Developing a Risk Analysis and Decision Making Strategy for an Offshore Wind Farm

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Abstract

The renewables sector and particularly offshore wind energy is a fast developing industry over the last few years. Especially activities related to the Installation, Operation and Maintenance (O&M) of offshore wind turbines becomes a challenging task with inherent risks. This paper assesses the risks related to the above stages of a wind farm lifecycle using the FMECA (Failure Mode, Effects and Criticality Analysis) and HAZID (Hazard Identification) methods. All works, from installation to O&M are considered together with the wind turbine main components. An integrated risk analysis methodology is presented addressing personnel Safety (S), Environmental impact (E), Asset integrity (A) and Operation (O). The above is supplemented by a cost analysis with the aid of BBN (Bayesian Belief Networks) method in order to assist the decision making process related to installation and O&M tasks. All major risks and critical wind turbine components are identified as well as measures are suggested in order to prevent or mitigate them. Moreover, inspection and maintenance plans are elaborated in general for the mentioned activities.

Introduction

Wind power is known to humans since ancient times. It is a form of energy that not only has no time or place restrictions but it also contributes in reducing greenhouse gases emission and boosting the economy of countries that depend on oil and gas imports for the energy coverage [1]. These characteristics makes it appealing to industry that tries to exploit it by developing more and more onshore or offshore wind farms [2].

The rapidly expanding number of wind farms makes quantifying and managing the different elements of risk that are present in each of the installation, operation and maintenance stages of a wind turbine necessary. In this respect, risk analysis and decision making can be a key that will enable fast growth, investments, further technological development and reasonable cost of energy.

This paper presents the study regarding the investigation and assessment of the risk and reliability features of offshore wind turbines at different stages of its lifetime and identification of the critical components in terms of their operation in order to increase their availability and operability characteristics. A lot of risk analysis methods formerly or currently used in the offshore renewables and oil and gas sectors is examined as shown in section 2. The description of wind turbine and the demobilization of its components is demonstrated comprehensively in section 3, as well as the overall risk analysis methodology, including the HAZID and FMECA approaches, which are complemented with risk matrices for various consequence categories. Also, the cost benefit analysis with BBNs is presented in the same section. In Section 4 the outcomes of the analyses and the simulations are submitted highlighting the possibe high-risk areas and the most costly components. Finally, conclusions and recommendations for future research on the current study are shown in section 5.

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Literature review

Risk is defined in a different way by each one of us so there is not a universal definition of "risk". Generally it includes a combination of probabilities of occurrence and consequences of an unwanted outcome [3, 4, 5, 6, 7, 8]. Consequences can be loss of life, injuries, environmental, social and economic impacts [8, 9, 10, 11, 12]. Other views focus on both positive and negative aspects of risk[7, 8,13,14] and argue that one should not eliminate the other.

Hazard, is associated with risk but they are not the same. According to WHO [5] hazard is the "Inherent property of an agent or situation having the potential to cause adverse effects when an organism, system, or (sub) population is exposed to that agent". Similarly, [8, 11, 12, 15, 16, 17] describe hazard as situation likely to cause harm, injuries and damage. So while "hazard is any source of potential damage, harm or adverse health effects on something or someone under certain conditions", "risk is the chance or probability that something or someone will experience an adverse effect if exposed to a hazard" [18].

A probability is the way we have to express quantitatively the likelihood of an event or consequence to happen. According to past papers [6 , 7, 8, 11] probability can be either a subjective measure of uncertainty if it comes from expert's judgment, or a classical statistical approach. Determination of a probability and decision making in each case involves a certain degree of uncertainty that derives from our lack of important information [8, 10, 18, 19]. Decision makers face uncertainty when either the probabilities or the consequences are unknown or there are multiple outcomes for each alternative and that is the difference with risk, since risk exists when we know all the consequences but not which will definitely occur [8, 10, 19, 20, 21, 22].

The subject of risk analysis, risk assessment and risk management in general is a relatively new but extensively explored area with various studies contributing to its thorough examination. Effective risk mitigation is desirable by all individuals and companies, and risk management is or should be applied to all stages of a project lifetime [67]. Especially in the maritime and offshore industry the aim is to reduce the risks from major hazards that could jeopardize the integrity of the offshore structure and the health and safety of the workforce and ensure the protection of the environment [23, 68]. The correct identification of the hazards and their consequences is a key issue in providing information to aid decision making and increase the level of a project success. Thus there are many tools, processes, techniques and methodologies developed nowadays to cover this need.

Some of the main standards for risk management are those: Australian Standards/New Zealand Standards: 4360 2004, Association for Project Management [16], Project Risk Analysis & Management (PRAM) Guide 2nd edition [57], Project Management Institute [61], Guide to the Project Management Body of Knowledge (PMBoK): Chapter 11 [61], ISO/ IEC 31010:2009 [63] Standards and many more.

More specifically for offshore oil and gas industry, HSE introduced the Safety Case approach in 1992 [24], in which guidelines are given to operators of each offshore installation field for "reducing the risks from major accident hazards to the health and safety of the workforce employed on offshore installations or in connected activities". After that, many standards and codes have been established the last years as guidelines for this purpose. Although they refer mainly to oil industry they can have a good application on wind industry. The most important of them are from ISO [15], HSE [24], DNV [25, 26], IMO [27], ABS [28], OREDA [29] and Norsok [30].

Apart from standards there are various software tools for risk analysis valuable for the industry based on a quantitative approach of risk assessment. These are RBM (Risk Based Management) II released from the Dutch Government, PHAST and Synergi Life Risk Management from DNV GL, SHEPHERD a software property of Shell Global Solutions, RISKCURVES that is an integrated QRA software from TNO, EFFECTS that is a consequence analysis and damage calculation software from TNO, HAMSAGARS which is a QRA software from HAMS-GPS, RISKAN and many more [62].

The most known techniques of hazard identification are Expert Judgment, Check Lists and the structured techniques HAZID (Hazard Identification), PHA (Process Hazard Analysis), What-IF Method, FTA (Fault Tree Analysis), ETA (Event Tree Analysis), FMEA/FMECA (Failure Mode, Effects and Criticality Analysis), HAZOP (Hazard and Operability), Monte Carlo Simulation and Risk Ranking Matrix [31]. All of them can be applied in our area of interest;

offshore installations and more specifically offshore wind farms, with FMECA and HAZID, the two methods that are used in this study, being two of the most popular.

After all the necessary information about possible risks is gathered, risk evaluation is executed. The most well-known method of risk evaluation is ALARP (As Low As Reasonably Practical). The idea in this method is that the risk should be minimized to a point where it is acceptable but without expending grossly disproportionate cost, time and effort [32]. Regarding decision making, in the frame of risk mitigation and ALARP, one of the strongest tools that decision makers have to deal with the problems raised is Bayesian Belief Networks (BBNs) a tool for modeling under uncertainty by using conditional probabilistic calculations and graphical representation of the logical relationships between variables.

