A Framework for Sustainable Maintenance of Offshore Energy Structures

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Abstract- This paper proposes a structure for maintenance decision support suitable for application to renewable energy assets. The method combines subjective tacit knowledge of subject-area experts with well-structured Analytical Hierarchical Process (AHP) to elicit weights of criteria relevant for effects evaluation of possible failures modes towards support for component's maintenance decisions. The Technique for Ordered Preference using Similarity to Ideal Solution (TOPSIS) algorithm is adopted for aggregating the evaluation scores and achieving priority indexing given the conflicting characteristics of some criteria. Part of the highlights of the Framework is the implementation of the group experts, as well as individual expert's elicitations in a complimentary manner that eliminates subjective opinions and achieves a repeatable evaluation score. The conclusion of the analysis is the prioritisation of the component's failure; An indicative case study of offshore wind turbine jacket support structure is used to demonstrate the applicability of the approach and the analysis results-which shows priority failure modes for focused maintenance intervention as bending of Chord/Brace ($PI = 0.65$), collapse of Chord/Brace ($PI = 0.49$), buckling of Long piles ($PI = 0.46$), and Truss($PI = 0.45$), overturning of Skirt pile ($PI = 0.45$), and fatigue of Long pile ($PI = 0.45$), further demonstrates the capacity of the model to support maintenance decisions. Caution is exercised in the selection of criteria that would capture the objectives of the risk analyses by consulting wide range of industry experts.

Keywords- AHP, Expert, Offshore energy, TOPSIS, Wind turbine Support Structure

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1 INTRODUCTION

Global (offshore) energy businesses are still challenged by heightening level of competition. This has been attributed to the increase in the awareness of impacts of activities in this sector on Health, Safety, and Environment which come with stringent regulations and stiffer penalties for defaulters. It is feared that the recent outbreak of COVID-19 pandemic, which has significantly adversely affected industrial activities in the greater part of Asia, Europe, and the Americas, will further worsen the situation. The search continues for ways to remain both operational and competitive which includes sometimes acquisition of state-of-the-art industrial (physical) assets. For such actions to translate to the required expectation- boost in the company's competitive advantages, these assets must fulfil the expected life-cycle objectives and achieve a low levelized cost of production.

However, it is only natural that degradation sets in with use and time due to age-related mechanisms, causing depreciation in the level of integrity (Health and Safety Executive, 2010; Jackson, n.d.). Usually, depreciation could continue to a level where the assets could be considered unfit-for-purpose, and necessitating that appropriate maintenance intervention actions be taken to restore them to the desired level of integrity. Maintenance interventions of such nature are generally capital intensive and could be higher for offshore locations (Okoro, Kolios, & Cui, 2016). Sustainability of operation requires that maintenance interventions be planned on the available budget provisions for Operational Expenditure (OpEx) in the short, mid and long term. A sustainable maintenance plan, therefore, should focus limited resources on the most important failures: in this case, the failure that will mostly affect the objectives. This should be done on a basis of transparent considerations of uncertainties that matters, throughout the different stages of the asset's life cycles.

Many risk-based approaches to maintenance planning are widely practiced (Health and Safety Executive, 2010; Jackson, n.d.; Okoro et al., 2016), amongst which Failure mode and effect analysis (FMEA) method are predominant. Though FMEA methodology demonstrates good clarity in priority indexing in various cases in which it was applied (Cabanes, Hubac, Masson, & Weil, 2017; Kougioumtzoglou & Lazakis, 2015). However, the methodology lacks transparency in ways risks are considered (Zheng & Tang, 2020). The Risk Priority Number (RPN) in FMEA, is derived as in (1) (Carlson, 2012; Ratnayake, 2012; Stamatis, 2015).

$$RPN = S \times O \times D \qquad (1)$$

Where S= Severity represents the effect of the failure mode on the operation of the system of which the component is a part (International Standard Organisation, 2006); O= Occurrence is a measure of the likelihood of the failure mode been realized again before the next maintenance schedule and D= Detectability is a measure of the likelihood of the failure mode been detected before it is realized. These definitions are classified not only as subjective to the expert but also ambiguous. Other lapses on the use of FMEA are that in the evaluation of RPN, it considers Severity, Occurrence, Detectability has been equally important for all the failure modes which in reality is not so. FMEA is not condition-replicative i.e., it does not take into consideration the peculiarities in conditions of the components.

