Risk Analysis for Offshore Wind Turbines Using Aggregation Operators and VIKOR

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In various engineering actions, potential hazards are reduced, calculated, or controlled using a variety of risk analysis methodologies. The FMEA, or Failure Mode and Effects Analysis, is a very efficient strategy that may be used in this situation. When evaluating safety concerns, failure modes' likely causes and consequences are considered. Serious failures in the FMEA are identified using the Risk Priority Number (RPN). The RPN considers the effect of the probability of occurrence, probability of detection and severity by multiplying these three parameters. However, because of the formula's various flaws, it is frequently criticized.

In the current work, a hybrid approach using ViseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) and geometric averaging of ordered weights (OWGA) as an aggregation operator is used to assess risk for offshore wind turbines. While the OWGA technique is used to provide weight to risk indices, the VIKOR method is used to assess the relevance of failure modes of offshore wind turbine components. The method's final findings show it solves the issues with the traditional RPN technique and produces more logical outcomes.

KEY WORDS
~ Offshore wind turbines
~ Ordered weighted geometric averaging
~ Failure Mode and Effects Analysis
~ VIseKriterijumska Optimizacija I Kompromisno Resenje
~ Risk priority number
~ Risk analysis

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1. INTRODUCTION

Using fossil fuels on the seas produces greenhouse gases as a by-product. With growing concerns about their environmental effects, maritime industry stakeholders are exploring new methods and ways (Dinariyana et al., 2022). There are numerous ways to decrease carbon emissions in the maritime sector (Tuswan et al., 2023). Following the Paris Agreement on climate change and global emission reduction goals, the IMO presented an initial strategy for the decarbonisation of ships in 2018 (Kalajdžić et al., 2022). A wind turbine is one such system that is used on a large scale to increase the amount of energy production. The structure could be installed both onshore and offshore In terms of energy production, an offshore wind turbine is more productive than the onshore one because of the higher wind speed at sea. From the first installation until now, wind turbines are increasing in diameter and producing ever more renewable energy. The average service life of offshore wind units is approximately 20 years. During the service life, turbines stay in the same place and are exposed to all kinds of heavy weather along with severe waves. The relevant sector is not fully mature, as adverse environmental effects lead to dangerous consequences for such structures.

While the installation of offshore wind farms is increasing, the number of studies to determine safety criteria is also increasing. Identifying and assessing risks is crucial to the successful progress of wind turbine projects. Regardless of the size or scope of a project, if time has not been taken to identify, assess, classify, prioritise, and assess the potential risks, it cannot be completed on time and according to the spending plan. Risk-based development of offshore wind turbine projects will be crucial to reduce or prevent the possibility of human, environmental or material damage. Many wind turbine accidents occur because of the size, variety, and weights of system components, transportation, changing environmental conditions, insufficient maintenance, collision, etc. Since most of the risks mentioned are very dangerous, it is important to develop risk-based design processes for offshore wind turbine operations, to examine the effectiveness of different analysis approaches, and to increase scientific studies on this subject.

Risk management remains a critical pillar in the industry, and the decision-makers take seriously the matter of identifying, analysing, and controlling risk factors, due to the huge impact that may be caused (Lamii et al., 2022). The decision-makers employ a variety of investigative models and methodologies to process risk assessment (Taç, 2022; Bayraktar and Nuran, 2022; Taç and Çelik, 2022). Projects in the marine sector usually employ certain tactics. The FMEA is a technique frequently used for strategic risk analysis. Before they affect the system, faults, problems, and failures resulting from the framework, structure, process, and/or operation are found and eliminated using the FMEA. Identification of prospective failure modes, investigation of the underlying causes and effects of various component failure modes, and decision-making on how to reduce or entirely eradicate the degree of highly dangerous failures are the key objectives of the FMEA. Inspections can assist in locating and resolving failure modes that negatively impact complicated units and enhance their performance throughout the editing and progressing stages.

The subject technique is used as dynamic equipment to improve the planning process, manufacturing processes, operations, and repair. During the Apollo mission in the 1960s, the aviation industry in the United States created the FMEA to examine the consequences of the system and individual equipment failures, people or structure safety, system sustainability, and overall performance. Portage Motor discovered the FMEA on a set of cars for regulatory and safety assessment in the late 1970s and was used to develop production and blueprint (Liu et al. 2013, 2015a, 2016a, 2016b).

A risk priority number (RPN) is used to assess the effects of failures in FMEA. The RPN computation considers the three risk factors S, O, and D, and assigns equal weights to each failure. This is a disadvantage of conventional RPN calculations. The weights should not be compared for various risk analysis scenarios; therefore, this is illogical. In addition, these three parameters are multiplied to calculate the RPN value, which is irrational because it is extremely sensitive to changes in criticality factor evaluations. Finally, the same RPN value can represent completely different risk outcomes. In recent years, comparative studies focused on RPN limits have been published. To estimate ratings of likely failures, Yang et al. (2008) employed a combined approach that included fuzzy rules and the Bayesian technique. Chang et al. (2009) made a novel reliable allocation approach based on maximal entropy referenced weighted averaging. Chin et al. (2009) achieved a study regarding the FMEA approach based on the analysis of data envelopment. Lin et al. (2011) introduced a hazard analysis technique with integrated quantitative basis that was used in padded examinations with impact diagram. Yang et al. (2011) used the Bayesian strategy with a fuzzy basis to focus on different potential failures. To simulate incompleteness, subjective conviction levels were assigned to the related section of the standards in their approach. A new RPN approach was introduced by Zhang and Chu (2011) to create more accurate RPN values in the fuzzy domain, in which an integrating weighted least squares technique was used. Chang et al. (2013) conducted an integrative analysis of the Grey Relativity Analysis (GR) and DEcision-MAking Trial and Evaluation Laboratory (DEMATEL) methodologies in addition to the FME and came up with a new practical approach. Yang and Wang (2015) proposed a fuzzy FMEA methodology to evaluate and combine system hazards associated with offshore operations. Shaghaghi and Rezaie (2012), Liu et al. (2011), Chang and Cheng (2011), and Liu et al. (2013) carried out a careful analysis of the existing literature in the last decade on various techniques for hazard assessment in the FMEA to tend to difficulties and improve the FME efficiency. Kang et al. (2017) introduced a novel hazard technique for evaluation called correlation-FMEA to obtain the correlation coefficients. The FMEA is used extensively in a variety of fields, including shipboard-integrated electric propulsion systems (Liu et al., 2019), yacht systems (Helvacioglu and Ozen, 2014; Mentes and Ozen, 2015; Mentes and Helvacioglu, 2022), offshore wind turbines (Dinmohammadi and Shafiee, 2013), and marine diesel engines (Emovon, 2016).

This investigation aims to offer a unique technique for offshore wind-turbine risk management that is effective. The approach considers the VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) technique and the ordered weighted geometric averaging (OWGA) aggregation operator. The recommended method resolves the problems with RPN computations and yields amazingly consistent results. To demonstrate the method's accuracy, several weighting strategies were also examined and the outcomes were compared.

2. FAILURE MODE AND EFFECTS ANALYSIS

The methodology is used to explain, recognize, and remove any defects, difficulties, or failures from the framework, structure, technique, or operation before approaching the customer.

