by calculating the grey relational coefficient between all comparability sequences and the reference sequence of the ideal target sequence and negative ideal target sequence).

Although many theories and methods have been introduced to FMECA to eliminate the defects of the traditional FMECA, the representation of expert's judgments on the evaluation of failure modes, the aggregation of experts' diversified evaluation information, and the determination of risk priorities of failure modes are still open issues, especially in terms of the defect of without considering the dependencies among different failure modes. In this paper, an integrated approach-based risk assessment model for FMECA was proposed to the existing defects, which integrates the strong expressive ability of Z-numbers to vagueness and uncertainty information, the strong point of the DEMATEL method in studying dependence among failure modes, the advantage of rough numbers in aggregating experts' diversity evaluation information, and the merit of VIKOR evaluation structure in flexibly modeling multi-criteria decision-making. Based on the integrated approach, the proposed risk assessment model can well capture and aggregate FMECA team members' diversity evaluations and prioritize failure modes under different types of uncertainties with considering the failure propagation. The rest of this paper is organized as follows. Some existing improvement methods to traditional FMECA are introduced in Section 2. Section 3 introduces the proposed new risk assessment model for FMECA using Z-number, rough number, DEMATEL method and VIKOR method. An illustrative case and the comparison and discussion for the proposed FMECA approach are respectively provided in Sections 4 and 5. Section 6 concludes the paper with a summary.

2. Literature Review

In the recent decades, scholars and researchers have done a lot of significant work to the improvements of FMECA. Among these improvement methods we can find they are mainly focusing on the following four aspects.

In term of the defect of traditional FMECA without considering the weights of risk factors, Hua et al. [33] introduced fuzzy analytic hierarchy process (FAHP) approach to FMECA for determining the weights of risk factors. Liu et al. [13] introduced a subjective weight and objective weight for risk factors by integrating fuzzy analytic hierarchy process (FAHP) and entropy method. Bozdag et al. [34] proposed a new fuzzy FMECA approach based on IT2 fuzzy sets for obtaining the uncertainty both in intrapersonal and interpersonal, which considers the optimal weights of risk factors and synthetizes them by using an ordered weighted averaging operator based on-cut. Liu et al. [35] introduced fuzzy digraph and matrix approach to FMECA for developing a new FMECA model with considering the relative weights of risk factors expressed by linguistic terms and transformed to fuzzy numbers, which determines the risk priorities of failure mode using their risk priority indexes that computed based on the formed corresponding fuzzy risk matrixes for failure modes. Zhou et al. [36] proposed a new generalized evidential FMECA (GEFMECA) model to handle the uncertain risk factors comprised of not only the conventional risk factors, but also the other incomplete risk factors. Based on the generalized evidence theory, the relative weights among all risk factors are well addressed. Liu et al. [37] proposed an integrated FMECA approach for the improvement of its performance based on the interval-valued intuitionistic fuzzy sets (IVIFSs) and multi-attributive border approximation area comparison (MABAC) method, in which the linear programming model is developed for obtaining the optimal weights of risk factors even if the weight information among risk factors is incompletely known.

In view of the defect that the evaluations obtained from FMECA team members are expressed in a linguistic way which are difficult to be converted directly and correctly into numerical value. To handle this case, fuzzy set theory and its improvement methods were introduced to FMECA by many researchers, which can be well used to transform the linguistic item into a mathematical formula and improve the decision making ability for FMECA in real application. Bowles and Peláez [2] first introduced fuzzy set theory into FMECA and proposed a technique based on fuzzy logic to prioritize failure modes in a system FMECA, which enables analysts to evaluate the failure modes using the linguistic terms directly and provides a more flexible structure to combine the parameters of risk factors. For dealing with the drawbacks of traditional fuzzy logic (i.e., rule-based) methods used in FMECA, Yang et al. [38] proposed a fuzzy rule-based Bayesian reasoning approach for the prioritization of failure modes. Jee et al. [39] presented a new fuzzy inference system (FIS)-based risk assessment model for FMECA to prioritizing failure modes, in which a new two-stage method is introduced for reducing the number of fuzzy rules which need to be gathered. By integrating FMECA and fuzzy linguistic scale method, Gajanand et al. [40] proposed a new strategy for the reliability-centered maintenance, in which the failure modes are prioritized by using the weighted Euclidean distance and centroid defuzzification based on fuzzy logic. Tooranloo et al. [41] proposed a new model for FMECA based on intuitionistic fuzzy approach, which evaluates failure modes under vague concepts and insufficient data. Jian et al. [42] proposed a new risk evaluation approach for failure mode analysis in FMECA by integrating intuitionistic fuzzy sets (IFSs) and evidence theory. In their method, linguistic items and intuitionistic fuzzy numbers are used to evaluate the risk factors of failure modes and then the evaluations are transformed into basic probability assignment functions based on evidence theory. Jiang et al. [43] assessed the risk factors of failure modes using fuzzy membership degree in their proposed fuzzy evidential method for FMECA, and ranked the failure modes by fusing the feature information of risk factors with D–S theory of evidence.

Aiming at the controversial mathematical formula for RPN calculation and the ranking problem of failure modes, many researchers have viewed the risk ranking problem of failure modes as a multiple criteria decision-making (MCDM) issue [16], and a lot of MCDM methods such as Analytical Hierarchy Process (AHP), technique for ordering preference by similarity to ideal solution (TOPSIS), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), grey theory, and VIsekriterijumska optimizacija i KOmpromisno Resenje (VIKOR) are introduced to FMECA. For example, Aydogan [44] introduced an integrated approach by using the rough AHP and fuzzy TOPSIS method for the performance analysis of organizations under fuzzy environment. Song et al. [20], taking advantage of the merit of rough set theory in manipulating uncertainty and the strength of the TOPSIS method in modeling multi-criteria decision making, proposed a new risk assessment model for FMECA. Liu et al. [45] introduced an intuitionistic fuzzy hybrid TOPSIS method to FMECA for determining the risk priorities of failure modes. Silvia et al. [46] proposed an maintenance approach based on by combining reliability analysis and MCDM method to optimize maintenance activities of complex systems, in which the AHP is used for weight evaluation of criteria and fuzzy TOPSIS method is responsible for risk ranking of failure modes identified in the system. Vahdani et al. [47] integrated fuzzy belief structure and TOPSIS method in FMECA to describe expert knowledge and rank failure modes in risk analysis. Zhou et al. [48] introduced grey theory and fuzzy theory into FMECA for the failure prediction of tanker equipment, in which the risk priorities of failure modes are determined by two criteria of the fuzzy risk priority numbers (FRPNs) obtained by fuzzy set theory and the grey relational coefficient obtained by grey theory. Liu et al. [28] introduced a new FMECA approach based on grey relational projection method (GRP) and D numbers for determining the risk priority orders of failure modes. Liu et al. [49] developed a framework for FMECA by integrating cloud model and PROMETHEE method for handling the representation of diversified risk evaluations of FMECA team members and the determination of the risk priorities of failure modes. Mandal et al. [50] presented a methodology utilizing VIKOR approach for ranking the human errors. Baloch et al. [51] integrated fuzzy VIKOR method and data envelopment analysis method into FMECA for determining the rankings of potential manners and selecting the most important impairment manner.

For better capturing and aggregating different experts' diversity evaluations which are difficult to be handled by traditional FMECA, evidential reasoning and Dempster–Shafer (D–S) Theory are introduced to FMECA in many literatures. Chin et al. [25] proposed an FMECA approach based on group-based evidential reasoning (ER) for capturing experts' diversity evaluations and prioritizing failure modes in the situation of various uncertainty. Liu et al. [52] proposed an improvement approach for FMECA based on fuzzy evidential reasoning (FER) and grey theory to solve the two shortcomings of traditional FMECA with respect to the acquirement and aggregation of different experts' evaluations and the determination of the risk priorities of failure modes. Liu et al. [53] proposed a new risk assessment model for the prioritization of failure modes in FMECA based on FER and belief rule-based (BRB) method. In their method, FER method is utilized to capture and aggregate the diversified, uncertain evaluations provided by experts and the relationships of nonlinear and uncertainty between risk factors and corresponding risk level are modeled by BRB method. Du et al. [54] proposed a new method in fuzzy FMECA based on evidential reasoning (ER) and TOPSIS method for precisely determining and aggregating the risk factors. Li et al. [55] proposed a new method by integrating D–S Theory, DEMATEL, and IFS method to prioritize alternatives and make risk assessment for system FMECA. Yang et al. [27] introduced D–S Theory to FMECA for analyzing different failure modes in the rotor blades of an aircraft engine under multiple evaluation sources with uncertainty. Su et al. [56] aiming at the method of Yang et al. proposed a modification for dealing with the combination of conflicting evidence by using the Gaussian distribution-based uncertain reasoning method to reconstruct the basic belief assignments (BBAs) with considering the weight of each expert. Shi et al. [57] proposed a aggregation method for aggregating hybrid preference information based on IFS and D–S Theory, which determines the weight of each expert based on the conflict degree that is obtained by computing the conflict coefficient with Jousselme distance [58]. Jiang et al. [59] proposed a modified method for improving the performance of evidence theory used in FMECA, which reassigns the basic belief assignments by considering the reliability coefficients obtained based on evidence distance to reduce the conflicts among expert's opinion [60].