This work proposes an approach to decision support that ensures sustainability in assets maintenance management based on risk assessment. The framework identifies the areas of risk exposures (uncertainties that matter) as multiple-criteria through a hierarchical breakdown that stems from Top management objectives herein captured under Severity-Occurrence-Detectability. In so doing, it delivers clarity in arriving at analysis conclusions- weights of criteria and score elicitation as well as achieving transparency in the aggregation of evaluation

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scores using a semi-quantitative risk assessment approach.

2 METHODOLOGY

The research methodology is demonstrated in Fig. 1. In most instances, objectives are clearly stated in the company's policy statement. However, further clarifications may be sought through stakeholder's engagement (Dodgson, Spackman, Pearman, & Phillips, 2009). Similarly, information on components available and their uses can be found in the catalogue. Such records serve as primary data. Another source of reliable (secondary) data is the peer-reviewed literature, particularly, the journals. 'What matters' as used in the definition of risk (International Standard Organisation, 2009) reflects the company's objectives. The criteria must be carefully chosen so that it captures the essence of the objectives. and can further be clarified through stakeholder engagement. In practice, the criteria can be identified through the historic record of invents in the industries or allied industries and supported by HAZOP/FMEA studies. In the context of the application, the uncertainties that matters are factors that could impact the trio of Occurrence, Severity and Safeguard similar to FMEA but besides, the framework has incorporated some criteria base on which these factors can be evaluated. The structure presented in this work aims to evaluate the risk of these failures using three criteria-Occurrence, Severity, and Safeguard. As these 3-criteria may sometimes appear to be vague, the second level of sub-criteria becomes necessary to make them more specific.

Usually in MCDM emphasis is laid on differentiating between the criteria in terms of perceived importance to set objectives. The difference of perceptions is captured through weighting whereby they are assigned values/weights. Many weighting schemes are rife. These schemes can be broadly classified under qualitative and quantitative methods. Popular amongst the qualitative methods is the Analytical Hierarchical Process (AHP) which derives weight based on pairwise comparison of the Criteria (Saaty, 2008; Zardari, Ahmed, Shirazi, & Yusop, 2015).

Weights can also be derived through the point allocation method (Malczewski, 1999). Another set of evaluation process deals with capturing the preference levels of the Failure modes across the sub-criterion. In recognition of the differences in areas of expertise and level of experiences of the experts, this study encouraged both individual and group participation of the experts in the evaluation process. Individual expert's perception of the performance of alternatives can be captured through framed questionnaires (Maheswaran & Loganathan, 2013). This may further be supported by coordinated group participation (Okoro & Kolios, 2018). Group participation often becomes highly necessary where there is a significant conflict of perceptions in the individual evaluation. In both evaluations, the elicitation of scores is guided by a well-formulated failure rating scale.

MCDA tools are systematically structured in such a way that evaluations (based on decision matrix) allow for comparison and priority order of alternatives. This study utilized Techniques of Ordered Priority using Similarity to Ideal Solution (TOPSIS) for the derivation of priority orders. TOPSIS has an algorithm for prioritization based on positive and negative IDEAL solutions (Maheswaran & Loganathan, 2013; Malczewski, 1999; Saaty, 2008).