To perform the FMEA on a particular product or service, a multifunctional team of industry experts must be formed initially. The accompanying step is to recognize all possible failure analysis techniques for the subject product or structure through a methodological discussion-based meeting. After that, these failure modes are evaluated by considering the event (O), severity (S), and detection (D) factors. The method's primary aim is to assess the shortcomings of systems, strategies, procedures, goods, or services to make sure that sufficient resources are allotted to the most dangerous areas.

The Risk Priority Number (RPN) is a further stage of the procedure that requires attention. The RPN is calculated for each cause of failure using the product of S, O, and D.

$$RPN = O \cdot S \cdot D \tag{1}$$

When O is the odds of an event occurring, S denotes its severity, which tends to have consequences, and D denotes detection, which depicts the amount of perceived danger before the impact of the event is recognized. Each of the three signs is typically scaled on a scale of 1 to 10 to determine the probability of failure (see Tables 1-3). More danger results in a higher RPN number. The final computations' findings indicate that improvements will be made mostly to high-danger failure modes.

Table 1.
Traditional ratings for the incidence of failure modes (Liu et al. 2012, 2013).

Rating	Probability of failure	Possible failure rate
10	Extremely high	≥ 1 in 2
9	Relatively high	1 in 3
8	Repeated failures	1 in 8
7	High	1 in 20
6	Moderately high	1 in 80
5	Moderate	1 in 400
4	Relatively low	1 in 2000
3	Low	1 in 15,000
2	Remote	1 in 150,000
1	Impossible	1 in 1,500,000

Table 2.
Traditional ratings for the severity of a failure mode (Liu et al. 2012, 2013).

Rating	Effect	Severity of effect
10	Dangerous with-out warning	The most serious severity ranking consequence is dangerous.
9	Dangerous with warning	Serious severity ranking consequence is dangerous.
8	Relatively high	An operational system collapses without compromising safety.
7	High	An operational system may function, but performance is affected seriously.
6	Moderate	An operational system or a product continues, and performance is degraded.
5	Low	The performance of the system is affected seriously, and maintenance work is required.
4	Relatively low	The performance of the system is less affected, maintenance work may be needed.
3	Minor	Minor effect on system performance.
2	Slight	Slight effect on system performance.
1	None	No extra effect.

Table 3.
Traditional ratings for detection of a failure mode (Liu et al. 2012, 2013).

Rating	Detection	Criteria
10	Impossible	Control of design cannot detect a possible cause of failure.
9	Relatively re-mote	Relatively less chance, the control of design will detect a possible cause of fail-ure.
8	Remote	Remote chance the control of design will detect a possible cause of failure.
7	Relatively low	Relatively low chance the control of design will detect a possible cause of fail-ure.
6	Low	Low chance the control of design will detect a possible cause of failure.
5	Moderate	Moderate chance the control of design will detect a possible cause of failure.
4	Moderately high	Moderately high chance the control of design will detect a possible cause of failure.
3	High	A high chance of the control of design will detect a possible cause of failure.
2	Relatively high	Relatively high chance the design control will detect a possible cause of failure.
1	Certain	Control of design will certainly detect a possible cause of failure.

2.1. Ordered Weighted Geometric Averaging

In the literature, there are several operators for aggregating data (Yager et al., 2012). Yager (1994) listed a few approaches for Ordered Weighted Aggregation (OWA) that are often utilized. The essential operator for aggregation is used to classify weighted aggregation approaches. Based on the rankings of the weighting gradients, the approach chooses the best heaps of the qualities (Chang et al., 2012).

OWA is a mapping operator with a dimension of n. OWA: $R_n > R$, specified by a related vector for weighting, $W = (w_1, w_2, \ldots, w_n)^T$ such that $\Sigma_{i=1}{}^{n} w_i = 1$ and w_i included [0,1] based on the Equation (2).

$$OWA(a_1, a_2, \ldots, a_n) = \sum_{i=1}^{n} w_i b_i \tag{2}$$

in which $[a_1, a_2, \ldots, a_n]$ and $[b_1, b_2, \ldots, b_n]$ are ordered arguments vectors such that for each j, $a_j > b_j$.

The values of OWA$(a_1, a_2, \ldots, a_n)$ complete the total value of the arguments $a_1, a_2, \ldots, a_n$.

O'Hagan (1988) developed a mechanism generating OWA to reduce entropy. O'Hagan's technique was going to address the problem of restricted optimisations. This procedure is based on the mathematical programming issue:

Maximise:

$$\sum_{i=1}^{n} w_i \ln b_i \tag{3}$$

$$\frac{1}{n-1} \sum_{i=1}^{n} (n-1) w_i, \quad 0 \le \alpha \le 1 \tag{4}$$

$$\Sigma_{i=1}{}^{n} w_i = 1; 0 \le w_i \le 1, i = 1, i = 1, \ldots, n \tag{5}$$

Additionally, Yager and Filev (1994, 1998) established a new class of S-OWA operators. Chiclana et al. (2000) cultivated the OWGA operator, which referred to the OWA operator with the inclusion of the geometric mean.

An ordered weighted geometric averaging (OWGA) operator of dimension n is represented as a mapping in the following OWA: $R_n > R$, defined by an associated exponential weighting vector $W = (w_1, w_1, \ldots, w_1)^T$, with wi included [0,1] and $\Sigma_{i=1}{}^{n} w_i = 1$ illustrated as:

$$\sum_{i=1}^{n} w_i = 1; 0 \le w_i \le 1, i = 1, i = 1, \ldots, n \tag{6}$$

where b_j is the j^{th} biggest element of the group of the n aggregated object $a_1, a_2, \ldots, a_n$ and $b_1 \ge b_2 \ldots \ge b_n$. The value of OWA $(a_1, a_2, \ldots, a_n)$ finalises the values of aggregated arguments $a_1, a_2, \ldots, a_n$.

In the hypothesis of OWA operators, the choice of related weights is a crucial topic. Fuller and Majlender (2001) generated a polynomial equation using Yager's OWA equation that may be able to identify the appropriate weighting variable with the most entropy. Using their method, the following weighting coefficient is produced:

$$\frac{j-1}{n-1}\, lnw_j = lnw_n + \frac{n-j}{n-1}\, lnw_1 > w_j = \sqrt[n-1]{w_1^{\,n-1} w_n^{\,j-1}} \tag{7}$$

and

$$w_n = \frac{((n-1)a-n)\, w_1+1}{(n-1)\, a+1-nw_1} \tag{8}$$

then,

$$\begin{aligned} & w_1\,[\,(\,n-1\,)+1-nw_1\,]\,n = \\ & \quad (\,(\,n-1\,)\,\alpha\,)\,n-1\cdot[\,(\,(n-1)\,\alpha-n\,)\,w_1+1\,] \end{aligned} \tag{9}$$

where the parameter of the situation that should be satisfied by the ideal value of w_1 (9) is the weight vector. Once w_1 is determined, it may be used to calculate w_n (8) which results in the remaining loads (7).

2.2. Generalised Mixing Operator (GMO)

According to Pereira and Ribeiro (2003), the GMOs might be yet another variant generalisation of the OWA method's value, in which traditional loads have gone out to the functions of weighting. Different weight-generating functions were presented, and Pereira and Ribeiro (2003) investigated the monotonicity of subject parameters implied by these functions. Additional information about combination operators may be found in their publications. For determining and aggregating risk-related values of failure causes in the LGS products, Shaghaghi and Rezaie (2012) presented a generalised mixture operator.