3. Proposed FMECA Approach

3.1. Methodologies

In this section, *Z*-number, rough number, DEMATEL method and VIKOR method are briefly introduced. These methods will be used in the proposed risk assessment model.

(1) *Z*-number

Z-number, a 2-tuple fuzzy numbers that includes the restriction of the evaluation and the reliability of the judgment, was first introduced by Zadeh in the year of 2011 for overcoming the limitation that fuzzy numbers does not consider the reliability of the information [61]. The idea of a *Z*-number is providing a mode for calculation with numbers that has partial reliability in the evaluation [62]. A *Z*-number can be utilized to express the information of an uncertain judgement in the form of two fuzzy numbers that the first fuzzy number indicates the fuzzy restriction and the second fuzzy number represents an idea of confidence, reliability, and probability. Thus, *Z*-number is more efficient than fuzzy number in describing the knowledge of human judgment since it describes both the restraint and reliability. Due to the powerful ability in modeling uncertain information in real world, *Z*-number has gained attention by some researchers and efforts have been made to apply *Z*-number to various situations such as in computing with words (CWW) [63] and decision making problems [64].

A *Z*-number can be denoted as Z = (A, R) where the first component is the fuzzy restriction for the evaluation of objects and the second component is the reliability of the first component. In *Z*-number, A and R are described in natural language using linguistic terms and presented in a fuzzy number form such as triangular or trapezoidal fuzzy numbers [61]. For example, in risk analysis, the severity of a failure mode is very high, with a confidence of very sure, then the *Z*-number for evaluating the failure mode can be written as Z = (Very high, Very sure).

(2) Rough number

Rough set theory as a mathematical tool for dealing with the imprecision, uncertainty and vagueness knowledge [65] has been extensively applied in the fields of knowledge discovery, data mining, decision analysis and pattern recognition. By using its lower approximation and upper approximation, rough set theory can fully express and describe the ambiguity and randomness of uncertain information and can lessen the information loss of aggregation process to a certain extent. Based on rough set theory, rough number is developed by Zhai et al. [66] for managing customers' subjective judgments and determining their boundary intervals. By introducing rough number to FMECA, the evaluations of experts in FMECA can be transformed to rough numbers by calculating their lower approximation and upper approximation on the basis of original data without any requirement of auxiliary information. Since it can effectively extract experts' actual opinion and reduce their subjectively in decision-making [67], in this section, rough number is applied to aggregate the evaluations of experts.

(3) DEMATEL method

Decision-making trial and evaluation laboratory (DEMATEL) method was first proposed in 1973 to solve the fragmented and antagonistic issues of world societies [68]. It is a method of system analysis using the structural modeling technique to find the influence relation among complex elements. DEMATEL is a tool of based on the graph theory and matrix, which constructs the direct influence matrix by means of the logical relation among various elements in the system and calculates the effect degree and cause degree of each element to other elements. Because of its ability to pragmatically visualize complicated causal relationships [69], DEMATEL can be used as an effective tool in studying the interdependence among elements in a complex systems and can be well used to identify the dependence among failure modes in FMECA process.

(4) VIKOR method

The VIKOR (VIsekriterijumska optimizacija i KOmpromisno Resenje) method was first proposed by Opricovic [70] to rank and select the optimum solution among a set of choices under different units criteria. As one of the MCDM method, VIKOR ranks alternatives based on the multicriteria ranking index by calculating the particular measure of "closeness" to the "ideal" solution [71]. It is an effective method in the field of multicriteria decision making especially in the case where the decision makers may not have enough knowledge to express their preferences at the beginning of system design [72]. Comparing to other MCDM methods, VIKOR helps decision makers reach a feasible decision closest to the ideal by proposing a compromised solution with an advantage rate. Moreover, it is facile to conduct without any parameter settings. Thus, VIKOR has been extensively applied to practical decision making issues.

3.2. The Proposed Risk Assessment Model for FMECA

In this paper, a new risk assessment model for FMECA by integrating Z-number, Rough number, DEMATEL method and VIKOR method is proposed. In the proposed approach, Z-number is introduced to express experts' judgements on the evaluation of failure modes, which has a strong ability to describe the knowledge of human beings by using a 2-tuple fuzzy numbers and can be well used in representing vagueness and uncertainty information. Rough number is applied to aggregate different types of evaluations transformed by the given 2-tuple fuzzy numbers of experts and manipulate the subjectivity and vagueness in the evaluation process. Based on its flexible boundary interval, the epistemic uncertainty of evaluations can be generally represented and the different sources of uncertainty can be effectively tackled in aggregation process. DEMATEL method is introduced to calculate the effect degree and cause degree of each failure mode by constructing the direct influence matrix of failure modes, which is a very effective tool to study the relationship among various failure modes in complex systems. Finally, VIKOR method is utilized to determine the risk priorities of failure modes under a compromise way, which can help experts achieving a reasonable ranking results on the basis of maximizing the group utility for the "majority" and minimizing the individual regret for the "opponent".

The framework of the proposed approach is depicted in Figure 1, which comprises four different stages. The first stage is to evaluate the failure modes by using Z-number, the second stage is the aggregation of different experts' evaluations based on rough number, the third stage is to determine the dependency among failure modes on the basis of historical failure data, and the fourth stage is to rank the failure modes using VIKOR method. The four stages are explained in detail as follows.

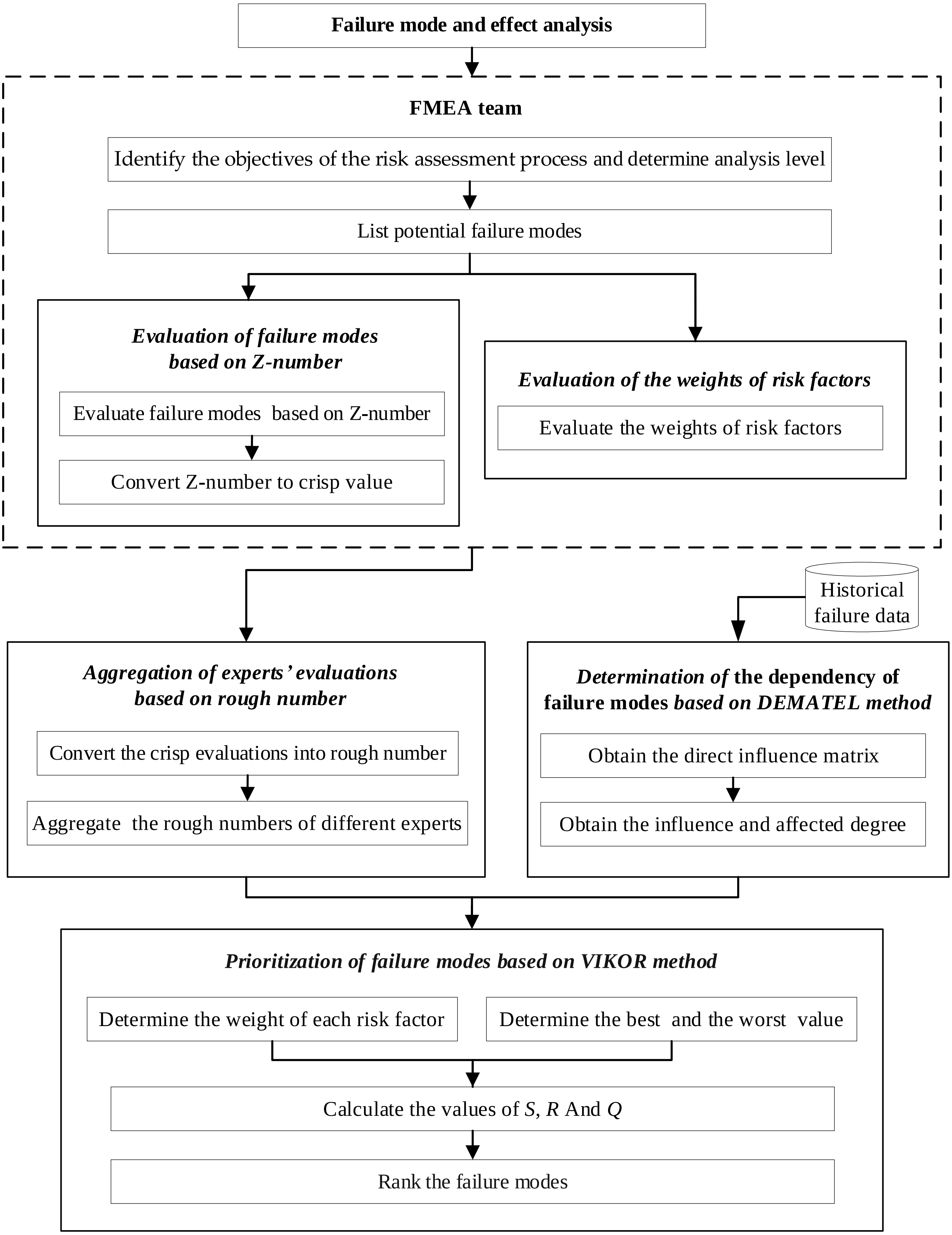

Figure 1. The framework of the proposed FMECA approach.