Risk management process in general, includes setting up the context, assessing the risk (hazard identification, risk analysis, and risk weighing), handling the risks, monitoring, communication and consultation, as well as the connection between these procedures. The efficiency of Risk management depends on the selection of the risk method. The suitability of each method depends on its strengths and weaknesses and on the needs of the project. Usually, two or more methods are combined in order to cover all stages or needs of a project's lifecycle and each other's weaknesses and flaws. This procedure has also been followed here. HAZID cannot support much detail and it is usually used for operational procedures. FMECA's complexity and the ever-increasing list of possible failure modes of the components make it difficult to be widely applied. A spherical and general overview though of both mechanical and operational aspects of an offshore wind turbine can be obtained when combining these two methods. Additionally, a financial perspective on the cost of critical components and their failure probabilities can be assessed through BBN analysis.

FMEA/FMECA-HAZID

FMEA is one of the first systematic techniques used to identify problem that may originate from system malfunctions. The concept of FMEA is reviewing all the components of a system and the causes or the ways in which a system can fail (Failure Mode) and then the consequence of these failures. The consequences can be categorized in terms of safety, reliability and environmental effect [8, 11, 17, 33, 34]. FMECA (Failure Modes, Effects. and Criticality Analysis) is the extended model of FMEA, so that criticality is taken into account. It is mainly used to rank the failure mode based on the severity of their consequences. FMEA/ FMECA are usually qualitative or semi-quantitative, and can be applied at any phase of project life cycle preferably at the early stages of a project since the designers can have the ability to change the probabilities of the critical failures [8, 33]. FMECA was originally part of risk management techniques developed for defense and nuclear industries in the 1940's. It was formally developed and applied by NASA in the 1960's to guarantee reliability of space program hardware and was quickly adopted by aerospace, petroleum, chemical and automotive industries [35].

FMEA and FMECA typically consist of several stages. Definition of the system components is the first step of the analysis. Then, identification of each component's failure mode as well as their effects is the next crucial level to the FMEA/FMECA approach. Next important step is analyzing the criticality of each failure and also estimating their rate. Ranking of failure modes and determination of critical items is another important stage of the procedure that due to the subjectivity of the applier a lot of attention and thorough review of the parameters need to be implemented. Design process then absorbs the method's results and helps identifying means of future reviewing and suggesting improvements in design.

Depending on the analysis we want to conduct a proper FMECA worksheet has to be formed. A representative worksheet is presented below where the name, function and operational mode of each element is mentioned and also all potential failure modes for each function and operational mode. Also, the failure mechanisms (corrosion, erosion, fatigue etc.) for each failure mode have to be listed and their acceptance criteria have to be chosen. Before the final decision of the criteria categories, a lot of reviews and papers were taken into consideration. Main references were IMO and ISO sources on the development of risk matrices, FSA applications and nuclear projects, where number of cases is small and technology may be obsolete but due to catastrophic consequences their outcomes must be taken into serious consideration. After thorough review we finalized our matrices as below [15, 23, 27, 36]:

The likelihood of their detection was evaluated with a ranking that is usually divided into five categories: 1 (almost impossible), 2 (low), 3 (moderate), 4 (high), 5 (almost certain). The effects that a failure may have on the subsystem itself

or on other components as well as failure rates should also be listed and classified most commonly to a five-level ranking: 1 (higly unlikely), 2 (remote), 3 (occasional), 4 (probable) and 5 (very frequent). The severity of the failure modes regarding the global effects has to be evaluated and ranked into five categories that in most cases, for computational reasons, are represented from numbers 1 to 5 representing: 1 (minor), 2 (marginal), 3 (major), 4 (critical) and 5 (catastrophic). It can be assumed here that categories are related with 1 fatality to equal 10 major injuries and 100 minor ones. Finally, mitigation measures that could prevent failure should be mentioned.

The risks linked to failure modes is a function of frequency of the failure mode and consequences of the outcomes and can be presented in the form of a risk ranking matrix to prioritize those that need immediate management.

An alternative to risk ranking matrix is the risk priority number (RPN) which is defined as:

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

Where

S is the rank of severity of the failure mode taken from the severity matrix

O is the rank of occurrence of the failure mode taken from the occurrence matrix

D is the rank of detection of the failure mode taken from the detection matrix

The RPN is not a measure of risk, but of risk priority. The smaller the RPN is the better since you can deal with this hazard later. Based on these two tools the responsible team should decide whether the system is acceptable or not and propose improvements that will reduce the likelihood of occurrence of failure, reduce the consequences of failure or increase the failure detection probability. After the improvements the FMECA worksheets and RPN have to be revised and updated [37].

The main drawbacks of FMECA method is the limitation in examination of human and other external factors, as well as focusing on a single initiating event and on the mode of operation. Furthermore, analysis is mainly based on team experience on evaluating the failure modes of the components inducting subjectivity in the procedure [38].

HAZID is one of the most common and frequent used techniques for hazard identification being carried out at the first stages of a project where not much detail is required [8, 11]. In HAZID the process is divided into nodes and with the aid of pre-defined guidewords for hazard identification, all undesirable consequences associated with the defined node are identified. Consequences are divided into broad categories such as human impacts, environmental impacts, and economic impacts that are then divided in subcategories based on the type of consequence. Checklists from previous similar HAZID can be used to assist the procedures. The same methodology as the FMECA is followed and risk matrices are constructed as well. Its application is wide: from marine and offshore industries to nuclear sector.

Since HAZID is applied to all aspects and operations and a complete evaluation of all hazards is performed, an extended list of potential hazards and recommendations for avoidance is produced. To this respect a well-defined system or activity is required in order to minimize time needed for the analysis [38, 39].

HAZID's in depth and time consuming analysis can counterbalance any omissions that can come of analysts' lack of experience as in the case of FMECA. Also, since FMECA covers mainly equipment failure modes and effects, HAZID comes to fill the gap in safety related studies.

BBN

Reasoning with uncertainty is common in all aspects of everyday life, so dealing with it has forced scientists even from sixteenth century to develop several approaches such as the frequentist or the subjective Bayesian that was widely adopted in more recent years. Bayesian Belief Networks (also known as Belief Networks, Causal Probabilistic Networks, Causal Nets, Graphical Probability Networks and Probabilistic Cause-Effect Models) were first developed in 1980s and they are based in statistics and artificial intelligence and they provide a simple way of building a "picture" of a decision

problem. They make a framework for decision support that takes into consideration variables with unknown state and influence on outcomes. So it is basically a tool for modeling under uncertainty by using conditional probabilistic calculations and graphical representation of the logical relationships between variables. This method is a more flexible tool than other methods (FTA, DFTA ETA etc.) as it can combine objective and subjective data like expert judgment and can resolve some disadvantages that more traditional methods have as intrinsic limitations such as system and component interconnectivities in multiple layers so that they simulate real state conditions, fault detection and system degradation. [40, 41, 42].