2.1 DESCRIPTION OF TOPSIS ALGORITHM

TOPSIS is a traditional multicriteria decision-making method that is predicated on the concept that a selected alternative should have the shortest distance from the positive ideal and the farthest from the negative ideal solution(Khamseh & Mahmoodi, 2014; Triantaphyllou, 2000). The formula to calculate the distance between each ideal point and each alternative is given in Malczewski (Malczewski, 1999) and shown as follows;

***Step (I):* Normalization of Decision matrix**

$$r_{ij} = \frac{v_{ij}}{\sqrt{\sum_{i=1}^{m} v_{i,j}^2}}; \begin{matrix} i = 1,2,3,\cdots,m \\ j = 1,2,3,\cdots,n \end{matrix} \quad (2)$$

Step (II): Weighted normalized values

$$u_{ij} = w_j \times r_{ij} : i = 1,2,3,\cdots,m; \quad j = 1,2,3,\cdots,n \quad (3)$$

***Step (III):* Derivation of A* and A— the positive and negative ideal solutions resp.**

$$A^* = \{u_1^*, u_2^*, \cdots, u_j^*, \cdots, u_n^*\} = \{(\underset{i}{max} u_{ij} | j \in J_1), (\underset{i}{min} u_{ij} | j \in J_2) \quad (4)$$
$$| for\ i = 1, \cdots m\}$$

$$A^- = \{u_1^-, u_2^-, \cdots, u_j^-, \cdots, u_n^-\} = \{(\underset{i}{min} u_{ij} | j \in J_1), (\underset{i}{max} u_{ij} | j \in J_2) \quad (5)$$
$$| for\ i = 1, \cdots m\}$$

where J_1 is the set of benefit attributes and J_2 is the set of cost attributes.

***Step (IV):* Calculation of separation measures i.e., n-dim. Euclidean distance metric**

$$S_i^* = \sqrt{\sum_{j=1}^{n} (u_{ij} - u_j^*)^2} \; i = 1, \cdots, m \quad (6)$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} (u_{ij} - u_j^-)^2} \; i = 1, \cdots, m \quad (7)$$

$$0 \le C_i^* = \frac{S_i^-}{S_i^+ + S_i^-} \le 1; i = 1, \cdots, m \quad (8)$$

Step (V): Choose the alternative in the decision matrix with the maximum C_i^* and rank the alternatives from most-to least-preferred in descending order. AHP is a structured process used to derives judgment of the weight of each criterion by comparing each against the others one at a time. The judgment is usually expressed in linguistic terms, often gathered through questionnaire surveys or/and interviews (Perera & Sutrisna, 2010). The linguistic variables are then converted to numerical values based on AHP absolute fundamental scale (Saaty, 2008). A typical AHP scale is shown in Table 1. Preferences for AHP are often based on its well-structured approach for weight computation that accommodates both qualitative and quantitative criteria and capability for consistency check of results.

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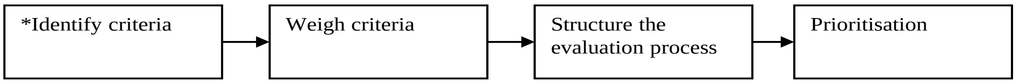

*Criteria identification may be identified through three steps [14]: 1) Identify objectives, 2) identify components of the system and functions (available in assets portfolios), 3) identify the uncertainties that matters

Fig. 1: Schematic of the methodology

Table 1: SAATY scale for AHP evaluation

Scale of importance	*Crisp score*
Equal importance	1
Moderate	3
Strong importance	5
Very Strong importance	7
Extremely preferred	9
Intermediate values	2,4,6,8

2.2 INDICATIVE CASE STUDY

For the indicative case study presented, the methodology is applied to a Jacket support structure for an offshore wind turbine. This structure consists essentially of Sub-structure which suspends Superstructure components: Blades, Tower, and Turbine nacelles. The Sub-structure (also known as the Jacket structure) is tower-like braced steel tubular structures that; keep the supper structure in a stable position clear of the waves and support laterally appendages- boat landing, staircase, etc.

2.3 COMPONENTS OF A JACKET PLATFORM

Jacket Structure: this is the part of the platform that supports the topsides and is generally submerged below the waterline. It is mainly designed to resist wave loads. *Transition Piece*: is a structural member in the form of a cone that links the turbine tower and the jacket structure (the leg). *Conductors*: they are long hollow straight or curved tubes that are embedded into the seabed through which electrical wires pass. They are usually provided with frames as a lateral support guide. Boat landing, Barge bumper, and riser guards: these components are required for berthing of supply vessels. *Launch truss*: are provided on one side of the jacket to facilitate the loading out on the barge. The launch trusses help in skidding the jacket from the barge to the sea at the site of installation. *Mud mat*: Mud mat is the bottom-most framing of the platform that helps the structure maintain stability against lateral forces from current and wave before piles are driven through the legs. Besides, it helps the platform to sink deeper in situations where the soil is too soft near the top layer of the seabed. In general, it provides adequate resistance to overturning. The diagram of the jacket support structure for an offshore wind turbine is shown in Fig. 3.