W(x) is the generalised mixing operator shaped by the n functions fi(x) and characterized as:

$$W\,(x) = \frac{\Sigma^n_{j=1} f_i\,(x_i\,)\, x_i}{\Sigma^n_{j=1} f_j\,(j_i\,)} \tag{10}$$

The mixing operator W(x) could be alternatively communicated as an average of weight, with functions of weighting replacing traditional loads.

$$W(x) = \Sigma^n_{i=1}\; w_i\,(\,x\,)\,(\,x_i\,) \tag{11}$$

With weighting functions:

$$W_i\,(x) = \frac{f_i\,(\,x_i\,)}{\Sigma^n_{i=1} f_i\,(\,x_i\,)} \tag{12}$$

Mixed operators are non-linear, differentiable, and compensative, yet not always monotonic (Pereira and Ribeiro, 2003). According to the same investigation, the monotonicity of the GMOs is produced by the generating functions of weighting. Compared to quadratic weighting methods, linear weighting functions are less sensitive to attribute satisfaction levels.

The effective version of the function for weight generation is:

$$Q(x) = \alpha\,\frac{q(x)}{q(1)} = \alpha\,\frac{1+(\,\beta-\gamma\,)\,x+\gamma x^2}{1+\beta} \tag{13}$$

where 0≤γ≤ 1 and γ ≤ β ≤ βc (γ) and 0<α <1. In addition, critical beta function βc(γ) is defined as:

$$\beta c(\gamma) = 1+\gamma \;\; for\;\; 0.5 \le \gamma \le 1 \tag{14}$$

and

$$\beta c(\gamma) = \sqrt{(\,\gamma\,(\,1+\gamma\,)\,)} \;\; for\;\; 0.5 \le \gamma \le 1 \tag{15}$$

At a point when the criterion satisfaction value is 1, the variable of a, which is 0.7, decides the value Q(1). The variable of b, which administers the curvature of the generating functions of quadratic effective weights, is set to 0.8 in the quadratic case. The variable of c oversees the ratio of the greatest and most reduced values of the weight-related functions and is set to 1.6 in the quadratic case.

2.3. Grey Relational Analysis (GRA)

Deng (1989) introduced the phrase "Grey Relativity Analysis," which refers to judgments that are influenced by imperfect information, such as operational, mechanism-related, structural, and behavioural information, but which are neither completely opaque nor deterministic. It investigates the behaviour of the framework through the use of connection analysis and model creation. This strategy may be used and achieved inside the FMEA system (Hang et al. 2001; Liu et al. 2013, 2015). Some other novel articles outline the utilization of subject technique alongside the FMEA philosophy for various businesses, e.g., clinical benefit measures, etc. (Li and Chen 2018, Shi et al., 2019).

This method contains 3 main steps:

1. Data pre-processing:

First, equation 16 is used to process the data:

$$x_i^*(k) = \frac{x^0_i(k) - \min x^0_i(k)}{\max x^0_j(k) - \min x^0_j(k)} \tag{16}$$

2. Grey Relational coefficient:

Equation 17 is used to obtain the GRA coefficient:

$$\xi i(k) = \frac{\Delta_{min} + \xi \Delta_{max}}{\Delta_{oi}(k) + \xi \Delta_{max}} \tag{17}$$

Δ_{oi} – is the deviation sequence

$$\Delta_{oi} = \| x_0^*(k) - x_i^*(k) \| \tag{18}$$

ξ – distinguished coefficient

The value of ξ is lower, and the ability of distinguished is higher. ξ= 0.5 is a widely used value.

3. Grey relational grade:

Grey relational grades are obtained with Equation 19:

$$\gamma_i = \frac{1}{n} \Sigma^n_{k=1} \omega_k(k)\, \xi(k) \tag{19}$$

$$\omega_k(k) = 1 \tag{20}$$

2.4. VIKOR Methodology

The viability of various force plans and state-of-the-art energy technology systems are only measured and compared using various multi-criteria decision-making (MDM) techniques, such as VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), to provide precise information for choosing the moral and appropriate alternatives. Sustainability has come to mean a variety of things including environmental preservation, social cohesion, economic development, community plan, alternative energy, green structure plan, etc., as a consequence of a deliberately ambiguous definition. The attempt to characterise and measure sustainability and its aims characterises current information on sustainability.

Opricovic created the foundations of VIKOR in his dissertation in 1979 and then implemented it in 1980. The research aims to provide a complete assessment of VIKOR practices in the literature. VIKOR strategy is used alone or in a combination with different methods for diversification, exploration, and surveys. There are many studies to illustrate the VIKOR method (Liu et al., 2015; Tian et al., 2018). Computation of VIKOR-related grades contains the following equations:

The unity grades are calculated as:

$$S_i = \Sigma^m_{j=1} \left(w_j \frac{x^+_i - x_{ij}}{x^+_i - x^-_i} \right) \tag{21}$$

The individual regrets are found using

$$R_i = \max_j \left(w_i \frac{x^+_i - x_{ij}}{x^+_i - x^-_i} \right) \tag{22}$$

Finally, VIKOR-related grades are computed with the equation (23):

$$Q_i = v \frac{s_i - s^*}{s^- - s^*} + (1 - v) \frac{R_i - R^*}{R^- - R^*} \tag{23}$$

w is weight. Terms can be calculated in different ways; the Shannon entropy is one of them.

2.5. Shannon Entropy

Entropy was first conceptualised by Shannon as a mathematical theory (Shannon, 1948). The amount of uncertainty addressed by the probability of discrete appropriation is judged by the notion in the information hypothesis. Entropy is a concept that may be used successfully in decision-making processes because it quantifies the overall information that is being transmitted to the decision-maker and measures the correlation between groups of data.

The concept has been extensively used in many disciplines, including science and economics. The weights for additional computations, such as calculating the implementation of a system of digital resources in digital libraries and the tanking of production, have recently been determined using the Shannon entropy (Samiei and Farzadi, 2020). In a different investigation, the Shannon entropy was used to help determine how to rank the determination of perceptual distinction (Ozturk and Atan, 2015).

The following steps might be used to obtain the Shannon entropy weights.

Step 1. The ranges of the decision matrix (performance indicators) must be normalised for the project to succeed.

$$p_{ij} = \frac{x_{ij}}{\Sigma^{m}_{i=1} x_{ij}} \qquad (24)$$

Step 2. Using the following equation, the entropy of project outcomes is calculated:

$$E_j = - k \, \Sigma^{m}_{i=1} \, p_{ij} \, lnp_{ij} \qquad (25)$$

in which k=1/ln(m)

Step 3. Describe objective weight based on the entropy principle:

$$W_j = \frac{1 - E_j}{\Sigma^{n}_{j=1} \, (1 - E_j)} \qquad (26)$$

3. PROPOSED METHOD'S PROCEDURE

The risk evaluation of offshore wind turbines has been established using a productive, multi-stage hybrid technique. The steps of the suggested technique are given below (Figure 1).