The approach is based on conceptualizing a model domain of interest as a graph of connected nodes and linkages. In the graph, nodes represent variables ($X = X_1, \dots, X_i, \dots, X_n$) and arcs represent direct connections between them ($X_i \rightarrow X_j$). Probabilistic relations rather than deterministic are used to describe the dependency relations [42].

The construction of a BBN is simple but as the variables increase in number, the complexity rises. Figure 1 shows the logical relationship between five hypothetical variables A through E. D is called parent or predecessor of B. Equivalently B is called a child or descendant of D. The arrow illustrates that the parent node has a direct influence on the child node. D and E do not have any parents and are called root nodes. A does not have any descendants and it is called leaf. The conditional probabilities are specified for each node to represent the influence of the parent nodes on its value using the chain rule from probability theory:

$$P(A, B, C, D, E) = P(A/B, C, D, E) \cdot P(B/C, D, E) \cdot P(C/E) \cdot P(E) \cdot P(D)$$
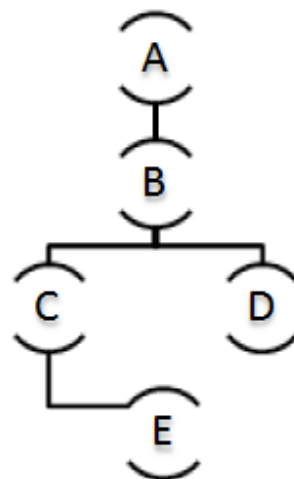

Figure 1a. Schematic BBN diagram.

 Thus, the BBN structure represents the independence between the variables by using conditional probabilities that represent the degree of belief in these relationships [40]. Main advantage of this method is the comprehensible graphic display of interrelation of examined system and failure modes.
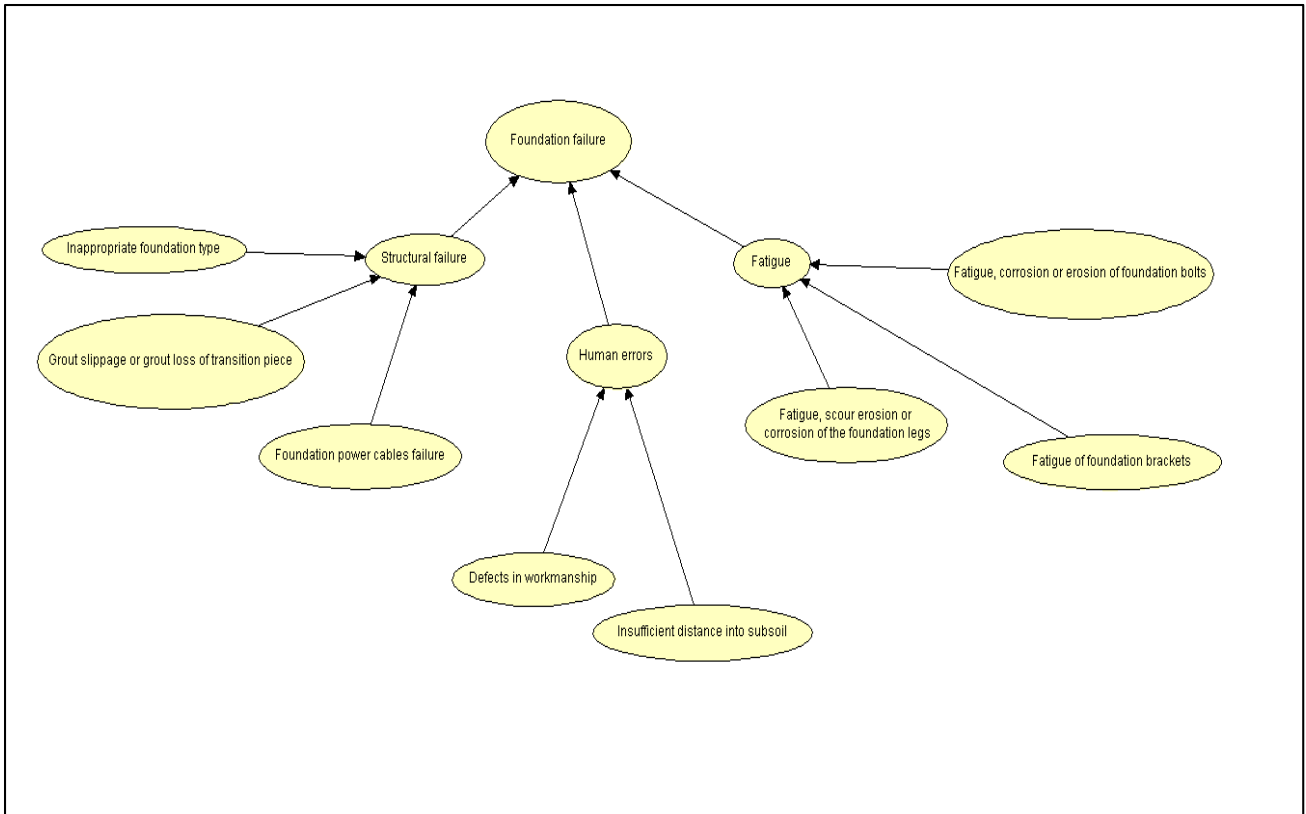
Figure 1b. BBN diagram showing possible failure causes of a wind turbine's foundation.

BBN construction has four stages: The first two stages are problem structuring. In these stages, the variables are identified and expressed as statistical variables, and the network structure is decided. The third stage is instantiation. In this stage, the conditional probabilities that may be derived from data or based on expert judgment are specified and the assessment functions are determined. The fourth stage is inference. In this stage, evidence in the form of knowledge about the states of the variables, is used to update the probabilities of all nodes by efficient algorithms. This procedure is called propagation and it can be quite difficult to perform as exact propagation is only feasible for small networks or discrete variables. Approximation algorithms though have been developed for larger networks and continuous variables [41].

Offshore renewable energy sector has seen numerous developments in the last few years as shown above, and undoubtedly has a promising future. Keeping this in our mind a risk analysis methodology suggested for implementation on a wind farm is presented in the next section.