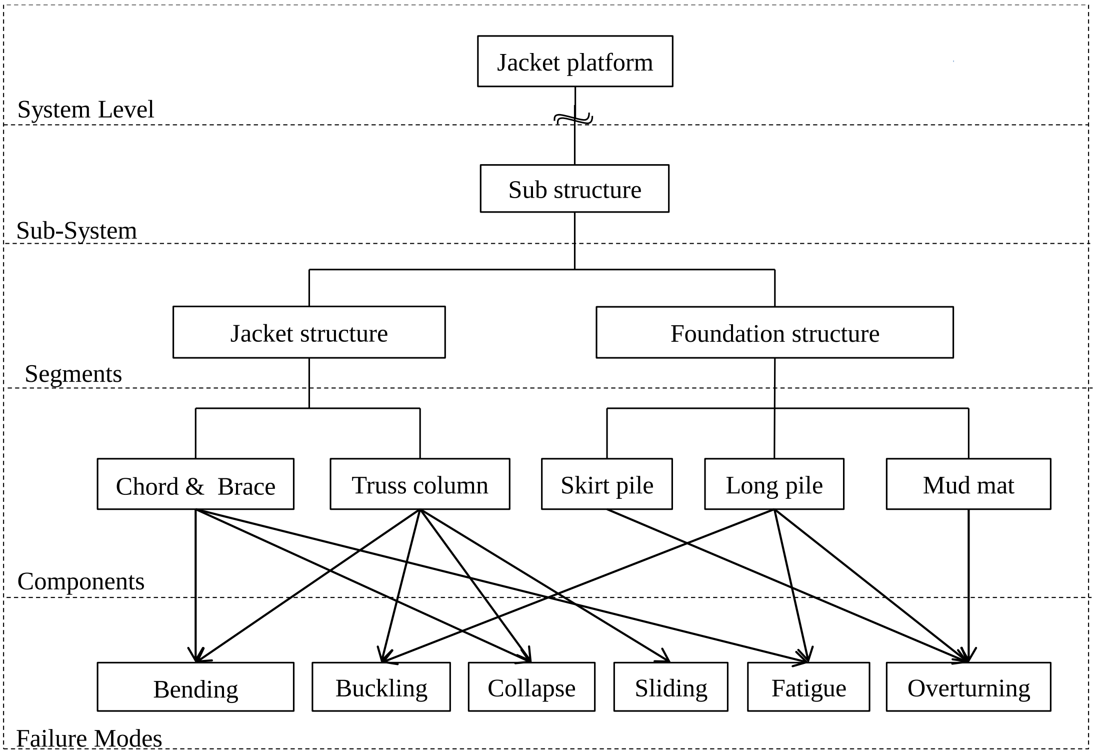

Fig. 2: Hierarchical structure for Offshore Wind Turbine Support Structure

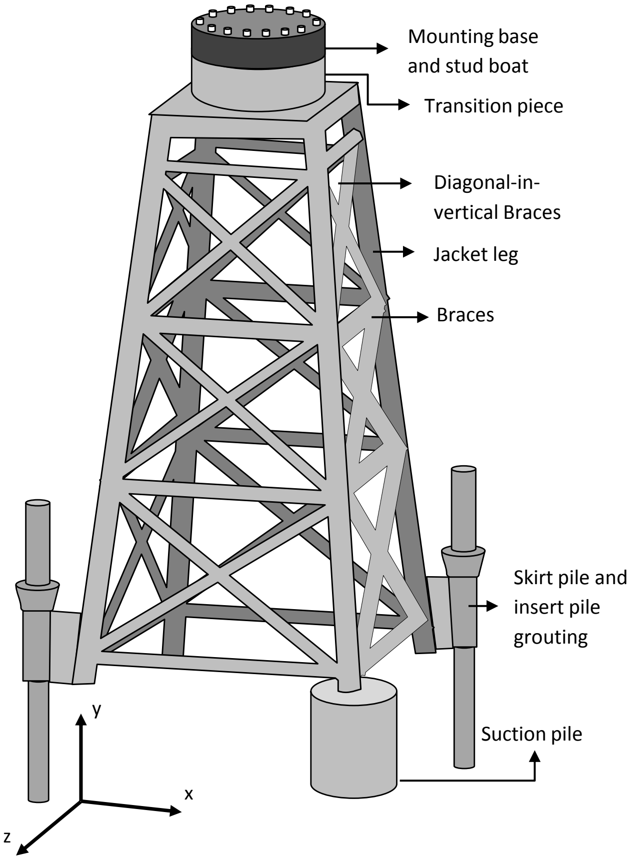

Fig. 3: Offshore Wind Turbine Support Structure

The Jacket structure (of Fig. 3) is broken down in hierarchical order from sub-system (higher) level to components (lower) levels as depicted inFig. 2: a form it is concieved much easier for the identification of failure modes (Ersdal, 2005). The list of identified failure modes includes; bending of Chord/Braces (A1), Bending of Truss (A2), Buckling of Truss(A3), Buckling of Long Pile(A4), Collapse of Chord/Braces(A5), Collapse of Truss Column(A6), Sliding of Truss column(A7), Fatigue of Chord/Brace(A8), Fatigue of Long Pile(A9), Overturning of Skirt Pile(A10), Overturning of Long Pile(A11), Overturning of Mudmat (A12).

2.4 CRITERIA: IDENTIFICATION AND EVALUATION

In the case study presented, the objective of the exercise is, in parts, achieving through-life fit-for-purpose conditions of the structure under a strict performance budgeting environment. The approach adopted is to identify and focus the limited resources on the high, and as such, priority risks. At the top level of consideration, the criteria: Occurrence, Severity, and Detectability (Ioannis, Theodoros, & Nikitas, 2012) are identified as capturing these objectives. However, in the practice proposed herein these criteria are further broken down into parameters to account for the various conditions of the components at which operation