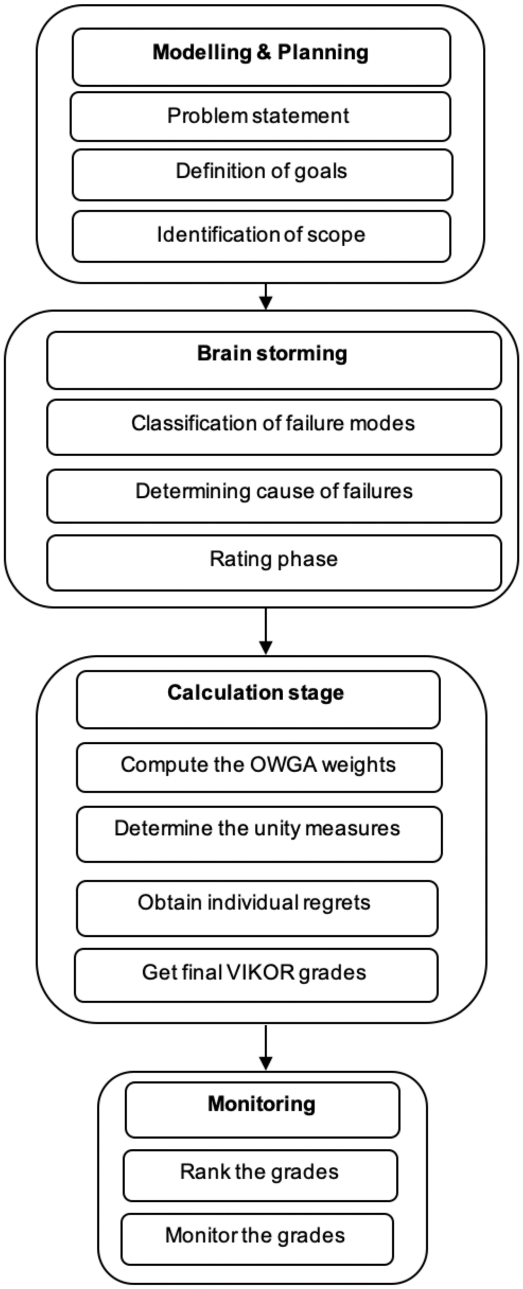

Figure 1.
The risk evaluation steps of offshore wind turbines.

Step 1. Modelling and planning: Modelling and planning are two important processes in engineering. Modelling involves creating a simplified representation of a complex system or process to understand its behaviour and make predictions about how it will behave under different conditions. Planning, on the other hand, involves developing a course of action to achieve a specific goal or objective.

Step 2. Brainstorming: Brainstorming is a powerful tool for risk analysis as it allows for the generation of new ideas and perspectives to identify potential risks that might not be obvious otherwise. It will be used effectively to investigate potential hazards that turbine components may encounter during their service life, to evaluate failure modes, and to determine the underlying causes of failures in the literature. Initially, the experts most suitable to contribute to the discussion will be identified at this stage based on their experience, knowledge, and expertise.

Step 3. Calculation stage: Aggregated ratings, the OWGA weights, normalisation, getting pre-weights, obtaining normalized weights, and getting aggregated assessment grades are all phases in the calculation process. The VIKOR technique is then applied to determine final grades.

Step 4. Monitoring: Even after implementing risk mitigation strategies, it is important to continue to monitor and review risks to ensure that they remain under control. This can involve regular assessments, audits, and reviews to identify any new risks that may have emerged.

4. MULTI-STAGE OFFSHORE WIND TURBINES RISK ASSESSMENT

To undertake the risk assessment of offshore wind turbines, a hybrid approach built on the FMEA, ordered weighted geometric averaging (OGWA), and VIKOR was used in this research. A comprehensive literature review and information obtained from experts were used in calculations with various strategies. The risk analysis and evaluation process to be carried out in this context are shown below step by step.

Stage 1. Modelling and planning: Offshore wind turbines involve many risks when considering the environmental conditions in which they are located, and it is very important to evaluate them correctly. Minor carelessness during the design phase can cause major failures or costly overhauls in the service life of turbines.

The purpose of this work is to create a technique that, by anticipating the risks that wind turbines can face in operation, can more precisely assess potential failure modes and causes. As a result, actions to avoid or at least to mitigate the consequences of key risks in the design process will be available.

Stage 2. Brainstorming: To identify the failure modes and reasons in offshore wind turbines, a thorough review of the literature on these machines was conducted. Five specialists with more than 10 years of wind turbine maintenance expertise also took part in a group interview. Experts examined offshore wind turbines and found probable failure modes and causes. After evaluating each failure mode according to the S, O, and D criteria, the RPN number was established. Higher RPN scores than lower RPN scores indicate higher-risk failure types. Table 4 displays the offshore wind turbine failure modes and accompanying RPN codes.

According to Table 4, there are 30 causes and 8 failure scenarios for the offshore wind turbine system. The current situation is shown with a directed graph in Figure 2. Here, the offshore wind turbine system has 8 essential FMs and 30 causes of failures.

Stage 3. At this stage, calculations were made with the OWGA, GMO, GRA, VIKOR + Shannon entropy, and OWGA + VIKOR techniques.

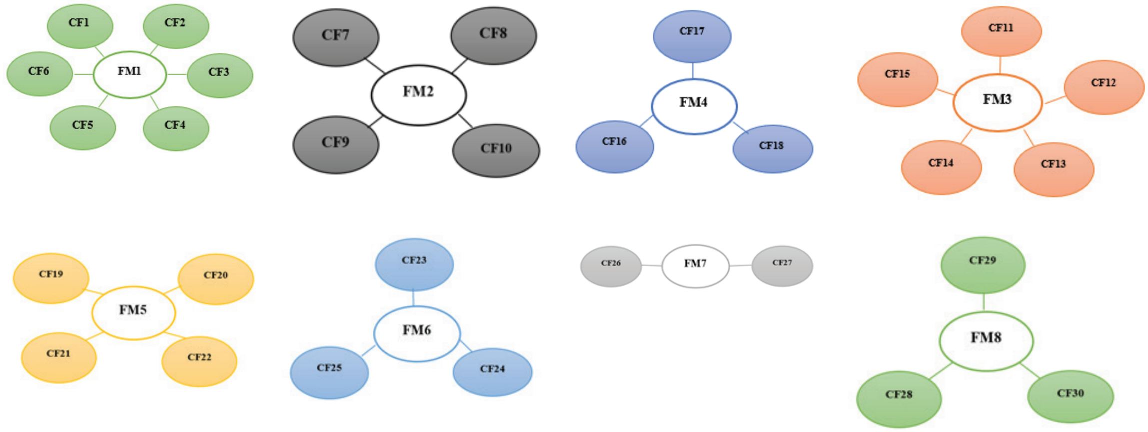

Figure 2.
Corresponding design of FMEA-directed graphs.

Table 4.
Failure modes with appropriated RPN values.