Methodology

In this section, a flowchart with the suggested risk analysis methodology is shown in Figure 2.
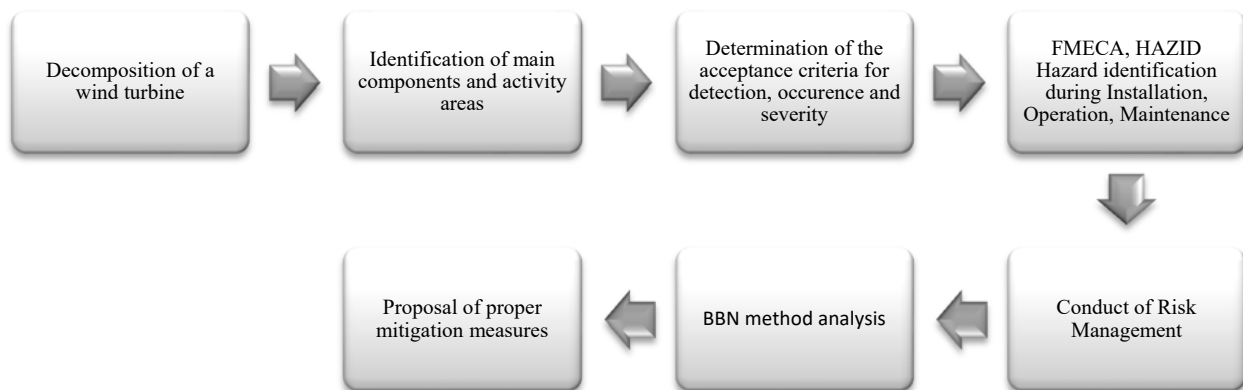
Figure 2. Methodology flow chart.

The first step is to decompose a wind turbine and identify its main components as well as the activity areas that we are interested in. The next stage is the determination of the acceptance criteria, so that the results of the risk analysis are compared with some predefined standards. After this stage, the risk analysis' main part takes place. At first hazard identification and hazard assessment is done. Then the risk management is conducted, where the potential hazards have to be eliminated or prevented from occurring. Also, BBN analysis was used to identify the most costly components in case of failure. Finally, a number of proper pro-active measures are proposed in order to mitigate the effects.

More specifically, after the first step a set of sixteen sub-assemblies and main parts was extracted (Table 1).

Table 1. Components of a wind turbine.

Systems	Components
Brake system	Brake disk, Spring, Motor
Cables	
Gearbox	Toothed gear wheels, Pump, Oil heater/cooler, Hoses
Generator	High speed shaft, Bearings, Rotor, Stator, Coil
Main frame	
Main shaft	Low speed shaft, High speed shaft, Bearings, Couplings
Nacelle housing	Nacelle
Pitch system	Pitch motor, Gears
Power converter	Power electronic switch, cable, DC bus
Rotor bearings	
Rotor blades	Blades
Rotor hub	Hub, Air brake
Screws	
Tower	Tower, Foundation
Transformer	Controllers
Yaw system	Yaw drive, Yaw motor

Later on, the activity areas that we are interested in are identified and more specifically installation, operation and maintenance of an offshore wind turbine. Keeping these in mind we can now proceed with the risk identification using FMECA and HAZID methods.

With the FMECA we identified the most critical components of a wind turbine since this method reviews the ways in which a system can fail and then the consequences of these failures. As mentioned in previous chapter, consequence, detection and probability Tables are established outlining the various levels of rankings as presented analytically in Tables2,3,4.

Table 2. Detection matrix [23].

Detection	Criteria: Likelihood of Detection by Design Control	Ranking
Almost impossible	Design control will not and/or cannot detect a potential cause/mechanism and subsequent failure mode; or there is no Design control	5
Low	Low chance the Design control will detect a potential cause/mechanism and subsequent failure mode	4
Moderate	Moderate chance the Design control will detect a potential cause/mechanism and subsequent failure mode	3
High	High chance the Design control will detect a potential cause/mechanism and subsequent failure mode	2
Almost Certain	Design control will almost certainly detect a potential cause/mechanism and subsequent failure mode	1

Table 3. Occurrence matrix [23].

Probability of Failure	Possible Failure Rates	Ranking
Very frequent: Failure is almost inevitable	From >= 1 in 2 To 1 in 3	5
Probable: Repeated failures	From 1 in 8 To 1 in 20	4
Occasional: Occasional failures	From 1 in 80 To 1 in 400	3
Remote: Relatively few failures	From 1 in 2000 To 1 in 15000	2
Highly unlikely: Failure is unlikely	From 1 in 150000 To <=1 in 1500000	1

Table 4. Severity matrix [23].

Severity class	Description				Ranking
	Personnel safety	Environmental impact	Asset integrity	Operation	
Minor	No injury	No damage/contamination	Negligible damage < 2k £	Minimal operation loss	A or 1
Marginal	Minor injury (first aid)	Minor damage/spillage, good effect of control measures (a few days)	Minor damage 2k - 20k £	Short operation loss (few hours)	B or 2
Major	Multiple minor injuries, major injury	Major damage/pollution, low effect of control measures (a few days to a month)	Localised damage 20k - 100k £	Minor replacement needed (operation loss < 1 day	C or 3
Critical	Multiple major injuries	Critical damage/pollution, minimal effect of control measures (more than a month)	Major damage 100k-3m £	Major repair needed (operation loss 1 day-week)	D or 4
Catastrophic	1 or more fatalities	Significant environmental impact, massive pollution (more than a year)	Damage >3 m, total loss	Total operation loss, replacement	E or 5

The Risk Priority Number (RPN) can now be calculated as a product of the probability index, the detection index and the severity index. In this way the risk levels that came out of the possible outcomes and vary from low to high are illustrated with a range of different colors as in Table 5.

Table 5. Risk index table.

Risk index table
Low Risk(negligible)
Moderate Risk (tolerable)
Significant Risk(specific measures to be taken)
High Risk (intolerable)

The consequence, probability and detection indexes are reviewed in terms of Personnel safety (S), Environmental protection (E), Asset integrity (A) and Operation of the device (O). Consecutively risk and RPN indexes are calculated in the same terms. Finally a risk matrix is formed as shown in Figure 3 where the potential risks and failure modes of the sub-assemblies are identified.

The HAZID method is used to identify the potential hazards during manufacture, transportation, installation, operation and maintenance. These hazards can be linked to the turbines, such as lifting operations and occupational dangers, or

indirectly, for example bad weather or fire. We repeat the same procedure as in FMECA method with the difference that a Risk Index instead of the RPN Index is now calculated. The form of the matrix is used shown in Figure 4.

All direct as well as the indirect hazards of above activities are analyzed for a better understanding of all the potential risks involved. Direct hazards concern those directly related to the wind turbine such as operation of ROVs (Remotely Operated Vehicles), underwater installation etc. Indirect hazards concern the ones related to the overall installation activity including the assisting vessels and crew (e.g. electrical shock, pollution, bad weather, etc.).