Step 1: Identify the objectives of the risk assessment process and determine the analysis level.

Step 2: Establish the FMECA team, list the potential failure modes and describe a finite set of relevant risk factors.

Suppose there are m failure modes in FMECA needed to be ranked according to the evaluations of failure modes and K experts are responsible for the evaluation with respect to the risk factors of severity, occurrence, detectability and failure propagation of failure modes.

Step 3: Evaluate the identified failure modes based on Z-number

In FMECA, failure modes are usually evaluated using linguistic variables such as very high, high, moderate, low, and very low, these evaluations are usually expressed in a fuzzy and imprecise way. In this section, failure modes are evaluated by using Z-number, which can not only express the evaluation of failure modes in a fuzzy and imprecise way, but also consider the confidence and reliability of the evaluations. In our work, failure modes are first evaluated according to Table 2, then the given linguistic terms are converted to fuzzy number according to Table 3. The transferred evaluations for failure mode in the form of 2-tuple fuzzy numbers are expressed as

$$Z = (A, B) = \{(\alpha_1, \alpha_2, \alpha_3), (\beta_1, \beta_2, \beta_3)\} \tag{1}$$

Table 2. Evaluation criterion for S, O, and D and the corresponding linguistic terms.

Severity	Occurrence	Detectability	Linguistic Variables
Failure is hazardous and causes system failure	Extremely high: Failure almost inevitable	Design control cannot detect failures	Extremely high (EH)
Failure involves hazardous outcomes	Very high	Very remote chance to detect failures	Very high (VH)
System is inoperable with loss of primary function	Repeated failures	Remote chance to detect failures	Relatively high (RH)
System performance is severely affected but functions	High	Very low chance to detect failures	High (H)
System performance is degraded, of which the comfort or convince functions may not operate	Moderately high	Low chance to detect failures	Moderately high (MH)
Moderate effect on system performance and system requires repair	Moderate	Moderate chance to detect failures	Moderate (M)
Small effect on system performance and system does not require repair	Relatively low	Good chance to detect failures	Relatively low (RL)
Minor effect on system performance	Low	High chance to detect failures	Low (L)
Very minor effect on system performance	Remote	Very high chance to detect failures	Very low (VL)
No effect	Nearly impossible	Design control will almost certainly detect failures	None (N)

Table 3. The relationship between linguistic terms and fuzzy numbers.

Linguistic Variables		Fuzzy Number
Fuzzy Restriction (A)	**Idea of Confidence (B)**	
High (EH)	Exactly Sure (ES)	(8.4, 10, 10)
Very High (VH)	Very Sure (VS)	(7.2, 8.4, 9.6)
High (H)	Sure (S)	(6, 7.2, 8.4)
Relatively High (RH)	Relatively Sure (RS)	(4.8, 6, 7.2)
Moderately High (MH)	Not Sure (NS)	(3.6, 4.8, 6)
Moderate (M)	Uncertain (U)	(2.4, 3.6, 4.8)
Relatively Low (RL)	Relatively Uncertain (RU)	(1.2, 2.4, 3.6)
Low (L)	Very Uncertain (VU)	(0, 1.2, 2.4)
Very low (VL)	Exactly Uncertainty (EU)	(0, 0, 1.2)

Step 4: Convert Z-numbers into crisp number.

For effectively aggregating the evaluations of experts, the Z-number form evaluations should be defuzzified to obtain a crisp value. The crisp value of evaluations can be obtained by

$$v = \frac{\int x\mu_B(x)dx}{\int 10\mu_B(x)dx} \cdot \frac{(\alpha_1 + 4 \times \alpha_2 + \alpha_3)}{6}, \tag{2}$$

$$\mu_B(x) = \begin{cases} 0, x \in (-\infty, \beta_1) \\ \frac{x-\beta_1}{\beta_2-\beta_1}, x \in [\beta_1, \beta_2] \\ \frac{\beta_3-x}{\beta_3-\beta_2}, x \in [\beta_2, \beta_3] \\ 0, x \in (\beta_3, +\infty) \end{cases} \tag{3}$$

where $\int$ is an algebraic integration, $\mu_B(x)$ is the membership function of triangular fuzzy number $(\beta_1, \beta_2, \beta_3)$.

Step 5: Aggregate the evaluations of K experts for each failure mode by using rough number.

For failure mode i $(i = 1, 2, \cdots, m)$ with respect to risk factor j $(j = S, O, D)$, the evaluations is denoted as $V_{ij} = \left\{v_{ij}^1, v_{ij}^2, \cdots, v_{ij}^K\right\}$. The first step in the aggregation process is to obtain the lower approximation and upper approximation of $v_{ij}^k (k = 1, 2, \cdots, K)$ by the following equations:

$$\underline{Apr}(v_{ij}^k) = \cup\left\{v_{ij}^t \in V_{ij} / v_{ij}^t \leq v_{ij}^k\right\}, \tag{4}$$

$$\overline{Apr}(v_{ij}^k) = \cup\left\{v_{ij}^t \in V_{ij} / v_{ij}^t \geq v_{ij}^k\right\}. \tag{5}$$

Based on the lower approximation and upper approximation of v_{ij}^k, the lower limit and upper limit of v_{ij}^k are obtained by

$$\underline{Lim}(v_{ij}^k) = \frac{1}{M_L} \sum v_{ij}^t \middle| v_{ij}^t \in \underline{Apr}(v_{ij}^k), \tag{6}$$

$$\overline{Lim}(v_{ij}^k) = \frac{1}{M_U} \sum v_{ij}^t \middle| v_{ij}^t \in \overline{Apr}(v_{ij}^k) \tag{7}$$

where M_L is the number of elements contained in $\underline{Apr}(v_{ij}^k)$, and M_U is the number of elements contained in $\overline{Apr}(v_{ij}^k)$.

Then the rough number of v_{ij}^k is obtained by its corresponding lower limit and upper limit, namely

$$RN(v_{ij}^k) = [\underline{Lim}(v_{ij}^k), \overline{Lim}(v_{ij}^k)]. \tag{8}$$

The interval between $\underline{Lim}(v_{ij}^k)$ and $\overline{Lim}(v_{ij}^k)$ is the rough boundary interval denoted as

$$RBnd(v_{ij}^k) = \overline{Lim}(v_{ij}^k) - \underline{Lim}(v_{ij}^k). \tag{9}$$

With the obtained rough numbers of $v_{ij}^k (k = 1, 2, \cdots, K)$, the rough sequence $RS(V_{ij})$ of V_{ij} can be obtained by

$$RS(V_{ij}) = \left\{[v_{ij}^L, v_{ij}^U]_1, [v_{ij}^L, v_{ij}^U]_2, \cdots, [v_{ij}^L, v_{ij}^U]_K\right\}. \tag{10}$$

Thus the rough number of the evaluation for failure mode i with respect to risk factor j (V_{ij}) is obtained by averaging the rough sequence, that is

$$RN(V_{ij}) = [v_{ij}^L, v_{ij}^U] = \frac{1}{K}\left([v_{ij}^L, v_{ij}^U]_1 + [v_{ij}^L, v_{ij}^U]_2 + \cdots + [v_{ij}^L, v_{ij}^U]_K\right). \tag{11}$$

Then the aggregated evaluation matrix EM for failure modes with respect to S, O and D is given as:

$$EM = \begin{vmatrix} [v^L_{1S}, v^U_{1S}] & [v^L_{1O}, v^U_{1O}] & [v^L_{1D}, v^U_{1D}] \\ \vdots & \vdots & \vdots \\ [v^L_{mS}, v^U_{mS}] & [v^L_{mO}, v^U_{mO}] & [v^L_{mD}, v^U_{mD}] \end{vmatrix} \tag{12}$$

In this step, DEMATEL method is applied to obtain the effect degree (R) and the cause degree (C) of each failure mode. The first procedure in DEMATEL method is to obtain the direct effect degree between any two failure modes, referred to as a_{ij} ($i = 1, 2, \cdots, m$; $j = 1, 2, \cdots, m$), which can be obtained by making statistical analysis for the historical failure data or the expertise and experience of experts. The value of a_{ij} represents the degree that failure mode j influenced by failure mode i, and the value of a_{ji} represents the degree that failure mode i influenced by failure mode j. In general, a_{ij} is not equal to a_{ji}. Specifically, $a_{ij} = 0$ if $i = j$. For m failure modes in FMECA, the direct relation matrix among these failure modes can be expressed as

$$A = \begin{vmatrix} 0 & a_{1m} & \cdots & a_{1m} \\ a_{21} & 0 & \cdots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & 0 \end{vmatrix}. \tag{13}$$

The initial direct relation matrix A can be normalized by using the following equations [73]

$$D = A \times S, \tag{14}$$

$$S = Min\left[\frac{1}{\max_{1 \le i \le m} \sum\limits_{j=1}^{m} a_{ij}}, \frac{1}{\max_{1 \le j \le m} \sum\limits_{i=1}^{m} a_{ij}}\right] \tag{15}$$

where the value of each element in matrix D ranges from 0 to 1.

Then the total relation matrix is obtained by the following equation

$$T = D(I - D)^{-1} = [t_{ij}]_{m \times m} \tag{16}$$

where I is the identity matrix.