may be considered unsafe, yet, often neglected when only S.O.D criteria are considered. For example, the occurrence criterion is further supported by interval (between each incident), the load and depth in relation to the environment of occurrence and operation condition (which could be normal or extreme) at the instance of occurrence. The consequence criterion is explained from the perspective of cost and having direct and indirect dimensions to cost.

Many of the parameters had been identified through a face-to-face interview session that explored “factors that could lead to a preference for a failure mode in a situation where both (failure modes) have the same impact on the criterion (Figueiredo & Oliveira, 2009).” Figure 4 presents the criteria, factors and their respective weights (in parenthesis). TOPSIS algorithms execute criterion scores either as benefit or cost functions. From what that has been presented as objectives of the study, it can be deduced that the orientation of the benefit criteria is towards the “high-risk” failures. That is the high values of these criteria tend towards high-risk estimates. The implication is that it is only the Detectability criterion parameters that have opposing orientation, as such is the cost criteria, while the Occurrence and Severity parameters are benefit criteria.

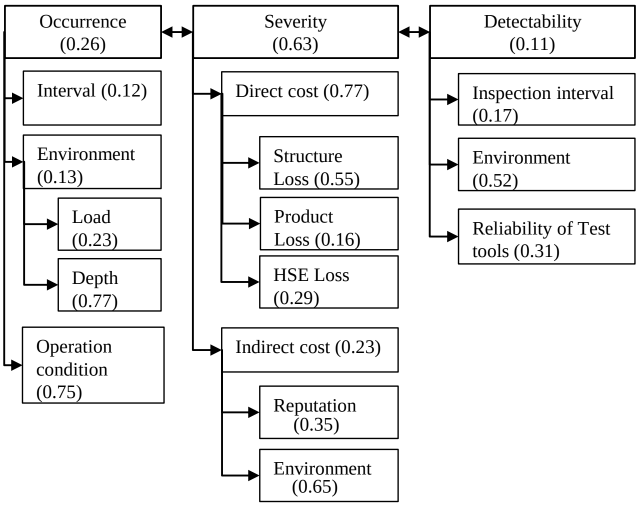

Fig. 4: Parameters of Occurrence Severity and Detectability

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Table 2. Decision matrix.