Risk management comes after the identification and assessment of the potential hazards. Risks on top of ranking have to be dealt with either by designing them out in the initial stages of a wind turbine by preventing them to occur or by alleviating the effects in case they occur. Finally and most importantly pro-active measures and emergency response actions for preventing reoccurrence should be taken. Finally, a cost benefit analysis of the repair costs based on the output of the risk assessment will be carried out. This will be done using Bayesian Belief Networks with the aid of HUGIN software.

The novelty of this thesis lies in the combination of three different methods for risk analysis and criticality identification. The integration of these risk assessments approaches, attempts to eliminate the drawbacks of each one as mentioned above and aid decision making in planning and implementing. Pairing HAZID and FMECA methods in the first stage of risk analysis makes our approach more comprehensive since it takes into consideration both the mechanical and the operational aspects of an offshore wind turbine, something that each method individually cannot do. In addition, using BBN analysis gives us the opportunity not only to identify the most costly components but also compare the results with the other two methods regarding the most critical components and their failure probabilities. Also, BBN method enables us to show dynamic interrelation between parent and child nodes in an effective, fast and direct way. Its graphical way of representation depicts effectively all system and components and their correlation.

Results

In this section the results of the FMECA, HAZID and BBN analyses are shown. It is important to mention that for the presentation of the highest-ranked critical components and hazards that originated from the FMECA for Risk Index are mentioned but also those with lower indices but severe consequences like multiple injuries, fatalities or collapse of the systems.

FMECA Results

For the identification of the most critical components we valued each of the components' failure causes with regards to detection, consequence and probability of failure for all four categories of interest. Taking as an example the pitch motor overloading,, one of the most common failure causes based on past research, we can explain the ranking procedure more efficiently. Regarding Asset we valued consequence with 4, since a shutdown of the turbine would have major impact on the energy production. For the same category we valued probability with 5 since overloading is a common incident, not only due to sensitivity of electrical parts but also due to high winds common in offshore areas. Also due to presence of sensors that can easily detect a fault we ranked detection with 2. By taking their product we calculate the RPN for this failure mode for Asset category:

$$RPN = A_C \times A_P \times A_D = 4 \times 5 \times 2 = 40 \tag{2}$$

Consecutively, we calculated all RPNs for the other three categories for this failure mode of Pitch system and in this respect for all components accordingly.

After ranking the components in terms of Safety, Asset, Environment and Operation, based on their RPN, as shown in Figure 3, we can summarize the results in one total ranking of components (Table 6, 7):

Table 6. FMECA analysis-Ranking of components in terms of Asset, Safety, Environment and Operation.

Ranking in terms of Operation	Max RPN
Pitch system	40
Rotor blades	24
Power generation system	20
Cables	18
Gearbox	18
Tower	16
Foundation	12
Main frame	12
Transformer	12
Yaw system	12
Rotor hub	12

Ranking in terms of Safety	Max RPN
Tower	16
Foundation	12
Cables	12
Rotor blades	12
Rotor hub	12
Main frame	9
Transformer	4
Gearbox	3
Pitch	2
Yaw	2
Power generation system	2

Ranking in terms of Asset	Max RPN
Pitch system	40
Yaw system	24
Rotor blades	18
Cables	18
Gearbox failure	18
Tower failure	16
Foundation	12
Main frame	12
Transformer	12
Rotor hub	12
Power generation system	12

Ranking in terms of Environment	Max RPN
Foundation	18
Cables	6
Rotor blades	6
Tower	4
Transformer	4
Gearbox	3
Main frame	3
Rotor hub	3
Pitch system	2
Yaw system	2
Power generation system	1

Table 7: FMECA analysis-Total ranking of components.

Total Ranking
Pitch system
Rotor blades
Foundation
Yaw system
Power generation system
Cables
Gearbox
Tower
Main frame
Rotor hub
Transformer

As shown in above Tables, the most sensitive component of the wind turbine in terms of Safety is the Tower as the consequences of a potential collapse would be catastrophic not only in case of fatalities but in all categories. Furthermore, the absence of sensors at the tower increases the possibility of undetected flaws that could lead to a possible failure compared to other components. The same applies for the foundation. The same can be validated by Dinmohammadi [43] in his study, where again Tower is ranked in the first place. As seen though in our study, all components have a relatively low RPN index as a total collapse is unlikely.

Foundation on the other side is the most failure prone component of the wind turbine in terms of Environment since foundation is in close contact with the sea and the seabed and again there is lack of sensors so any abnormalities in the

operation cannot be detected and undesired problems such as vibration can be a major disturbance to the sealife. Also, rotor blades can be a danger to the environment as they are responsible in many cases for bird fatality but not up to a great degree. Again, Dinmohammadi's study comes to validate results by placing Tower and Foundation, as well as Rotor blades in top positions. We can see though that in general the RPNs are low not only because most of the components are not in direct contact with the environment but also because legislation obligates companies to take proper measures for environment protection.

As far as Asset is concerned, the most sensitive component of the wind turbine is Pitch system not only due to high probability of failure but also because its failure means low energy production and thus less money earned for the company. The same applies for the Yaw system but although their probability and consequence indexes are high. Their detection indexes are low since there are a lot of sensors that could identify potential problems. Most of the RPNs in this category are high since any deviation from the normal operation costs a lot of money. Pitch system and Yaw system are also in the highest ranks of causes that can cause the biggest downtime in NREL studies [43, 45] and the two components with the greatest contribution to failure.

Finally, as already depicted in Table 6, pitch system plays an important role in the operation of a wind turbine, as it is one of the main components for the energy production, and consequently it is in the first place of the criticality ranking. Operation criterion is as we can observe the one with the highest RPN indexes since small operation disruptions are frequent due to a number of reasons. Its immediate correlation to Asset criterion leads to similar results.

As a conclusion we can say that the most critical component is the pitch system since it is amongst the top places in all rankings and aspects of criticality. Considering that electronic systems are sensitive and prone to failures it is justified that its probability index is really high in most of the cases. Also, as already said, the existence of sensors lowers the detection index but the importance of its malfunction causes the consequence index to raise. As a result we have a total of RPN 40 in most of the cases which ranks pitch system first in criticality terms. This is followed by rotor blades and foundation that have a high RPN due to high consequence index since a potential failure of the blades will have an impact on the energy production and a failure of the foundation can eventually lead to fatalities. At this point we have to say that these results are in accordance with past studies as already depicted in some examples [44, 45, 46, 47, 48 ,49, 64, 64] NREL 2013

Proper monitoring and maintenance can diminish the failure probabilities for most of the components. Thus as a general recommendation, the maintenance should take place in shorter periods of time instead of every two year that is now the average period.