The sums of rows and of columns in the total relation matrix T are the effect degree (R) and the cause degree (C) of failure modes, respectively, which are obtained by using the following equations

$$R = (r_1, r_2, \cdots, r_m) = \left[\sum_{j=1}^{m} t_{ij}\right]_{m \times 1}, \tag{17}$$

$$C = (c_1, c_2, \cdots, c_m) = \left[\sum_{i=1}^{m} t_{ij}\right]_{1 \times m} \tag{18}$$

where r_i in vector R is the sum of ith row of matrix T, which represents both the direct and indirect effects of failure mode i acting on the other failure modes, and c_j in vector C is the sum of jth column of matrix T, which represents both the direct and indirect effects of failure mode j caused by other failure modes.

Step 7: Obtain the ultimate decision making matrix for failure modes.

The effect degree (R) and the cause degree (C) of each failure mode are regarded as the risk factor for assessing the risk priority of failure mode, namely five risk factors as severity, occurrence, detectability, effect degree and cause degree are chosen in the proposed FMECA approach for the prioritization of failure modes. Thus the ultimate decision making matrix for failure modes is given as:

$$DM = \begin{vmatrix} [v_{1S}^L, v_{1S}^U] & [v_{1O}^L, v_{1O}^U] & [v_{1D}^L, v_{1D}^U] & v_{1R} & v_{1C} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ [v_{mS}^L, v_{mS}^U] & [v_{mO}^L, v_{mO}^U] & [v_{mD}^L, v_{mD}^U] & v_{mR} & v_{mC} \end{vmatrix} \quad (19)$$

where $v_{iR} = r_i$ and $v_{iC} = c_i$ are the effect degree and the cause degree of failure mode i respectively.

Step 8: Determine the weight of each risk factor.

As similar as the evaluations of failure modes, the relative weights among risk factors need to be assessed by experts and aggregated using rough number, the rough numbers for the weights of risk factors are expressed as

$$W = \left[\; [w_S^L, w_S^U] \quad [w_O^L, w_O^U] \quad [w_D^L, w_D^U] \quad [w_R^L, y_R^U] \quad [w_C^L, w_C^U] \; \right]. \quad (20)$$

Step 9: Determine the risk rankings of failure modes using VIKOR method.

In this step, VIKOR method is applied to determine the risk rankings of failure modes. Firstly the weights of risk factors in rough number form need to be converted to crisp value by the following equation:

$$w_j = \lambda(1 - \frac{w_j^U - w_j^L}{2(\beta - \alpha)}) + (1 - \lambda)\frac{w_j^U + w_j^L}{2(\beta - \alpha)}, j = S, O, D, R, C \quad (21)$$

where w_j is weight of risk factor j, w_j^U and w_j^L are the lower limit and upper limit of the rough number of risk factor j, $\beta = \max_j w_j^U$,$\alpha = \min_j w_j^L$ λ, is a discount factor, expressing the effect degree of rough boundary interval imposing on the weight of risk factor. $0 \leq \lambda \leq 1$, and the greater the value of λ, the more effect is imposing on the weight of risk factor, here suppose $\lambda = 0.5$.

The normalized weight of each risk factor is obtained by using the following equation:

$$w_j' = \frac{w_j}{\sum_{l=1}^{5} w_l}, j = S, O, D, R, C. \quad (22)$$

In VIKOR method, the first step is to determine the optimal and the worst value of each risk factor in DM, which is determined by

$$v_j^* = \begin{cases} \max_i v_{ij}^U \,, j = S, O, D \\ \max_i v_{ij} \,, j = R, C \end{cases}, \quad (23)$$

$$v_j^- = \begin{cases} \min_i v_{ij}^L \,, j = S, O, D \\ \min_i v_{ij} \,, j = R, C \end{cases}. \quad (24)$$

Based on v_j^* and v_j^-, the values of S_i and R_i can be calculated by the following relations

$$S_i = \sum_{j=1}^{3} w_j' \frac{\left\{ (v_{ij}^L - v_j^*)^2 + (v_{ij}^U - v_j^*)^2 \right\}^{1/2}}{\left| v_j^* - v_j^- \right|} + \sum_{j=4}^{5} w_j' \frac{\left| v_{ij} - v_j^* \right|}{\left| v_j^* - v_j^- \right|}, j = S, O, D, R, C, \quad (25)$$

$$R_i = \max_j (w_j' \frac{\left\{ (v_{ij}^L - v_j^*)^2 + (v_{ij}^U - v_j^*)^2 \right\}^{1/2}}{\left| v_j^* - v_j^- \right|}, w_j' \frac{\left| v_{ij} - v_j^* \right|}{\left| v_j^* - v_j^- \right|}) \,, j = S, O, D, R, C. \quad (26)$$

Then the values of Q_i $(i = 1, 2, \cdots, m)$ are determined by

$$Q_i = v\frac{S_i - S^*}{S^- - S^*} + (1 - v)\frac{R_i - R^*}{R^- - R^*} \tag{27}$$

where S^* is the minimum value of S_i and S^- is the maximum value of S_i, R^* is the minimum value of R_i and R^- is the maximum value of R_i, v is the weight of the strategy of "the majority of criteria" (or "the maximum group utility"), whereas $1 - v$ is the weight of the individual regret. Here suppose $v = 0.5$.

Based on the values of S, R and Q, the failure modes can be prioritized with three ranking lists. Moreover, VIKOR method proposes a compromise solution, the failure mode ($FM^{(1)}$), which is the best ranked by the measure Q (Minimum) if the following two conditions are satisfied:

C1. Acceptable advantage: $Q(FM^{(2)}) - Q(FM^{(1)}) \geq 1/(m-1)$, where $FM^{(2)}$ is the failure mode with second position in the ranking list by Q.

C2. Acceptable stability in decision making: The failure mode $FM^{(1)}$ must also be the best ranked by S or/and R. This compromise solution is stable within a decision making process, which could be: "voting by majority rule" (when $v > 0.5$ is needed), or "by consensus" $v \approx 0.5$, or "with veto" ($v < 0.5$).

If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of:

- Failure mode $FM^{(1)}$ and $FM^{(2)}$ if only the condition **C2** is not satisfied,

  or
- Failure mode $FM^{(1)}$, $FM^{(2)}$, ..., $FM^{(M)}$ if the condition **C1** is not satisfied.

$FM^{(M)}$ is determined by the relation: $Q(FM^{(M)}) - Q(FM^{(1)}) < 1/(m-1)$ for maximum M.

4. Case Study: Application to the Risk Analysis of the Failure Modes in Offshore Wind Turbine Pitch System

In this section, the proposed approach is used to the risk prioritization of the failure modes in offshore wind turbine pitch system. There are seven main malfunctions of the pitch system, namely, pitch bearing failure, pitch gearbox failure, pitch motor failure, pitch actuator failure, backup power and charger failure, encoder and limit switch failure, and control module failure. Each of the malfunctions could cause the pitch system failure and eventually result in the turbine shutdown. In order to ensure the operation quality and safety of the pitch system, it is necessary to analyze the malfunctions, excavate the potential failure reasons, and identify the weak links and dangerous source of the system.

In this case, four experts with different backgrounds and professional knowledge were invited to identify and evaluate the potential failure modes of pitch system. They are from wind turbine manufacturer, pitch system manufacturer, wind farm and the operation and maintenance enterprise for wind turbine respectively, and all of them have rich experience and knowledge about the fault analysis and diagnosis of pitch system. Based on the analysis of the historical data of pitch system in a wind farm subordinate to Huaneng Group and the experts 'experience knowledge, twenty-four failure modes which are able to cause the seven kinds of malfunctions were identified, and the four experts are responsible for evaluating the severity, occurrence, detectability and failure propagation of these failure modes.

For identifying the weak links and dangerous source of the system, the identified failure modes should to be prioritized based on the values of their severity, occurrence, detectability, effect degree, and cause degree. The twenty-four failure modes and the corresponding code are given in Table 4, and the propagation relationship among different failure modes are provided in Figure 2, which reveals the dependency of the failure modes participated in the failure propagation.

Table 4. The potential failure modes and their code.