Item	Failure modes	End effects	Cause of failure	Abbreviation	S	O	D	RPN
1	Deformation of bearing	Equipment damage	1. Improper grease	CF1	4	7	5	140
2			2. Overtighten/loosen bearing shaft matching	CF2	4	6	6	144
3			3. Over tighten/loosen bearing-shaft cap maching	CF3	4	6	5	120
4			4. Electric corrosion of rollaway nest	CF4	4	5	5	100
5			5. Deformation of shaftware	CF5	4	7	4	112
6			6. Failure of the cooling system	CF6	4	5	3	60
7	Overheat	OWT shutdown	1. Shaft failure	CF7	3	4	3	36
8			2. Overload of turbine	CF8	3	5	5	75
9			3. Failure of air cooling system	CF9	3	6	3	54
10			4. Partial short circuit on stator winding	CF10	3	7	5	105
11	Wind-related failures	OWT shutdown	1. Failure of cable insulation	CF11	4	8	5	160
12			2. Interturn short circuit	CF12	4	6	4	96
13			3. Winding corrosion	CF13	4	8	7	224
14			4. Long-term overload	CF14	5	7	5	175
15			5. Electric sequence reverse	CF15	4	5	4	80
16	Convertion failure	Disconnect to grid	1. Load mutation	CF16	3	6	6	108
17			2. Low voltage on the power grid	CF17	3	7	5	105
18			3. Fault of cooling system	CF18	3	7	5	105
19	Transformation winding failure	Disconnect to grid	1. Excessive system oscillation	CF19	3	7	6	126
20			2. Constant overload in transformer	CF20	3	6	4	72
21			3. Iron core corrosion	CF21	3	8	8	192
22			4. Overvoltage	CF22	3	7	4	84
23	Output voltage error	Disconnect to grid	1. Friction of rotor-stator	CF23	3	7	8	168
24			2. Failure of computer timing	CF24	3	4	4	48
25			3. Failure of rational speed sensor	CF25	3	5	7	105
26	Yaw positioning inaccuracy	Inefficiency	1. Accuracy of wind direction sensor	CF26	3	5	6	90
27			2. Excessive yaw gear distance	CF27	3	5	3	45
28	Fracture of mooring line	OWT shutdown	1. Extreme marine environment	CF28	5	4	3	60
29			2. Fatigue damage	CF29	3	6	7	126
30			3. Collision	CF30	4	4	2	32

4.1. OWGA Methodology

First, the OWGA weights have been calculated by making use of Equations 7-9. An affectability of the investigation by utilising unique qualities was introduced to assess their effects on hazard evaluations. A maximal amount of entropy regarding weight estimation was utilised in the suggested method. n=3 and a=0.7 were taken accordingly for final calculations.

Table 5.
Obtained OWGA weights.

OWGA WEIGHTS

α	W_1	W_2	W_3
0.5	0.3333	0.3333	0.3333
0.6	0.4384	0.3232	0.2384
0.7	0.554	0.292	0.154
0.8	0.6819	0.2358	0.082
0.9	0.8263	0.147	0.026
1	1	0	0

Table 6.
OWGA methodology.

Cause of failures	Severity	Occurrence	Detection	0.5	0.6	0.7	0.8	0.9	1
CF1	4	7	5	5.19	5.05	4.87	4.65	4.36	4
CF2	4	6	6	5.24	5.02	4.79	4.55	4.29	4
CF3	4	6	5	4.93	4.81	4.66	4.48	4.27	4
CF4	4	5	5	4.64	4.53	4.42	4.29	4.15	4
CF5	4	7	4	4.82	4.79	4.71	4.56	4.34	4
CF6	4	5	3	3.91	4.01	4.08	4.12	4.1	4
CF7	3	4	3	3.3	3.29	3.26	3.21	3.13	3
CF8	3	5	5	4.22	4	3.77	3.53	3.27	3
CF9	3	6	3	3.78	3.75	3.67	3.53	3.32	3
CF10	3	7	5	4.72	4.46	4.16	3.82	3.44	3
CF11	4	8	5	5.43	5.28	5.07	4.8	4.45	4
CF12	4	6	4	4.58	4.56	4.5	4.4	4.24	4
CF13	4	8	7	6.07	5.72	5.34	4.93	4.49	4
CF14	5	7	5	5.59	5.57	5.52	5.41	5.25	5
CF15	4	5	4	4.31	4.3	4.27	4.21	4.13	4
CF16	3	6	6	4.76	4.43	4.09	3.74	3.38	3
CF17	3	7	5	4.72	4.46	4.16	3.82	3.44	3
CF18	3	7	5	4.72	4.46	4.16	3.82	3.44	3
CF19	3	7	6	5.01	4.65	4.27	3.88	3.46	3

CF20	3	6	4	4.16	4.02	3.84	3.62	3.34	3
CF21	3	8	8	5.77	5.2	4.65	4.1	3.55	3
CF22	3	7	4	4.38	4.23	4.02	3.75	3.42	3
CF23	3	7	8	5.52	4.98	4.47	3.97	3.48	3
CF24	3	4	4	3.63	3.53	3.41	3.29	3.15	3
CF25	3	5	7	4.72	4.33	3.97	3.63	3.3	3
CF26	3	5	6	4.48	4.17	3.87	3.58	3.29	3
CF27	3	5	3	3.56	3.54	3.48	3.38	3.23	3
CF28	5	4	3	3.91	4.12	4.33	4.55	4.77	5
CF29	3	6	7	5.01	4.59	4.18	3.79	3.39	3
CF30	4	4	2	3.17	3.39	3.6	3.78	3.92	4

From Equation 9, W_1 was calculated as

$$W_1 \cdot [2 \times 0.7 + 1 - 3 \cdot W_1]^3 = [(20)^3 \cdot (2 \cdot 0.7 - 3) \cdot W_1 + 1 \qquad (27)$$

Then, by using W_1 and Eq. (8), W_3 was obtained as

$$W_3 = \frac{((3-1) \cdot 0.7 - 3)\, w_1 + 1}{(3-1) \cdot 3 + 1 - 3 * w_1} \qquad (28)$$

Finally, by using Equation 7, W_2 was found that:

$$W_2 = \sqrt[3-1]{w_1^{3-2}\, w_3^{2-1}} \qquad (29)$$

The values of weights are $W_1 = 0.554$, $W_2 = 0.292$, and $W_3 = 0.154$ respectively.

The final OWGA grade is

$$OWGA_w\,(4,7,5) = 4^{0.554} \times 7^{0.292} \cdot 5^{0.154} = 4.87 \qquad (30)$$

The OWGA weights were calculated for different α values. The OWGA values obtained are presented in Table 5 and the RPN of each cause of failure in Table 6. Table 7 shows how the causes of failure are ranked in order of importance.

Table 7.
Ranking based on OWGA methodology.

No:	Item	Value
1	CF14	5.5162
2	CF13	5.3381
3	CF11	5.0686
4	CF1	4.8747
5	CF2	4.7929
6	CF5	4.7101
7	CF3	4.6602
8	CF21	4.6463
9	CF12	4.5028
10	CF23	4.4686
11	CF4	4.4186
12	CF28	4.3302
13	CF19	4.2749
14	CF15	4.2693
15	CF29	4.185
16	CF10	4.1566
17	CF17	4.1566

18	CF18	4.1566
19	CF16	4.0868
20	CF6	4.0843
21	CF22	4.0162
22	CF25	3.968
23	CF26	3.8749
24	CF20	3.8394
25	CF8	3.7676
26	CF9	3.673
27	CF30	3.595
28	CF27	3.4826
29	CF24	3.4107
30	CF7	3.2629

4.2. VIKOR Methodology

This approach uses Shannon entropy to obtain the weights. The attribute weights were obtained with Equations 24-26. Then, VIKOR degrees of causes of failures were obtained with these weights and Equations 20-22. First, normalisation of the arrays of the decision matrix was found in the Shannon entropy method where

$$p_{ij} = \frac{x_{,j}}{\Sigma^{m}_{i=1} x_{ij}} = \frac{4}{105} = 0.0381 \qquad (31)$$

Then, the entropy measure of outcomes was calculated as

$$Ej = -k\Sigma^{m}_{i=1} p_{ij} \ln p_{ij} = -1 - \ln(3) \cdot 3.3861 \cdot 0.3810 \cdot \ln(0.0381) = 3.3861 \qquad (32)$$

where

$$k = \frac{1}{\ln(m)} \qquad (33)$$

The weights were defined based on the concept of entropy. The W_1 was calculated as

$$W_i = \frac{1 - E_j}{\Sigma^{n}_{j=1}(1 - E_j)} = \frac{1\text{-}3.3861}{-6.21} = 0.3352 \qquad (34)$$

After computing the other weights of failure modes accordingly, the weight of each criterion was found as: $W_1 = 0.3352; W_2 = 0.3344; W_3 = 0.3304$.