HAZID Results

As far as the HAZID analysis is concerned again the hazards are evaluated in terms of Safety, Asset, Environment and Operation and summarized for each category. Below are the highest risks summarized for each category and their risk indexes in brackets.

During the manufacturing process in Safety terms, electrical hazard due to human error (36) or poor communication between workers (24) is appears to be the greatest hazard, whilst in all other aspects of the manufacturing process the risk indexes are rather low as most of the works are automated and human factor is not widely involved. OSHA also mentions exposure to chemicals as major factor, which was note taken into account in our study as process was considered mostly automated.

Similarly, during the transportation process, in terms of Safety, Environment, Operation and Asset, collision between CTV, FSV, Jack-up vessels, helicopters and wind turbines during worker's transportation due to bad weather (36) or human error (24), as well as load falls during unload due to bad weather (27), human error (24), or poor communication between workers (24) seem to be high in rank of possible hazards. BLS and OSHA refer to all of the above causes of risk during transportation stages validating our results.

During the installation process, where a vast number of humans are present, Safety criteria play an important role as expected, and hazards are present in all stages. Main areas of concern are collision between CTV and FSV or wind turbines during worker's transportation due to bad weather (36), workers' fall from heights due to human error (36), poor

communication between workers (36) or bad weather conditions (36), electrical shock due to human error (36) or poor communication between workers (36), fire or explosion due to fuel hose failure, ignition sources available, fuel tanks overflow, poor communication, human error (45), hot work on deck, poor housekeeping or hot work during bunkering (36), physiological hazards due to personnel slips, trips and falls (36) or man overboard (36), hazards during cable installation due to entangled cables around foundation during installation (36) or trawling capsizing from accidental dragging (36). In the same way, in terms of Environment, Asset and Operations major hazards are dropped/swinging equipment/device/tethers while installing, lowering/retrieving from water due to poor communication (24), stability loss of vessel due to cargo shifting (24) and fire or explosion due to fuel hose failure, ignition sources available, fuel tanks overflow, poor communication or human error (27). Even though not in rating order falls, fire or explosion and ergonomics are mentioned as top hazards in OSHA directives. They also appear in high frequency in IRSST and Caithness accident database.

During the operation process, where human factor is usually not present hazards are mainly linked with components' failure. In Safety and Operation aspects main causes of hazard are fire or explosion of turbine due to lightning (36) or strong winds (24), weather hazards due to ice throw/fall (27) or lightning, transportation hazards due to bad weather conditions (27) or human error (27). In Asset terms additionally, tower collapse due to buckling failure due to exceeded design loads (36) or improper installation of the tower-fastening system (24) can lead to a great loss to the company. In terms of Environment though, sea and seabed pollution due to noise and vibration (18) plays the most important role.

Similarly to the Installation process, during the maintenance process major hazards lay on electrical shock and workers' fall due to human error (36) or poor communication between coworkers (36), physiological hazards due to entry to confined spaces (tanks, store rooms, etc.) (30), personnel slips, trips and falls (36) or man overboard (36) and hazards during cable or foundation maintenance due to entangled cables around foundation during installation (36) or trawling capsizing from accidental dragging (36). All of the above mainly concern Safety, Asset and Operations criteria. On the other hand, in terms of Environment, in this aspect of maintenance process the risk indexes are rather low.

In an effort to interpret ranking of risks that are present in each of the stages of the wind farm's life we can see that in the case of manufacturing, it is observed that the biggest hazard is electrical shock either by human error or poor communication between the workers. This is reasonable since most of the manufacturing processes are automated and electricity is the only source of hazard that workers may come in touch with. This also justifies why all the other risk indexes in the manufacturing process are very low.

As far as transportation is concerned we can see that collision between vessels or vessels and other means of transportation, such as helicopters, is the lead cause of failure in all four aspects of risk analysis. Human error or bad weather conditions are the main reasons for that. Collisions can have a huge impact not only in Safety, since human lives can be lost but also in Environment as harmful substances can be spilled in the sea and in Asset and Operation as lost or destroyed components mean a lot of time and money loss for the company. Also, load falls during load and unload of turbine components is another major hazard of transportation as expected, especially in terms of Safety and Environment for the same reasons that collision is dangerous.

During the installation process the major hazards regard safety as it is the only stage of a turbine's life that a large number of workers are involved. A large range of hazards that could lead to injuries or deaths is present during this stage such as collision between transportation means, falls from heights, electrical shocks, fires or explosions but also severe physiological hazards. Nevertheless, due to increased number of procedures during the installation process a lot of diverse hazards appear in terms of operation, asset and environment such as stability loss of vessels, dropped/swinging equipment/device/ tethers while installing, tower collapse due to improper torqueing of the base or trawling capsizing from accidental dragging. Considering that time matters to a company since it is important for the energy production to start as soon as possible all these accident consist a major delay that needs definitely to be avoided. As seen above, we can say that in the case of maintenance it is noticed that most of the hazards are in common with the installation stage.

In the same manner, in operation process no personnel or external factors are involved with the turbine. Thus the human factor does not play an important role at this stage. Since the turbine is unmanned safety is not of as great importance as it was for the other stages. Exceeding loads, such as aerodynamic, hydrodynamic, slamming, ice load and fatigue from waves [50, 51], and operational malfunction though can have serious impacts in Environmental, Asset and Operation

terms. Weather conditions, are the main failure causes during the operation process. Weather is a considerable risk factor as all assembly techniques can only be done in calm sea. Work becomes extremely difficult or dangerous in rough sea and project delays may occur. These temporary interruptions of work mean huge increases in the construction cost of offshore wind farms.

We can say as a conclusion that Safety is the top area of importance during all stages of a wind turbine's life cycle since there is interference with human lives, and that can be seen from the high risk indexes in the risk matrix. Additionally, capital loss may be of great interest to the company and that is obvious since Asset and Operation also have high risk indexes in most of the failure causes along the risk matrix.

European Agency for Safety and Health at Work [60], Caithness database, IRSST [59] and UA department of Labor [58] validate at a great point the frequency and severity of hazards where the human factor is involved as described in above sections.

Undesired event/Hazard	Cause	Consequences	Consequence index				Probability index				Detection index				RPN				Risk control options/ measures
			S	E	A	O	S	E	A	O	S	E	A	O	S	E	A	O	
1.Brake system failure	Breaking power lost from overheating of the metal in brake rotors or drums	System disruption, blade damage, fire or shutdown	2	1	3	3	1	1	1	1	3	3	3	3	6	3	9	9	Proper design, monitoring and inspection
	Brake damage due to grease or oil on brakes	System disruption, blade damage, fire or shutdown	2	1	3	3	1	1	1	1	3	3	3	3	6	3	9	9	Proper design, monitoring and inspection
	Breaking power loss due to brake pads wearing thin	System disruption, blade damage, fire or shutdown	2	1	3	3	1	1	1	1	3	3	3	3	6	3	9	9	Proper design, monitoring and inspection

Figure 3. Part of FMECA Matrix.