Code	Failure Modes	Code	Failure Modes
FM1	Bearing internal component failure	FM13	IGBT damage
FM2	Crack or fracture of bolt connected with hub	FM14	Backup battery or capacitor failure
FM3	Gear failure of the gearbox	FM15	Charger failure
FM4	Bearing failure of the gearbox	FM16	Pitch angle A/B encoder failure
FM5	Oil spill of the gearbox	FM17	Pitch angle limit switch failure
FM6	Short circuit and open circuit of motor winding	FM18	Blade angle failure
FM7	Bearing failure of the motor	FM19	Hardware failure of controller module (PLC failure)
FM8	Motor brake failure	FM20	Power conversion module failure
FM9	Motor fan failure	FM21	Switches/contactors/relays failure
FM10	Motor wiring and interface problems	FM22	heater and cooling fan failure
FM11	Motor overload	FM23	Input/output line failure
FM12	Communication failure	FM24	Pitch safety chain module failure

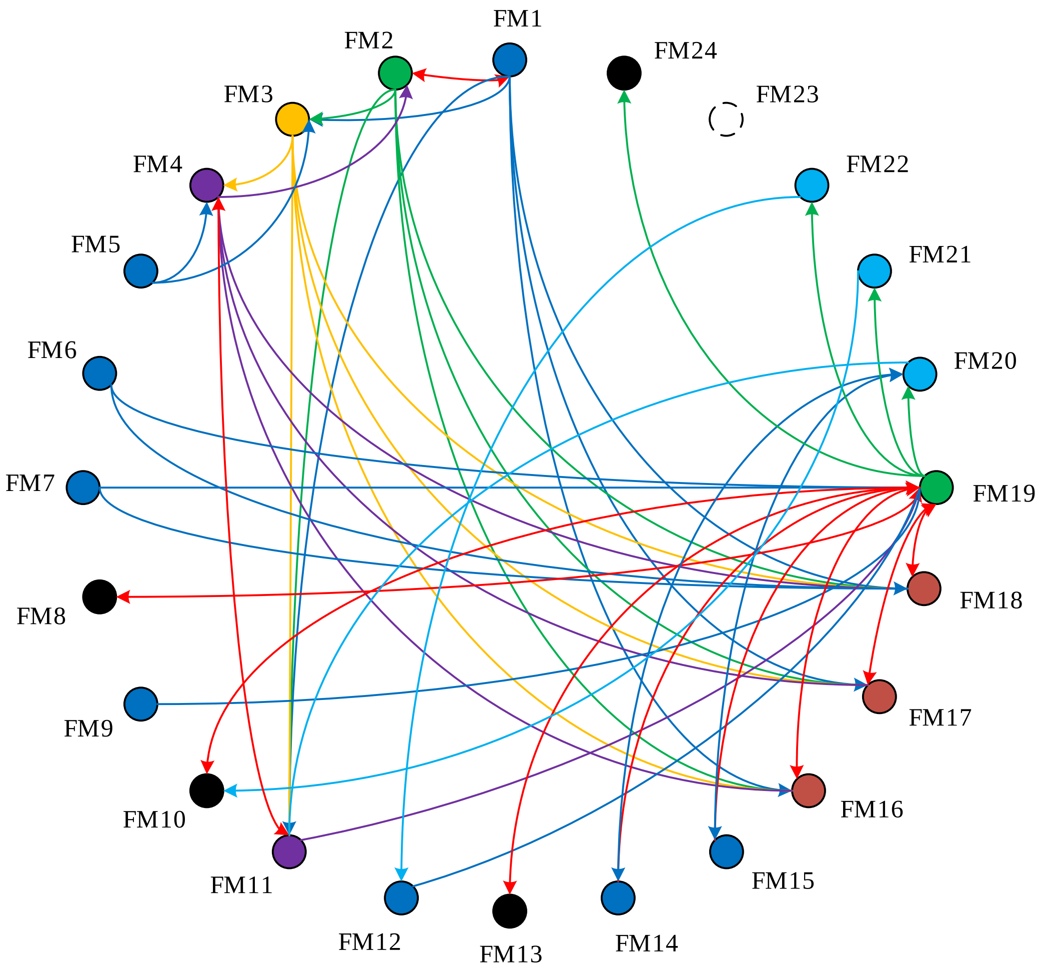

Figure 2. The propagation relationship among different failure modes.

The direct relation matrix among the failure modes obtained based on the historical failure data is given as follows:

$$A = \begin{vmatrix}
0 & 0.3 & 0.2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 & 0 & 0 & 0.1 & 0.1 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.4 & 0 & 0.2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 & 0 & 0 & 0.1 & 0.1 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.3 & 0 & 0 & 0 & 0 & 0 & 0 & 0.4 & 0 & 0 & 0 & 0 & 0.3 & 0.3 & 0.3 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 & 0 & 0 & 0.3 & 0.3 & 0.3 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.4 & 0.4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0.3 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.4 & 0.1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.3 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.4 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.3 & 0.5 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0.4 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0.3 & 0 & 0 & 0.2 & 0.2 & 0.2 & 0 & 0.3 & 0.3 & 0.2 & 0 & 0.2 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.1 & 0 & 0 & 0.2 & 0.2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{vmatrix}$$

According to Table 2, the twenty-four potential failure modes were evaluated with respect to severity, occurrence and detectability, and the evaluations for these failure modes were transformed to Z-numbers according to Table 3. The evaluations given by expert 1 and the corresponding Z-numbers for these evaluations are presented in Tables 5 and 6, respectively. For the sake of space, the other three experts' evaluation information are provided in Appendix A. It is necessary to mention that in our work, the weights of importance of experts are considered as equal. Since each of them has his/her good points, it is difficult to assign a subjective weight to each expert. After converting the Z-numbers into the crisp values, the evaluations (in the form of crisp value) given by the four experts were aggregated by using rough number. The aggregation results are presented in Table 7.

Table 5. The assessment on S, O and D of the twenty-four potential failure modes given by expert 1.

Code	Severity	Occurrence	Detectability	Code	Severity	Occurrence	Detectability
FM1	(VH, VS)	(RL, NS)	(M, S)	FM13	(MH, RS)	(MH, NS)	(L, NS)
FM2	(RH, S)	(RL, NS)	(RH, S)	FM14	(L, NS)	(RH, RS)	(L, RS)
FM3	(MH, S)	(M, RS)	(M, NS)	FM15	(L, NS)	(L, NS)	(RL, RS)
FM4	(MH, S)	(L, NS)	(M, NS)	FM16	(VL, RS)	(RH, U)	(RL, U)
FM5	(L, NS)	(MH, NS)	(VL, S)	FM17	(VL, NS)	(MH, U)	(RL, NS)
FM6	(MH, RS)	(RH, U)	(L, RS)	FM18	(VL, U)	(L, NS)	(RL, U)
FM7	(RL, NS)	(M, NS)	(M, NS)	FM19	(RL, RS)	(L, RS)	(L, RS)
FM8	(RL, RS)	(M, U)	(RL, S)	FM20	(RL, NS)	(VL, RS)	(L, RS)
FM9	(L, U)	(MH, NS)	(RL, S)	FM21	(L, NS)	(M, U)	(L, NS)
FM10	(L, RS)	(M, NS)	(RL, NS)	FM22	(VL, RS)	(L, NS)	(L, RS)
FM11	(M, NS)	(RL, NS)	(L, RS)	FM23	(L, RS)	(RL, RS)	(L, U)

According to the direct relation matrix among the failure modes, the effect degree and the cause degree of each failure mode were obtained by using DEMATEL method. In this paper, the effect degree and the cause degree are considered as two risk factors, which reveal the correlation strength between each failure mode and the other failure modes. The greater the effect degree of a failure mode, the more likely the failure mode will lead to other failures/faults to happen, meaning it has a higher severity. The greater the cause degree of a failure mode, the more likely the failure mode can be caused by other failure modes, meaning it has a higher probability of occurrence. The effect degrees and the cause degrees of failure modes are presented in Table 7, thus the ultimate decision matrix for the twenty-four potential failure modes with respect to five risk factors is formed. Similarly, the evaluations of the weights of risk factors were aggregated and presented in Table 8.

Table 6. The transformed Z-numbers of the twenty-four potential failure modes given by expert 1.