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**
(Wgt)	(0.03)	(0.01)	(0.03)	(0.20)	(0.27)	(0.08)	(0.14)	(0.05)	(0.09)	(0.01)	(0.02)	(0.06)	(0.03)
A01	6.5	9.3	2.3	2.1	9.2	1.2	2.8	2.6	2.5	3.6	2.2	4.6	3.6
A02	7.6	8.5	8.5	9.2	5.4	1.4	4.2	3.8	6.2	5.5	4.2	3.8	2.8
A03	1.5	7.5	3.2	9.1	9.3	1.4	6.7	2.5	6.7	7.5	2.8	4.2	6.5
A04	1.7	6.8	3.5	1.3	5.2	9.3	2.5	6.2	9.1	8.7	6.2	8.5	7.5
A05	8.2	3.5	6.8	9.3	5.1	9.2	3.5	3.5	3.5	3.2	5.2	8.5	7.5
A06	2.5	1.5	3.2	9.3	9.1	9.4	8.7	8.7	8.5	7.8	6.5	7.2	6.5
A07	7.5	3.5	8.4	9.5	5.1	1.2	8.8	3.5	8.2	9.5	3.5	2.8	1.5
A08	2.5	7.3	4.5	9.2	5.1	1.3	5.3	3.7	2.8	1.7	5.3	7.4	8.2
A09	3.2	8.1	1.5	1.2	5.3	1.2	2.5	8.2	6.4	3.2	3.1	5.7	4.7
A10	1.6	4.6	8.7	9.1	5.3	5.2	8.7	2.6	4.2	4.5	4.3	5.7	5.1
A11	1.2	9.0	6.7	1.3	9.2	9.3	7.3	6.0	5.7	7.5	8.0	6.3	8.7
A12	4.0	3.4	5.0	1.2	5.3	9.2	3.0	3.1	4.2	3.6	8.2	5.0	3.3