Undesired event/Hazard	Cause	Consequences	Consequence index				Probability index				Detection index				Risk index				Risk control options/ measures
			S	E	A	O	S	E	A	O	S	E	A	O	S	E	A	O	
MANUFACTURING PROCESS																			
Electrical hazard	Equipment failure	Injuries or fatalities	4	1	1	1	3	1	1	1	2	2	2	2	24	2	2	2	Proper maintenance of the equipment
	Human error	Injuries or fatalities	4	1	1	1	3	1	1	1	3	3	3	3	36	3	3	3	Appropriate training and proper rest before the start of the shift
	Inadequate PPE	Injuries or fatalities	4	1	1	1	2	1	1	1	2	2	2	2	16	2	2	2	Regular checks of proper use of PPE and proper information about their utility
	Poor communication between coworkers	Injuries or fatalities	4	1	1	1	2	1	1	1	3	3	3	3	24	3	3	3	Appropriate training
Hearing problems	Extensive noise from the equipment	Deafness or dizziness	3	1	1	1	3	1	1	1	2	2	2	2	18	2	2	2	Use of proper PPE
	Inadequate PPE	Deafness or dizziness	3	1	1	1	2	1	1	1	2	2	2	2	12	2	2	2	Regular checks of proper use of PPE and proper information about their utility

Figure 4. Part of the HAZID Matrix

BBN Results

BBN method complements the previous analysis conducted using HAZID and FMECA and can confirm or refute the results not only by identifying the most costly components but also compare the results with the other two methods regarding the most critical components and their failure probabilities. The key feature of BBNs is their ability to model and reason about uncertainty and their graphical, articulate appearance.

BBN can be quite complex and it may be necessary to break it down to subcategories. In this case, we avoid computational intensive and time consuming process. In our approach we divided the main system into 11 subsystems. When necessary, in complicated systems, a further division was made to simplify the calculations into categories such as electrical failure, structural failure, human error and external parameters as in below Figures 5,6,7,8.

More specifically, the 11 subsystems were: Cables, Foundation, Yaw, Transformer, Tower, Rotor blades, Pitch, Main frame, Power generation, Rotor hub and Gearbox. Due to plethora and diversity of failure modes, Cables subsystem was further divided into electrical failure, structural failure and external parameters. For the same reasons, Foundation was divided into structural failure, fatigue and human errors. In a similar way, Pitch system's subcategories were structural failure, electrical failure, overloading and other causes (structures as shown on other studies [47, 48, 52].

After implementing the data for each subcategory, as for example shown in Table 8 for Pitch system, we identified and ranked the most critical components and their probability of failure (Table 9). In the final stages of our approach we incorporated the annual cost estimate for each component in order to get an approximation of the total annual cost in case of failure.
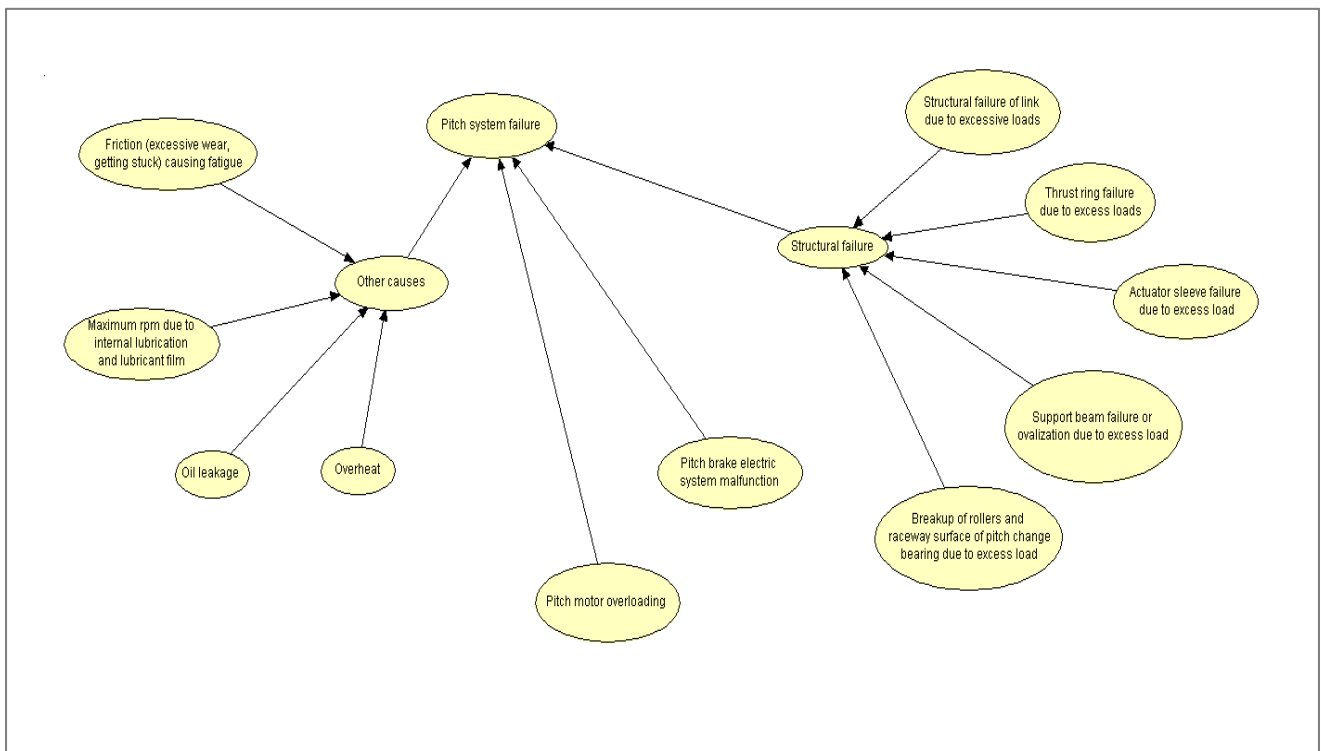