Code	Severity	Occurrence	Detectability
FM1	{(7.2, 8.4, 9.6),(7.2, 8.4, 9.6)}	{(1.2, 2.4, 3.6), (3.6, 4.8, 6)}	{(2.4, 3.6, 4.8), (4.8, 6, 7.2)}
FM2	{(4.8, 6, 7.2), (6, 7.2, 8.4)}	{(1.2, 2.4, 3.6), (3.6, 4.8, 6)}	{(4.8, 6, 7.2),(6, 7.2, 8.4)}
FM3	{(3.6, 4.8, 6), (6, 7.2, 8.4)}	{(2.4, 3.6, 4.8), (4.8, 6, 7.2)}	{(2.4, 3.6, 4.8), (3.6, 4.8, 6)}
FM4	{(3.6, 4.8, 6), (6, 7.2, 8.4)}	{(0, 1.2, 2.4), (3.6, 4.8, 6)}	{(2.4, 3.6, 4.8), (3.6, 4.8, 6)}
FM5	{(0, 1.2, 2.4), (3.6, 4.8, 6)}	{(3.6, 4.8, 6), (3.6, 4.8, 6)}	{(0, 0, 1.2), (6, 7.2, 8.4)}
FM6	{(3.6, 4.8, 6), (4.8, 6, 7.2)}	{(6, 7.2, 8.4), (2.4, 3.6, 4.8)}	{(0, 1.2, 2.4), (4.8, 6, 7.2)}
FM7	{(1.2, 2.4, 3.6), (3.6, 4.8, 6)}	{(2.4, 3.6, 4.8), (3.6, 4.8, 6)}	{(2.4, 3.6, 4.8), (3.6, 4.8, 6)}
FM8	{(1.2, 2.4, 3.6), (4.8, 6, 7.2)}	{(2.4, 3.6, 4.8), (2.4, 3.6, 4.8)}	{(1.2, 2.4, 3.6), (6, 7.2, 8.4)}
FM9	{(0, 1.2, 2.4), (2.4, 3.6, 4.8)}	{(3.6, 4.8, 6), (3.6, 4.8, 6)}	{(1.2, 2.4, 3.6), (6, 7.2, 8.4)}
FM10	{(0, 1.2, 2.4), (4.8, 6, 7.2)}	{(2.4, 3.6, 4.8), (3.6, 4.8, 6)}	{(1.2, 2.4, 3.6), (3.6, 4.8, 6)}
FM11	{(2.4, 3.6, 4.8), (3.6, 4.8, 6)}	{(1.2, 2.4, 3.6), (3.6, 4.8, 6)}	{(0, 1.2, 2.4), (4.8, 6, 7.2)}
FM12	{(0, 1.2, 2.4), (4.8, 6, 7.2)}	{(4.8, 6, 7.2), (2.4, 3.6, 4.8)}	{(1.2, 2.4, 3.6), (2.4, 3.6, 4.8)}
FM13	{(3.6, 4.8, 6), (4.8, 6, 7.2)}	{(3.6, 4.8, 6), (3.6, 4.8, 6)}	{(0, 1.2, 2.4), (3.6, 4.8, 6)}
FM14	{(0, 1.2, 2.4), (3.6, 4.8, 6)}	{(6, 7.2, 8.4), (4.8, 6, 7.2)}	{(0, 1.2, 2.4), (4.8, 6, 7.2)}
FM15	{(0, 1.2, 2.4), (3.6, 4.8, 6)}	{(0, 1.2, 2.4), (3.6, 4.8, 6)}	{(1.2, 2.4, 3.6), (4.8, 6, 7.2)}
FM16	{(0, 0, 1.2), (4.8, 6, 7.2)}	{(4.8, 6, 7.2), (2.4, 3.6, 4.8)}	{(1.2, 2.4, 3.6), (2.4, 3.6, 4.8)}
FM17	{(0, 0, 1.2), (3.6, 4.8, 6)}	{(3.6, 4.8, 6), (2.4, 3.6, 4.8)}	{(1.2, 2.4, 3.6), (3.6, 4.8, 6)}
FM18	{(0, 0, 1.2), (2.4, 3.6, 4.8)}	{(0, 1.2, 2.4), (3.6, 4.8, 6)}	{(1.2, 2.4, 3.6), (2.4, 3.6, 4.8)}
FM19	{(1.2, 2.4, 3.6), (4.8, 6, 7.2)}	{(0, 1.2, 2.4), (4.8, 6, 7.2)}	{(0, 1.2, 2.4), (4.8, 6, 7.2)}
FM20	{(1.2, 2.4, 3.6), (3.6, 4.8, 6)}	{(0, 0, 1.2), (4.8, 6, 7.2)}	{(0, 1.2, 2.4), (4.8, 6, 7.2)}
FM21	{(0, 1.2, 2.4), (3.6, 4.8, 6)}	{(2.4, 3.6, 4.8), (2.4, 3.6, 4.8)}	{(0, 1.2, 2.4), (3.6, 4.8, 6)}
FM22	{(0, 0, 1.2), (4.8, 6, 7.2)}	{(0, 1.2, 2.4), (3.6, 4.8, 6)}	{(0, 1.2, 2.4), (4.8, 6, 7.2)}
FM23	{(0, 1.2, 2.4), (4.8, 6, 7.2)}	{(1.2, 2.4, 3.6), (4.8, 6, 7.2)}	{(0, 1.2, 2.4), (2.4, 3.6, 4.8)}
FM24	{(1.2, 2.4, 3.6), (3.6, 4.8, 6)}	{(0, 0, 1.2), (2.4, 3.6, 4.8)}	{(0, 1.2, 2.4), (2.4, 3.6, 4.8)}

Table 7. Decision matrix for the twenty-four failure modes.

Code	Severity	Occurrence	Detectability	Effect Degree	Cause Degree
FM1	[5.08, 6.58]	[1.3, 1.58]	[1.61, 2.78]	0.69	0.17
FM2	[4.01, 4.28]	[1.19, 1.4]	[2.25, 3.73]	0.74	0.14
FM3	[2.63, 3.37]	[1.38, 2.09]	[1.38, 1.88]	0.80	0.52
FM4	[2.63, 3.37]	[0.63, 1.1]	[1.37, 1.65]	0.74	0.34
FM5	[0.59, 0.7]	[1.96, 2.2]	[0.24, 0.48]	0.54	0
FM6	[2.48, 3.75]	[3.33, 4.97]	[0.83, 1.19]	0.37	0
FM7	[1.66, 2.56]	[1.2, 1.91]	[1.27, 1.55]	0.30	0
FM8	[1.91, 3.38]	[1.33, 2.07]	[0.96, 1.69]	0.20	0.47
FM9	[0.54, 0.9]	[1.94, 2.7]	[0.93, 1.46]	0.20	0.00
FM10	[0.59, 1.21]	[1.05, 1.89]	[0.65, 1.02]	0.20	0.20
FM11	[1.49, 1.97]	[1.3, 1.58]	[0.83, 1.19]	0.20	0.67
FM12	[0.67, 1.81]	[2.61, 4.07]	[0.86, 1.3]	0.27	0.19
FM13	[2.12, 2.7]	[1.98, 2.25]	[0.63, 0.9]	0.33	0.31
FM14	[0.61, 1.33]	[3.74, 4.94]	[1.14, 1.74]	0.52	0.21
FM15	[0.56, 0.98]	[0.46, 0.7]	[0.77, 1.04]	0.41	0.16
FM16	[0.2, 0.92]	[2.37, 3.02]	[0.78, 1.26]	0.13	0.72
FM17	[0.32, 1.63]	[1.55, 1.91]	[0.94, 1.6]	0.13	0.72
FM18	[0.18, 0.91]	[0.58, 0.8]	[0.96, 1.37]	0.13	0.96
FM19	[1.06, 1.39]	[0.63, 0.9]	[0.7, 1.06]	1.20	1.59
FM20	[0.72, 1.07]	[0.09, 0.27]	[0.69, 0.98]	0.38	0.71
FM21	[0.7, 1.4]	[0.89, 1.08]	[0.65, 1.08]	0.18	0.31
FM22	[0.34, 0.83]	[0.47, 0.54]	[0.83, 1.19]	0.19	0.24
FM23	[0.83, 1.28]	[0.49, 0.97]	[0.5, 0.83]	0	0
FM24	[0.98, 1.94]	[0.07, 0.17]	[0.58, 0.95]	0	0.24

Table 8. The evaluations and weights for risk factors.

Experts	*S*	*O*	*D*	*R*	*C*
Expert 1	0.4	0.3	0.3	0.3	0.3
Expert 2	0.5	0.3	0.2	0.2	0.2
Expert 3	0.35	0.35	0.3	0.3	0.2
Expert 4	0.4	0.35	0.35	0.3	0.2
Aggregation results	[0.38, 0.44]	[0.31, 0.34]	[0.26, 0.32]	[0.26, 0.30]	[0.21, 0.24]
weights	0.27	0.21	0.19	0.18	0.15

After the aggregation process, VIKOR method was applied to sort the risks of the failure modes based on the decision matrix. The risk priorities of the twenty-four failure modes were determined by calculating the measure of closeness to the weighted vectors of positive ideal point. In the stage of VIKOR method, the optimal and the worst value of each risk factor were determined by Equations (22) and (23), and the values of S, R and Q for all failure modes were computed by using Equations (24)–(26) and presented in Table 9. A failure mode would be closer to the optimal values as the corresponding measure values approaches to zero. Thus, the failure modes can be prioritized or ranked according as the values of S, R, and Q in descending order. In order to make the ranking results better accepted by decision-makers, VIKOR method provides a compromise solution as illustrated in Section 3.2.

Table 9. The values and rankings of S, R and Q for all failure modes.

Code	*S*		*R*		*Q*	
	Value	Ranking	Value	Ranking	Value	Ranking
FM1	0.614	1	0.214	2	0.013	1
FM2	0.655	2	0.223	4	0.079	2
FM3	0.736	3	0.215	3	0.128	3
FM4	0.822	7	0.249	6	0.322	5
FM5	1.038	16	0.354	21	0.871	20
FM6	0.765	4	0.210	1	0.140	4
FM7	0.940	11	0.268	8	0.494	8
FM8	0.881	8	0.239	5	0.343	6
FM9	1.008	15	0.350	20	0.829	17
FM10	1.058	18	0.339	18	0.840	18
FM11	0.951	12	0.290	9	0.576	10
FM12	0.905	10	0.320	12	0.636	12
FM13	0.902	9	0.249	7	0.397	7
FM14	0.798	6	0.335	15	0.586	11
FM15	1.084	21	0.347	19	0.890	21
FM16	0.951	13	0.360	23	0.809	15
FM17	0.967	14	0.337	16	0.747	13
FM18	1.038	17	0.361	24	0.893	22
FM19	0.794	5	0.320	11	0.531	9
FM20	1.059	19	0.339	17	0.841	19
FM21	1.067	20	0.331	14	0.820	16
FM22	1.117	22	0.358	22	0.957	24
FM23	1.154	24	0.330	13	0.898	23
FM24	1.137	23	0.307	10	0.805	14