Using the Shannon entropy weights, VIKOR-related grades were calculated. First, all risk indicators, beneficial and non-beneficial criteria, were found. Then, we proceeded with the unity measure as below:

$$S_i = \Sigma^{m}_{j=1}\left(w_j \cdot \frac{x^{+}_{i} - x_{ij}}{x^{+}_{i} - x^{-}_{i}}\right) = \Sigma^{3}_{j=1}\left(0.335 \cdot \frac{5-4}{5-3}\right) = 0.416 \qquad (35)$$

Furthermore, regret measure was computed for each cause of failure.

$$R_i = \max_1\left(w_i \cdot \frac{x^{+}_{i} - x_{ij}}{x^{+}_{i} - x^{-}_{i}}\right) = \max(0.168; 0.084; 0.165) = 0.168 \qquad (36)$$

Minimum and maximum values of Si and Ri were gathered. Finally, VIKOR-related grades were found as

$$Q_i = v \cdot \frac{s_i - s^*}{s^- - s^*} + (1-v) \cdot \frac{R_i - R^*}{R^- - R^*} = 0.5 \cdot \left(0.335 \cdot \frac{0.416\text{-}0.223}{0.945\text{-}0.223}\right) = 0.141 \qquad (37)$$

Then, all the other cases were calculated separately and displayed in Tables 8 and 9. The prioritisation causes of failures were obtained and given in Table 10.

Table 8.
VIKOR methodology.

Cause of Failure	S	O	D				S	R	Q
CF1	4	7	5	0.167616	0.083597	0.16519	0.416403	0.167616	0.141245
CF2	4	6	6	0.167616	0.167194	0.110126	0.444937	0.167616	0.160999
CF3	4	6	5	0.167616	0.167194	0.16519	0.5	0.167616	0.199117
CF4	4	5	5	0.167616	0.250791	0.16519	0.583597	0.250791	0.501558
CF5	4	7	4	0.167616	0.083597	0.220253	0.471466	0.220253	0.334138
CF6	4	5	3	0.167616	0.250791	0.275316	0.693723	0.275316	0.649911
CF7	3	4	3	0.335233	0.334388	0.275316	0.944937	0.335233	1
CF8	3	5	5	0.335233	0.250791	0.16519	0.751213	0.335233	0.86589
CF9	3	6	3	0.335233	0.167194	0.275316	0.777743	0.335233	0.884256
CF10	3	7	5	0.335233	0.083597	0.16519	0.584019	0.335233	0.750146
CF11	4	8	5	0.167616	0	0.16519	0.332806	0.167616	0.083373
CF12	4	6	4	0.167616	0.167194	0.220253	0.555063	0.220253	0.39201
CF13	4	8	7	0.167616	0	0.055063	0.22268	0.167616	0.007136
CF14	5	7	5	0	0.083597	0.16519	0.248787	0.16519	0.018073
CF15	4	5	4	0.167616	0.250791	0.220253	0.63866	0.250791	0.539677
CF16	3	6	6	0.335233	0.167194	0.110126	0.612553	0.335233	0.769899
CF17	3	7	5	0.335233	0.083597	0.16519	0.584019	0.335233	0.750146
CF18	3	7	5	0.335233	0.083597	0.16519	0.584019	0.335233	0.750146
CF19	3	7	6	0.335233	0.083597	0.110126	0.528956	0.335233	0.712027
CF20	3	6	4	0.335233	0.167194	0.220253	0.72268	0.335233	0.846137
CF21	3	8	8	0.335233	0	0	0.335233	0.335233	0.577918
CF22	3	7	4	0.335233	0.083597	0.220253	0.639083	0.335233	0.788265
CF23	3	7	8	0.335233	0.083597	0	0.41883	0.335233	0.63579
CF24	3	4	4	0.335233	0.334388	0.220253	0.889874	0.335233	0.961881
CF25	3	5	7	0.335233	0.250791	0.055063	0.641087	0.335233	0.789653
CF26	3	5	6	0.335233	0.250791	0.110126	0.69615	0.335233	0.827771
CF27	3	5	3	0.335233	0.250791	0.275316	0.86134	0.335233	0.942128
CF28	5	4	3	0	0.334388	0.275316	0.609704	0.334388	0.765442
CF29	3	6	7	0.335233	0.167194	0.055063	0.55749	0.335233	0.731781
CF30	4	4	2	0.167616	0.334388	0.330379	0.832384	0.334388	0.919598

Table 9.
VIKOR methodology.

	S	O	D
f*j	5	8	8
f-j	3	4	2
S*	0.2227	R*	0.16519
S-	0.9449	R-	0.33523

Table 10.
Ranking based on VIKOR + Shannon entropy method.

No:	Cause of Failure	Value
1	CF13	0.007136
2	CF14	0.018073
3	CF11	0.083373
4	CF1	0.141245
5	CF2	0.160999
6	CF3	0.199117
7	CF5	0.334138
8	CF12	0.39201
9	CF4	0.501558
10	CF15	0.539677
11	CF21	0.577918
12	CF23	0.63579
13	CF6	0.649911
14	CF19	0.712027
15	CF29	0.731781
16	CF10	0.750146
17	CF17	0.750146
18	CF18	0.750146
19	CF28	0.765442
20	CF16	0.769899
21	CF22	0.788265
22	CF25	0.789653
23	CF26	0.827771
24	CF20	0.846137
25	CF8	0.86589
26	CF9	0.884256
27	CF30	0.919598

28	CF27	0.942128
29	CF24	0.961881
30	CF7	1

Table 11.
VIKOR + OWGA methodology calculation and ranking.