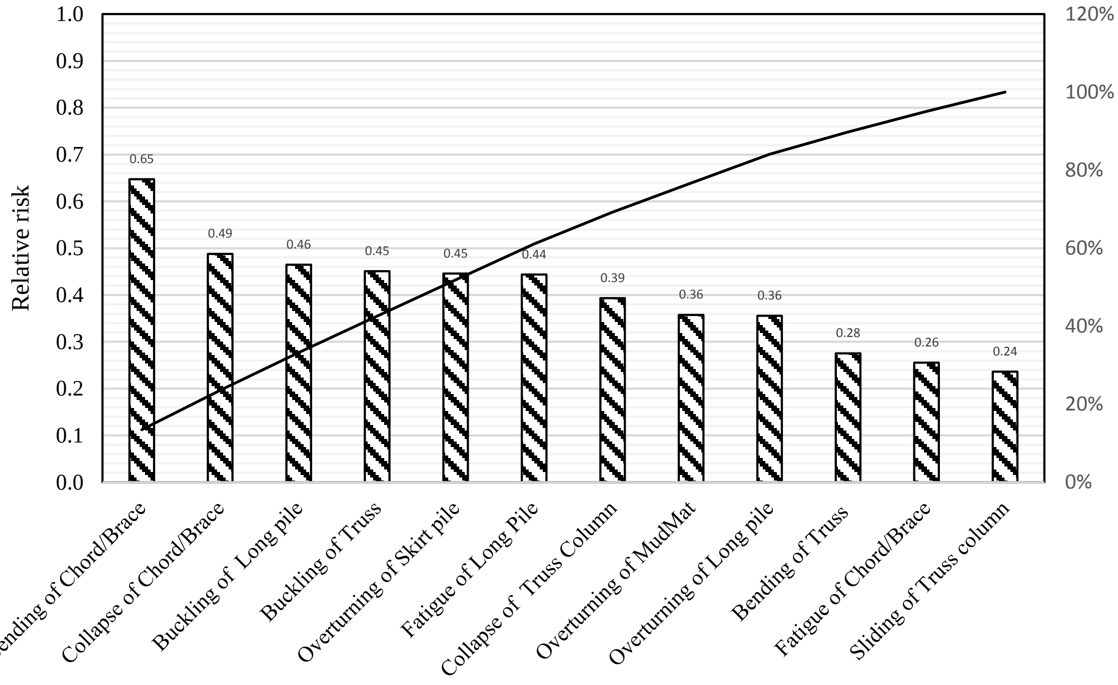

Fig. 5: Risk index of Failure modes

3 RESULTS AND DISCUSSION

The decision matrix formed from the aggregated scores of individual DM's evaluations is shown in Table 2 and the resulting ranking of the failure modes is presented in Table 3.

Table 3. Failure mode Ranking

Failure Mode	*P. I*	*Rank*
Bending of Chord/Brace	0.65	1.00
Bending of Truss	0.45	4.00
Buckling of Truss	0.45	5.00
Buckling of the Long pile	0.26	11.00
Collapse of Chord/Brace	0.44	6.00
Collapse of Truss Column	0.49	2.00
Sliding of Truss column	0.46	3.00
Fatigue of Chord/Brace	0.36	9.00
Fatigue of Long Pile	0.24	12.00
Overturning of Skirt pile	0.39	7.00
Overturning of the Long pile	0.36	8.00
Overturning of Mud Mat	0.28	10.00

Fig. 5 shows the plots of the risk indices (represented here by the heights of the bars) of the twelve failure modes and cumulative risk indices. The analysis identifies six target failure modes that constitute over 60% of the total risk content of the identified 12-failure modes. It should be noted that the result of the analysis is unique/peculiar to the conditions captured during the analysis and should not be used out of context as the plant's conditions may vary over the cause of operation and time. However, this model provides the opportunity for scenario forecasting which allows information on plant's conditions to be updated with the current and future inspection findings thus giving it the required flexibility (beyond the traditional FMEA). More so, having a record of the plant's conditions together with conclusions of risk assessment makes the decision making retraceable: another feat that cannot be achieved with traditional FMEA.

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4 CONCLUSION

This work reports an application of Multi-Criteria Decision Analysis in risk assessment of offshore structures. The analytical prowess of AHP and TOPSIS are combined in the development of robust/structured model for performing prioritization of Component's Failure Modes. Such conclusions find application in support of critical decisions such as maintenance decisions. The procedure begins with the identification of Failure Modes, (which is based on suggestions from an extant literature review and expert's opinion) and evaluation criteria, followed by preparation and evaluation of questionnaires for the derivation of criteria weights and decision matrix.

A salient aspect of the work is the consideration of Condition-dependent parameters of the main criteria which reflects the true-state of the structure. Prioritization of the component failure mode is achieved through a hybrid process involving Experts knowledge, AHP and TOPSIS that explored comparative judgments of impacts (both beneficial and non-beneficial) of these Failure Modes on the integrity of the structure captured using an array of criteria hence provides order according to the significance of the risk.

The method was demonstrated on a jacket support structure for offshore wind energy turbines. The analysis identified five significant failures of the structure as "Bending of Chord/Braces, Collapse of Chord/Brace, Buckling of the Long pile, Buckling of Truss and Overturning of Skirt pile." Classification of significance (which can be context-dependent) has been defined for failure modes with a priority index that is greater than 0.4. This result proves well with the experiences of offshore industry experts involved in the analysis. However, there is a need to improve on the way of deciding the values of input to the final decision matrix beyond the use of average score; a method that does not always represent the distribution of the elicited scores per failure mode per criteria. Possibility of considering such input as a stochastic distribution bounded by a range of the elicited scores by the experts, so that the result of the ranks will be expressed as a probability is to be explored with application extending to offshore oil and gas systems.

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