By comparing the risk rankings of the twenty-four failure modes, we see that in the pitch system the weakest link from a reliability standpoint is the pitch bearing, whose failure modes are ranked first and second in all failure modes identified in pitch system, and followed by the pitch gearbox and pitch motor. The failure of pitch bearing may lead to blade pitch to be out of sync or cannot pitch, causing impeller aerodynamic imbalance and fan speeding, which can result in the failure of safely starting and stopping the turbine, and bring about the blade rupture and other accidents. The pitch gearbox is also the key component that affects the reliability of the pitch system, whose failures of gear and bearing in the gearbox are ranked third and fifth in all failure modes. Through statistical analysis of historical fault data of pitch system, we found that the failure of pitch bearing and pitch gear accounts for 71% of the failure of the whole pitch system, which reveals that attention should be paid to these failure modes, and necessary measures and controls should be taken to lessen the possibility of their occurrence. There are many types of failure of pitch motor, among which the most serious failure modes are short circuit and open circuit of motor winding and motor brake failure, ranked fourth and sixth in all failure modes, respectively. It can also be seen that the failures of bearings, gear and other mechanical components have higher rankings, while the failures of switch, line and other electrical components have relatively lower rankings. This is because mechanical failures are difficult to be detected in time, and electrical failures are easy to be detected according to the abnormal current and voltage signals. Thus, in the reliability design of pitch system, higher reliability should be allocated to mechanical components, and in order to identify the failures of the mechanical components such as bearings and gears early before accidents to ensure the reliable operation of wind turbine, it is necessary to study the on-line monitoring technology for the mechanical failures of pitch system.

From the above analysis, we see that the ranking results of the twenty-four potential failure modes are in accordance with the practical engineering background, which proves the effectiveness of the proposed approach in practical application.

5. Comparison and Discussion

To further demonstrate the validity and availability of the proposed approach, three comparable method of traditional FMECA, fuzzy TOPSIS and combination weighting-based fuzzy VIKOR were also applied in the case study. The ranking results of the three methods are given in Table 10 and compared with that of the proposed FMECA approach. Based on the rankings in Table 10, it can be seen that the four approaches have a certain degree of similarity on the overall ranking trends of the twenty-four failure modes. For example, FM1 is recognized as the most critical failure mode in the four approaches since it has the highest or second-highest risk ranking. In each of approach, the top four ranked failure modes all contain FM1, FM2, and FM3, and the lowest ranked failure mode is all FM22. Moreover, failure mode FM15, FM17 and FM21 have very similar rankings in the four approaches. However, there are also some failure modes whose rankings of are very different in the four approaches, such as FM4, FM5, FM9, FM11, FM13, FM14, FM16, FM18, FM19, FM20 and FM24. The reasons contributing to the different rankings are analyzed as follows.

First, the weights of risk factors are different in the four approaches. The traditional FMECA reckons the weights of risk factors as equal, which is not reasonable in actual case. Since under the hypothesis of equal weights, some risk factors may be overestimated and others may be underestimated. In the fuzzy TOPSIS, fuzzy VIKOR and the proposed approach, such equal weight assumption is abandoned by determining the real weights of risk factors based on evaluations of experts. In the three kinds of approaches, the weights of risk factors are evaluated by experts using linguistic items. Meanwhile, the fuzzy TOPSIS determines the weight of risk factors by fuzzy AHP method, in which the weight of risk factors is $(w_S = 0.41, w_O = 0.31, w_D = 0.28)$. The fuzzy VIKOR determines the weight of risk factor based on a combined weighting method integrated by fuzzy AHP and entropy method, in which the weight of risk factors is $(w_S = 0.4, w_O = 0.38, w_D = 0.22)$. The proposed approach determines the weight of risk factors based on rough number and Equations (20) and (21), in which the weight of risk factors is $(w_S = 0.27, w_O = 0.21, w_D = 0.19, w_R = 0.18, w_C = 0.15)$. Take the FM14 as an example, although experts evaluate FM14 with respect to occurrence with high value, they put relatively low importance on occurrence. Thus, FM14 gets relatively high ranking in the traditional FMECA compared to the rankings in the other three approaches, since occurrence is overestimated when regarding the weights of severity, occurrence and detectability as equal in traditional FMECA.

Table 10. The values and rankings of S, R and Q for all failure modes.

Code	Traditional FMECA		Fuzzy TOPSIS		Fuzzy VIKOR		Proposed Approach	
	RPN	Ranking	CC	Ranking	Q	Ranking	Q	Ranking
FM1	115.28	1	0.211	1	0.194	2	0.013	1
FM2	110.91	2	0.192	3	0.258	3	0.079	2
FM3	74.38	4	0.177	4	0.260	4	0.128	3
FM4	48.13	10	0.159	9	0.528	9	0.322	5
FM5	18.56	17	0.104	19	0.822	17	0.871	20
FM6	105.00	3	0.209	2	0.018	1	0.140	4
FM7	56.00	7	0.157	10	0.427	7	0.494	8
FM8	52.59	9	0.175	5	0.348	6	0.343	6
FM9	32.81	14	0.128	14	0.737	13	0.829	17
FM10	25.00	15	0.125	15	0.799	16	0.840	18
FM11	35.00	12	0.128	13	0.506	8	0.576	10
FM12	52.94	8	0.160	8	0.584	11	0.636	12
FM13	56.11	6	0.151	11	0.271	5	0.397	7
FM14	60.00	5	0.166	6	0.577	10	0.586	11
FM15	11.39	21	0.076	23	0.952	23	0.890	21
FM16	35.44	11	0.160	7	0.743	14	0.809	15
FM17	33.75	13	0.145	12	0.723	12	0.747	13
FM18	14.22	18	0.113	17	0.941	22	0.893	22
FM19	13.92	20	0.086	20	0.846	18	0.531	9
FM20	10.00	23	0.083	22	0.937	21	0.841	19
FM21	24.06	16	0.121	16	0.771	15	0.820	16
FM22	8.59	24	0.065	24	0.987	24	0.957	24
FM23	14.06	19	0.085	21	0.887	19	0.898	23
FM24	10.16	22	0.104	18	0.908	20	0.805	14

The second reason is the different representation and aggregation method for experts' evaluation information in the four approaches. As we know, FMECA is a team collaboration behavior which cannot be implemented alone on an individual basis [25]. On one hand, traditional FMECA, fuzzy TOPSIS and fuzzy VIKOR aggregate different experts' evaluations by average method. The aggregation results by this method are largely influenced by expert's opinion with subjectively and uncertainly. In fact, because of the different experience and backgrounds of experts, the evaluations of experts may be different and diverse, and some of which may be vague, imprecise and uncertain. In the proposed approach, the evaluations of different experts were aggregated by rough number, which could effectively aggregate the diversity evaluations and reduce the subjectivity and uncertainly in aggregation process. On the other hand, traditional FMECA, fuzzy TOPSIS and fuzzy VIKOR evaluate failure modes in the form of crisp number or triangular fuzzy number. Although fuzzy numbers are able to deal with the human vagueness evaluation to some extent, it does not consider the reliability of the restricted evaluation. In the proposed approach, the limitations of fuzzy number are overcome by Z-number, which describe the evaluations of failure modes by using 2-tuple fuzzy numbers. Compared to fuzzy number, Z-number has a stronger ability to express vague and uncertain information.

The third reason is the different ranking mechanism for failure modes in the four approaches. The traditional FMECA ranks the failure modes by multiplying the values of S, O, and D, which is questionable as mentioned in Introduction section. While the fuzzy TOPSIS, fuzzy VIKOR and the proposed approach take the ranking problem of failure modes as a multiple criteria decision-making (MCDM) issue and rank the failure modes by TOPSIS and VIKOR method. One difference between TOPSIS and VIKOR method is the different mechanism of aggregation function for ranking in the two methods. The aggregation function of VIKOR method represents the distance from the optimal values [72] with the ranking index of aggregating all risk factors, the weights of risk factors, and the balance between group and individual satisfaction. While the aggregation function of TOPSIS method represents the distances from the optimal value and from the worst value, which introduces the ranking index by summing these distances without considering their relative importance. The other difference between these two methods is the different means of normalization. The VIKOR method utilizes linear normalization method for normalizing, while the TOPSIS method uses vector normalization method. Moreover, the VIKOR method proposes a compromise solution with an advantage rate.

The last and most critical reason is that the traditional FMECA, fuzzy TOPSIS and fuzzy TOPSIS do not consider the propagation effect among failure modes, while the proposed approach considers. The failure propagation takes into account how a failure of a component could spread within a system, leading other components to failure. In fact, the practical impact to system reliability of the failure propagation is to increase the severity and occurrence of failure modes which can cause the occurrence of other failure modes or be affected by other failure modes. It can be seen that a very different ranking of failure mode is found in FM19 between the proposed approach and the other three approaches, which is ranked as twentieth in the traditional FMECA and fuzzy TOPSIS, eighteenth in the fuzzy VIKOR and ninth in the proposed approach. The remarkably different ranking for FM19 result from its high effect degree and cause degree. The high effect degree indicates that FM19 has a large possibility of causing other failures, which means its severity can be increased through the failure propagation. The high cause degree indicates that FM19 is more likely to be caused by other failures, which means its occurrence can be increased through the failure propagation. Thus, due to consideration of the failure propagation, the ranking of FM19 has greatly increased in the proposed approach compared to the ranking in the other three approaches, and so does the other failure modes such as FM3, FM4, FM20, etc.