Cause of Failure	S	O	D				S	R	Q
CF1	4	7	5	0.277	0.073	0.077	0.427	0.277	0.352
CF2	4	6	6	0.277	0.146	0.051	0.474	0.277	0.376
CF3	4	6	5	0.277	0.146	0.077	0.500	0.277	0.389
CF4	4	5	5	0.277	0.219	0.077	0.573	0.277	0.425
CF5	4	7	4	0.277	0.073	0.103	0.453	0.277	0.365
CF6	4	5	3	0.277	0.219	0.128	0.624	0.277	0.451
CF7	3	4	3	0.554	0.292	0.128	0.974	0.554	0.764
CF8	3	5	5	0.554	0.219	0.077	0.850	0.554	0.702
CF9	3	6	3	0.554	0.146	0.128	0.828	0.554	0.691
CF10	3	7	5	0.554	0.073	0.077	0.704	0.554	0.629
CF11	4	8	5	0.277	0	0.077	0.354	0.277	0.316
CF12	4	6	4	0.277	0.146	0.103	0.526	0.277	0.401
CF13	4	8	7	0.277	0	0.026	0.303	0.277	0.290
CF14	5	7	5	0	0.073	0.077	0.150	0.077	0.114
CF15	4	5	4	0.277	0.219	0.103	0.599	0.277	0.438
CF16	3	6	6	0.554	0.146	0.051	0.751	0.554	0.653
CF17	3	7	5	0.554	0.073	0.077	0.704	0.554	0.629
CF18	3	7	5	0.554	0.073	0.077	0.704	0.554	0.629
CF19	3	7	6	0.554	0.073	0.051	0.678	0.554	0.616
CF20	3	6	4	0.554	0.146	0.103	0.803	0.554	0.678
CF21	3	8	8	0.554	0	0	0.554	0.554	0.554
CF22	3	7	4	0.554	0.073	0.103	0.730	0.554	0.642
CF23	3	7	8	0.554	0.073	0	0.627	0.554	0.591
CF24	3	4	4	0.554	0.292	0.103	0.949	0.554	0.751
CF25	3	5	7	0.554	0.219	0.024	0.799	0.554	0.676
CF26	3	5	6	0.554	0.219	0.051	0.824	0.554	0.690
CF27	3	5	3	0.554	0.219	0.128	0.901	0.554	0.727
CF28	5	4	3	0	0.292	0.128	0.420	0.292	0.356
CF29	3	6	7	0.554	0.146	0.026	0.726	0.554	0.640
CF30	4	4	2	0.277	0.292	0.154	0.723	0.292	0.508
f * j	5	8	8	S*	0.15	R*	0.077		
f - j	3	4	2	S-	0.9743	R-	0.554		

In the OWGA + VIKOR technique, the previously obtained OWGA weights are used in the VIKOR value calculation process. The calculations have been carried out and given in Table 16. As the alpha (a) and weight (w) changed, the obtained VIKOR values also changed that led to a change in the ranking of causes of failures. Consequently, a=0.7 were chosen for comparison, and the illustration of the obtained final grades is demonstrated in Table 17.

Stage 4: Prioritisation of the cause of failure was evaluated for conventional RPN, GMO, OWGA, GRA, VIKOR and the hybrid methodology proposed in Table 18. The experts evaluated the results obtained in all strategies and decided that the multi-stage hybrid method gave sensible results.

Stage 5: At this stage, an FMEA report is planned and experts recommend preventive or mitigating actions to improve critical causes of failures. This can result in a more productive OWT, saving financial resources and time. Corrective measures should be taken to reduce hazards.

Table 12.

Comparison based on different a values.

	0.5		**0.6**		**0.7**		**0.8**		**0.9**		**1**	
1	CF13	0.194	CF14	0.160	CF14	0.114	CF14	0.079	CF14	0.043	CF14	0
2	CF14	0.208	CF13	0.239	CF13	0.29	CF28	0.270	CF28	0.158	CF28	0
3	CF11	0.250	CF11	0.279	CF11	0.316	CF13	0.348	CF13	0.415	CF1	0.5
4	CF1	0.292	CF1	0.319	CF1	0.352	CF11	0.361	CF11	0.420	CF2	0.5
5	CF2	0.306	CF5	0.339	CF28	0.356	CF1	0.391	CF1	0.438	CF3	0.5
6	CF3	0.333	CF2	0.340	CF5	0.365	CF5	0.398	CF5	0.440	CF4	0.5
7	CF21	0.333	CF3	0.360	CF2	0.376	CF2	0.414	CF2	0.454	CF5	0.5
8	CF5	0.347	CF12	0.379	CF3	0.389	CF3	0.420	CF3	0.456	CF6	0.5
9	CF23	0.375	CF4	0.412	CF12	0.401	CF12	0.427	CF12	0.459	CF11	0.5
10	CF12	0.389	CF28	0.423	CF4	0.425	CF4	0.450	CF4	0.475	CF12	0.5
11	CF4	0.417	CF15	0.431	CF15	0.438	CF15	0.457	CF15	0.477	CF13	0.5
12	CF19	0.431	CF21	0.438	CF6	0.451	CF6	0.464	CF6	0.479	CF15	0.5
13	CF15	0.444	CF6	0.451	CF30	0.508	CF30	0.500	CF30	0.500	CF30	0.5
14	CF29	0.444	CF23	0.479	CF21	0.554	CF21	0.682	CF21	0.826	CF7	1
15	CF10	0.458	CF19	0.519	CF23	0.591	CF23	0.711	CF23	0.845	CF8	1
16	CF17	0.458	CF10	0.538	CF19	0.616	CF19	0.725	CF19	0.849	CF9	1
17	CF18	0.458	CF17	0.538	CF10	0.629	CF10	0.732	CF10	0.851	CF10	1
18	CF16	0.472	CF18	0.538	CF17	0.629	CF17	0.732	CF17	0.851	CF16	1
19	CF28	0.472	CF29	0.539	CF18	0.629	CF18	0.732	CF18	0.851	CF17	1
20	CF6	0.486	CF30	0.552	CF29	0.640	CF22	0.739	CF22	0.853	CF18	1
21	CF22	0.486	CF22	0.558	CF22	0.642	CF29	0.748	CF29	0.865	CF19	1
22	CF25	0.486	CF16	0.559	CF16	0.653	CF16	0.755	CF16	0.867	CF20	1
23	CF26	0.514	CF25	0.579	CF25	0.676	CF20	0.768	CF20	0.872	CF21	1
24	CF20	0.528	CF20	0.599	CF20	0.678	CF9	0.775	CF9	0.874	CF22	1
25	CF8	0.542	CF26	0.599	CF26	0.689	CF25	0.777	CF25	0.884	CF23	1
26	CF9	0.556	CF9	0.619	CF9	0.691	CF26	0.784	CF26	0.886	CF24	1
27	CF30	0.583	CF8	0.619	CF8	0.702	CF8	0.791	CF8	0.888	CF25	1
28	CF27	0.597	CF27	0.659	CF27	0.728	CF27	0.804	CF27	0.892	CF26	1
29	CF24	0.611	CF24	0.679	CF24	0.751	CF24	0.827	CF24	0.908	CF27	1
30	CF7	0.639	CF7	0.699	CF7	0.764	CF7	0.834	CF7	0.911	CF29	1

5. RESULTS AND DISCUSSION

This section compares the OWGA, GRA, GMO, VIKOR, and VIKOR + OWGA outputs, and highlights the strengths of the proposed hybrid prioritisation technique. The ranking results of all thirty causes of failures using all the methodologies are shown in Table 13. Since the traditional RPN approach does not give reliable results, it has been neglected in comparison with other methods.

The most critical cause of failure in the GMO method is "CF21: Iron core corrosion", "CF13: Winding corrosion", "CF14: Long-term overload", "CF23: Friction of rotor-stator", and "CF11: Failure of cable insulation ". The order of criticality in the OWGA method is "CF14: Long-term overload", "CF13: Winding corrosion", "CF11: Failure of cable insulation", "CF1: Improper grease", and "CF2: Overtighten/loosen bearing shaft matching". When GRA and VIKOR calculations are compared with the OWGA, only "CF14: Long-term overload" and "CF13: Winding corrosion" sequences

Table 13.
Comparison of causes of failures.

No	TRADITIONAL RPN	GMO	OWGA	GRA	VIKOR	VIKOR + OWGA
1	CF13	CF21	CF14	CF13	CF13	CF14
2	CF21	CF13	CF13	CF14	CF14	CF13
3	CF14	CF14	CF11	CF11	CF11	CF11
4	CF23	CF23	CF1	CF1	CF1	CF1
5	CF11	CF11	CF2	CF2	CF2	CF28
6	CF2	CF1	CF5	CF3	CF3	CF5
7	CF1	CF2	CF3	CF5	CF5	CF2
8	CF19	CF19	CF21	CF12	CF12	CF3
9	CF29	CF29	CF12	CF4	CF4	CF12
10	CF3	CF5	CF23	CF21	CF15	CF4
11	CF5	CF3	CF4	CF23	CF21	CF15
12	CF16	CF25	CF28	CF15	CF23	CF6
13	CF10	CF10	CF19	CF19	CF6	CF30
14	CF17	CF17	CF15	CF29	CF19	CF21
15	CF18	CF18	CF29	CF10	CF29	CF23
16	CF25	CF16	CF10	CF17	CF10	CF19
17	CF4	CF28	CF17	CF18	CF17	CF10
18	CF12	CF12	CF18	CF6	CF18	CF17
19	CF26	CF4	CF16	CF16	CF28	CF18
20	CF22	CF22	CF6	CF22	CF16	CF29
21	CF15	CF26	CF22	CF25	CF22	CF22
22	CF8	CF15	CF25	CF28	CF25	CF16
23	CF20	CF6	CF26	CF26	CF26	CF25
24	CF6	CF20	CF20	CF20	CF20	CF20
25	CF28	CF8	CF8	CF8	CF8	CF26
26	CF9	CF9	CF9	CF9	CF9	CF9
27	CF24	CF30	CF30	CF27	CF30	CF8
28	CF27	CF27	CF27	CF30	CF27	CF27
29	CF7	CF24	CF24	CF24	CF24	CF24
30	CF30	CF7	CF7	CF7	CF7	CF7

have changed. The proposed method has the same first 4 critical rankings as the OWGA. The 5th critical CF value in the VIKOR+OVGA method is "CF28: Extreme marine environment", and this CF is the 17th most critical value in the GMO, the 12th most critical value in the OWGA, the 22nd most critical value in the GRA, and the 19th most critical value in VIKOR. This shows that the proposed method gives consistent outputs with closer consideration of the criterion weights. In addition, "CF21: Iron core corrosion", which is the most critical CF in the GMO, was ranked 14th in the order of importance in the proposed method. Since the severity value of CF21 is low, it should not be the most critical CF. Therefore, the proposed method gives consistent results.

In addition, it was observed that the two least critical CFs were "CF30: Collision" and "CF24: Failure of computer timing" in all methods, respectively. "CF27: Excessive gear distance", in the 28th place, was obtained in other methods, except the GRA (at the 27th place in the GRA). It is possible to make other inferences by analysing Table 18 in detail.

From the previous calculations, the same VIKOR methods had been calculated in two different ways. In the first calculation, Shannon entropy was used to obtain aggregated weights. In the second calculation, the previously calculated OWGA weights were applied. Except for a few failure modes, most of them are relatively close to each other and even some of the failure modes had the same level of criticality, such as CF11, CF1, CF22, CF20, CF9, CF27, CF24, and CF7. There was a considerable gap only in a single failure mode, which is CF30. In the first version of the VIKOR method, CF30 was the 27th, but according to the second version of the calculation, the same failure mode is 13th. The cause of failure priority values obtained by different methods is given graphically in Figure 3.

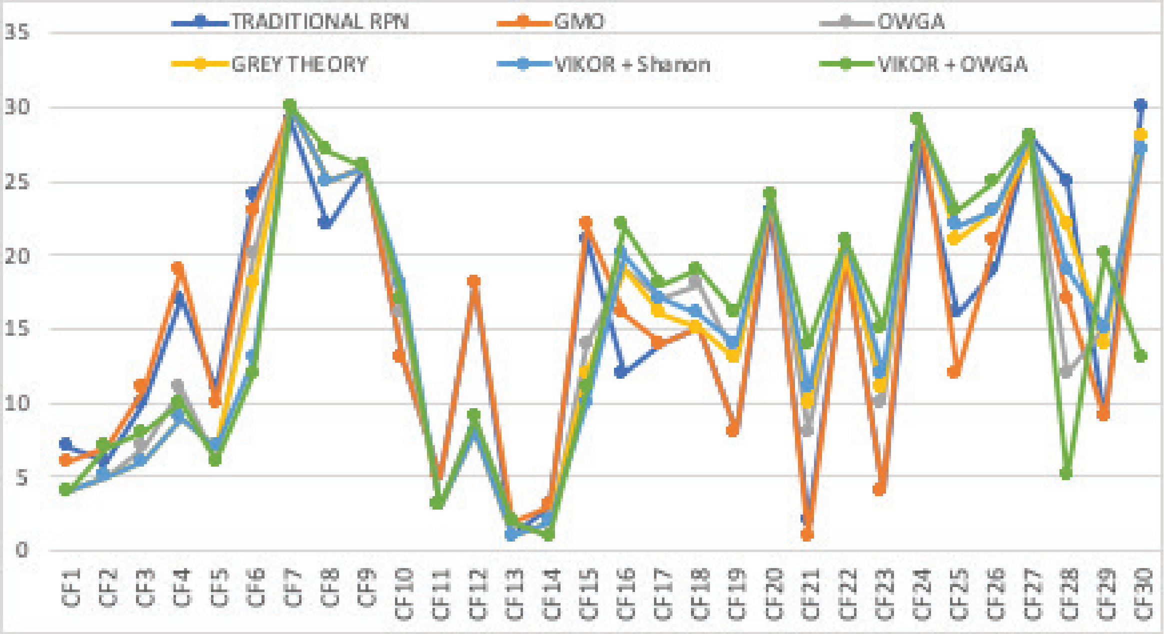

Figure 3.
Comparison of ratings of over 30 causes of failures.t

6. CONCLUSION

In this paper, a method that can be effectively used for grading offshore wind turbine failure modes and causes of failures is proposed. The new technique uses the OWGA as a weighting technique and VIKOR for ranking modes and considers the correct weighting of S, O and D variables used in risk prioritisation. In comparison to the GMO, OWGA, GRA, and VIKOR techniques, it has been observed that the current methodology avoids the shortcomings of traditional risk prioritization and more accurately reflects the influence degree of S, O, and D on the outcomes. The method will help those dealing with OWT safety to critically analyse failure modes/causes of failures. The field experts who supported the study agreed that the current method is more applicable and suitable per the results obtained.

Some area specialists have tried the acquired outcomes in the plan interaction and concurred that the system is more viable and helpful.

The advantageous points of the proposed strategy can be summed up as follows:

- In the suggested technique, comparative indicators of weights (S, O, D) are used in the calculation process.
- It is easier and more appropriate to differentiate the modes of failure that have the same RPN numbers.
- There is no limitation to the application of the subject technique in different industries.
- Similarly, the proposed method can be implemented in all the phases of the process, such as design, production, decommission, etc.
- This method helps planners and architects assess, eliminate or reduce hazards by criticality in ranking the severity of failure modes. The computing is pretty simple and can be calculated by general computational tools.

Future work will mainly focus on fuzzy field applications of these techniques. Data will be specified in linguistic variables to control for potential risks in offshore wind turbines. In addition, since the techniques proposed in the current study have a strong mathematical background and give rational results, they can be used in the evaluation of many risk problems in the industry.

CONFLICT OF INTEREST

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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