6. Conclusions

Although FMECA has been extensively used in many fields for risk analysis, there are still some flaws that limit its performance of application in actual case, especially in terms of the issues of the representation of expert's opinions on the evaluation of failure modes, the aggregation of experts' diversity evaluations, and the determination of risk priorities of failure modes. In this paper, a new risk assessment model is proposed by using an integrated approach, which integrates the strong expressive ability of Z-numbers to vagueness and uncertainty information, the strong point of DEMATEL method in studying the dependence among failure modes, the advantage of rough numbers for aggregating experts' diversity evaluations, and the strength of VIKOR method to flexibly model multi-criteria decision-making problems. Based on the integrated approach, the proposed risk assessment model has the follow advantage features compared to the traditional FMECA and its variant:

1. The proposed model can well describe the judgements of experts on the evaluation of failure modes by using 2-tuple fuzzy numbers (Z-number) that the first fuzzy number represents the fuzzy restriction of the evaluation and the second fuzzy number represents its confidence or reliability.
2. The proposed model can effectively aggregate the diversity evaluations of experts by using rough number, which can reduce the subjectivity and uncertainty of evaluations in aggregation process and help to inspect the consistency of experts' perspective in decision making.
3. The proposed model takes the dependency among failure modes into consideration to identify the effect degree and cause degree of each failure mode by using DEMATEL method, which can recognize the potential high risk failure modes by analyzing the effects of failure propagation.
4. The proposed model determines the risk priorities of failure modes by using VIKOR method, which ranks the failure modes in a compromise way and helps experts in

FMECA team to reach a feasible ranking results based on maximizing the group utility for the "majority" and minimizing the individual regret for the "opponent".

To validate the performance of application in real case of the proposed FMECA approach and verify its effectiveness, the proposed risk assessment model is applied to the risk analysis of the failure modes in offshore wind turbine pitch system. By analyzing the ranking results of the twenty-four potential failure modes, we see that the proposed FMECA approach can be well used in real case, especially in the situations that the evaluations of experts are vague and uncertain and the failure modes are interacted with each other. Through the comparison with other approaches, we see that the ranking results obtained by proposed approach are more rational and more consistent with the actual results.

As a recommendation for future research, it is suggested that the evaluations of different experts for failure modes should be aggregated in the form of Z-number without converting the Z-numbers into crisp value, and some efficient fusion approaches should be excavated and applied to aggregation process. Moreover, the complexity of the proposed approach needs to be optimized to make it more applicable in practice. Moreover, in future work, the proposed model will be applied for risk management decision making in other fields of quality and reliability engineering to further verify its effectiveness.

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Nomenclature

v	Crisp value of evaluation
$\mu_{\mathrm{B}}(x)$	Membership function of a triangular fuzzy number
$(\alpha_1, \alpha_2, \alpha_3)$	Triangular fuzzy number for fuzzy restriction in Z-number
$(\beta_1, \beta_2, \beta_3)$	Triangular fuzzy number for idea of confidence in Z-number
$\underline{\underline{Apr}}(v)$	Lower approximation of v
$\overline{\overline{Apr}}(v)$	Upper approximation of v
$\underline{Lim}(v)$	Lower limit of v
$\overline{Lim}(v)$	Upper limit of v
M_L	Number of elements contained in $\underline{\underline{Apr}}(v)$
M_U	Number of elements contained in $\overline{\overline{Apr}}(v)$
$RN\ (v)$	Rough number of v
$Bnd\ (v)$	Boundary region of v
a_{ij}	Degree that a failure mode influenced by another failure mode
R	Effect degree
C	Cause degree
w_j	Weight of criterion (or risk factor)
v_j^*	Optimal value of risk factor
v_j^*	Optimal value of risk factor

Appendix A

Table A1. The assessment on *S*, *O* and *D* of the twenty-four potential failure modes given by expert 2.

Code	Severity	Occurrence	Detectability	Code	Severity	Occurrence	Detectability
FM1	(RH, S)	(M, NS)	(RH, RS)	FM13	(M, RS)	(MH, NS)	(RL, NS)
FM2	(RH, RS)	(RL, NS)	(M, U)	FM14	(M, RS)	(RH, NS)	(RL, RS)
FM3	(MH, RS)	(MH, U)	(M, RS)	FM15	(RL, RS)	(L, NS)	(L, RS)
FM4	(MH, RS)	(M, U)	(M, NS)	FM16	(M, NS)	(RH, U)	(M, NS)
FM5	(L, NS)	(RH, U)	(VL, RS)	FM17	(RH, RS)	(M, U)	(L, NS)
FM6	(RH, S)	(RH, NS)	(RL, NS)	FM18	(M, NS)	(RL, U)	(M, NS)
FM7	(MH, RS)	(M, U)	(M, U)	FM19	(RL, RS)	(L, NS)	(RL, RS)
FM8	(H, RS)	(MH, NS)	(L, RS)	FM20	(RL, NS)	(L, U)	(RL, NS)
FM9	(RL, NS)	(RH, NS)	(L, RS)	FM21	(M, NS)	(RL, U)	(M, NS)
FM10	(M, NS)	(M, U)	(RL, NS)	FM22	(L, NS)	(L, NS)	(RL, RS)
FM11	(M, NS)	(M, NS)	(RL, RS)	FM23	(RL, RS)	(L, NS)	(RL, NS)
FM12	(MH, RS)	(RH, U)	(L, NS)	FM24	(MH, RS)	(VL, U)	(RL, NS)

Table A2. The assessment on *S*, *O* and *D* of the twenty-four potential failure modes given by expert 3.

Code	Severity	Occurrence	Detectability	Code	Severity	Occurrence	Detectability
FM1	(EH, S)	(M, NS)	(RL, NS)	FM13	(RH, NS)	(RH, U)	(L, RS)
FM2	(H, RS)	(M, NS)	(MH, RS)	FM14	(L, U)	(EH, U)	(RL, RS)
FM3	(RH, RS)	(MH, NS)	(RL, RS)	FM15	(L, U)	(RL, U)	(L, RS)
FM4	(RH, RS)	(RL, NS)	(RL, RS)	FM16	(VL, NS)	(VH, U)	(L, NS)
FM5	(RL, U)	(RH, U)	(L, NS)	FM17	(VL, NS)	(RH, U)	(M, RS)
FM6	(RH, RS)	(EH, NS)	(L, RS)	FM18	(VL, NS)	(RL, U)	(RL, NS)
FM7	(MH, RS)	(MH, NS)	(RL, RS)	FM19	(RL, RS)	(RL, NS)	(L, RS)
FM8	(MH, S)	(MH, NS)	(L, RS)	FM20	(RL, U)	(VL, U)	(L, NS)
FM9	(RL, U)	(RH, NS)	(L, S)	FM21	(RL, RS)	(M, RU)	(L, NS)
FM10	(L, NS)	(MH, NS)	(L, NS)	FM22	(RL, NS)	(L, U)	(L, RS)
FM11	(MH, NS)	(M, NS)	(L, RS)	FM23	(RL, RS)	(RL, RU)	(L, NS)
FM12	(L, U)	(VH, NS)	(RL, RS)	FM24	(RL, NS)	(L, RU)	(L, NS)

Table A3. The assessment on *S*, *O* and *D* of the twenty-four potential failure modes given by expert 4.

Code	Severity	Occurrence	Detectability	Code	Severity	Occurrence	Detectability
FM1	(VH, RS)	(RL, NS)	(M, NS)	FM13	(M, NS)	(MH, U)	(L, NS)
FM2	(RH, RS)	(RL, NS)	(RH, RS)	FM14	(L, NS)	(EH, RS)	(M, RS)
FM3	(M, RS)	(RL, U)	(RL, NS)	FM15	(L, NS)	(L, RU)	(L, RS)
FM4	(M, RS)	(L, U)	(RL, NS)	FM16	(VL, NS)	(H, NS)	(RL, U)
FM5	(L, NS)	(MH, U)	(L, NS)	FM17	(VL, NS)	(MH, U)	(RL, NS)
FM6	(M, NS)	(EH, RS)	(RL, RS)	FM18	(VL, U)	(L, U)	(RL, U)
FM7	(RL, RS)	(RL, U)	(RL, NS)	FM19	(L, NS)	(L, NS)	(L, NS)
FM8	(RL, RS)	(RL, U)	(M, RS)	FM20	(L, U)	(VL, RU)	(RL, U)
FM9	(L, U)	(M, U)	(RL, RS)	FM21	(L, U)	(RL, U)	(L, NS)
FM10	(L, U)	(RL, RU)	(L, U)	FM22	(L, U)	(L, U)	(RL, NS)
FM11	(RL, NS)	(RL, NS)	(RL, NS)	FM23	(L, NS)	(L, RU)	(L, U)
FM12	(L, NS)	(VH, RS)	(RL, RS)	FM24	(L, NS)	(VL, RU)	(RL, U)

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