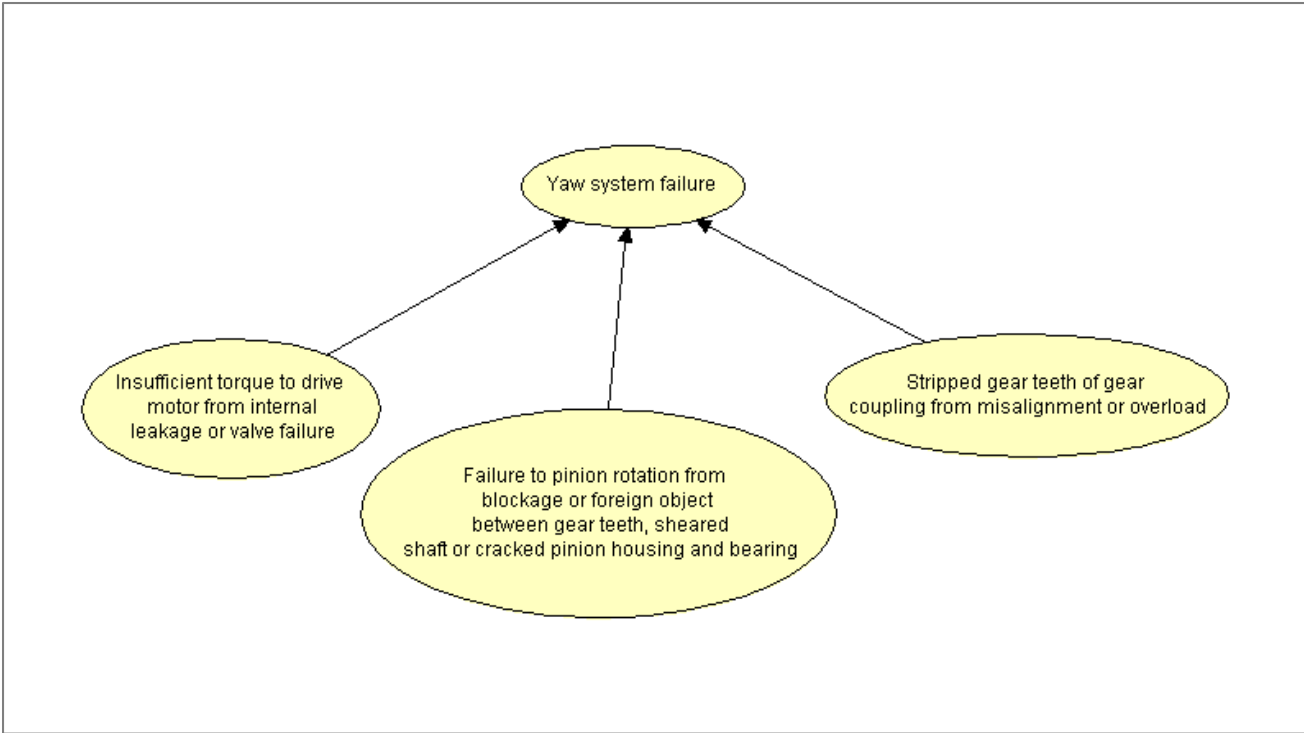**Figure 5.** BBN diagram showing possible failure causes of a wind turbine's pitch system.

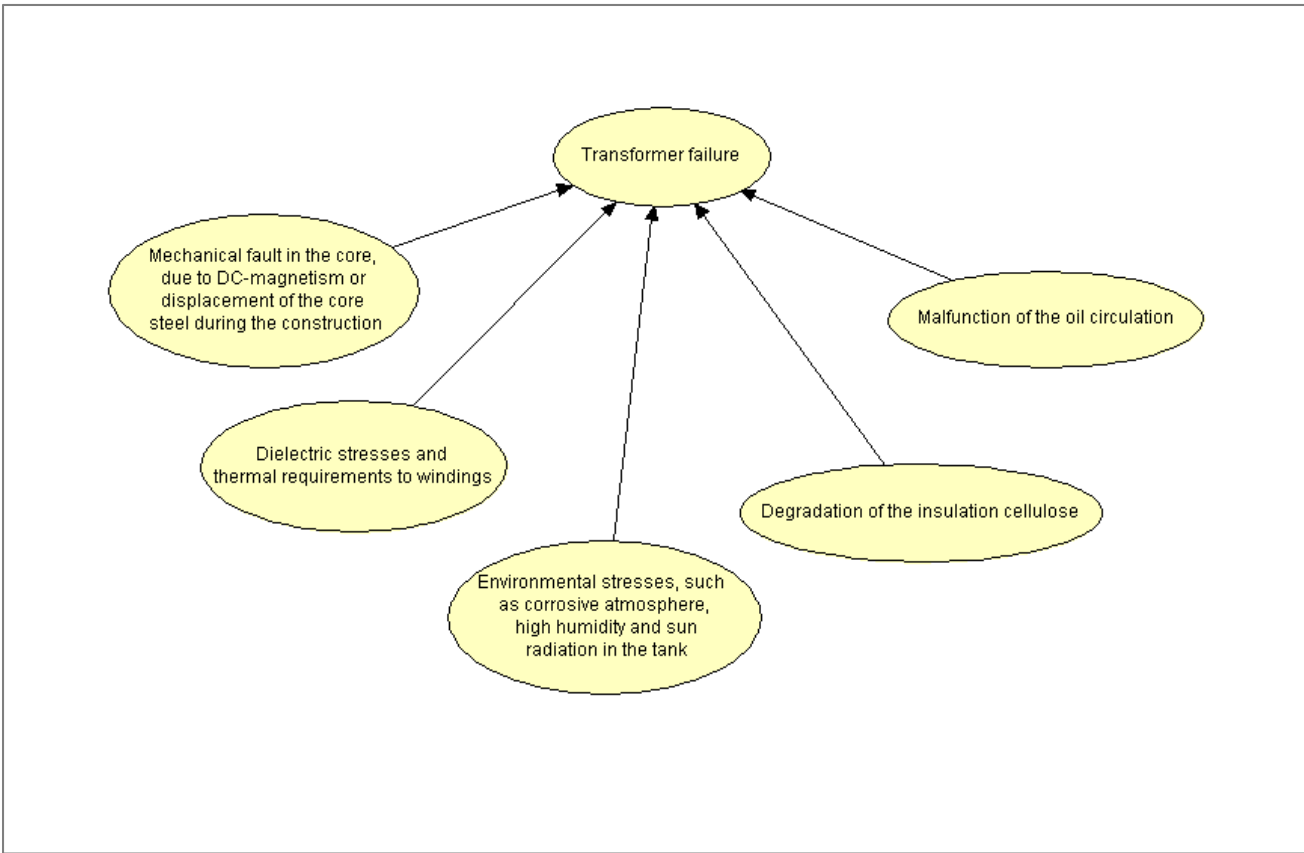**Figure 6.** BBN diagram showing possible failure causes of a wind turbine's yaw system.

Figure 7. BBN diagram showing possible failure causes of a wind turbine's transformer.
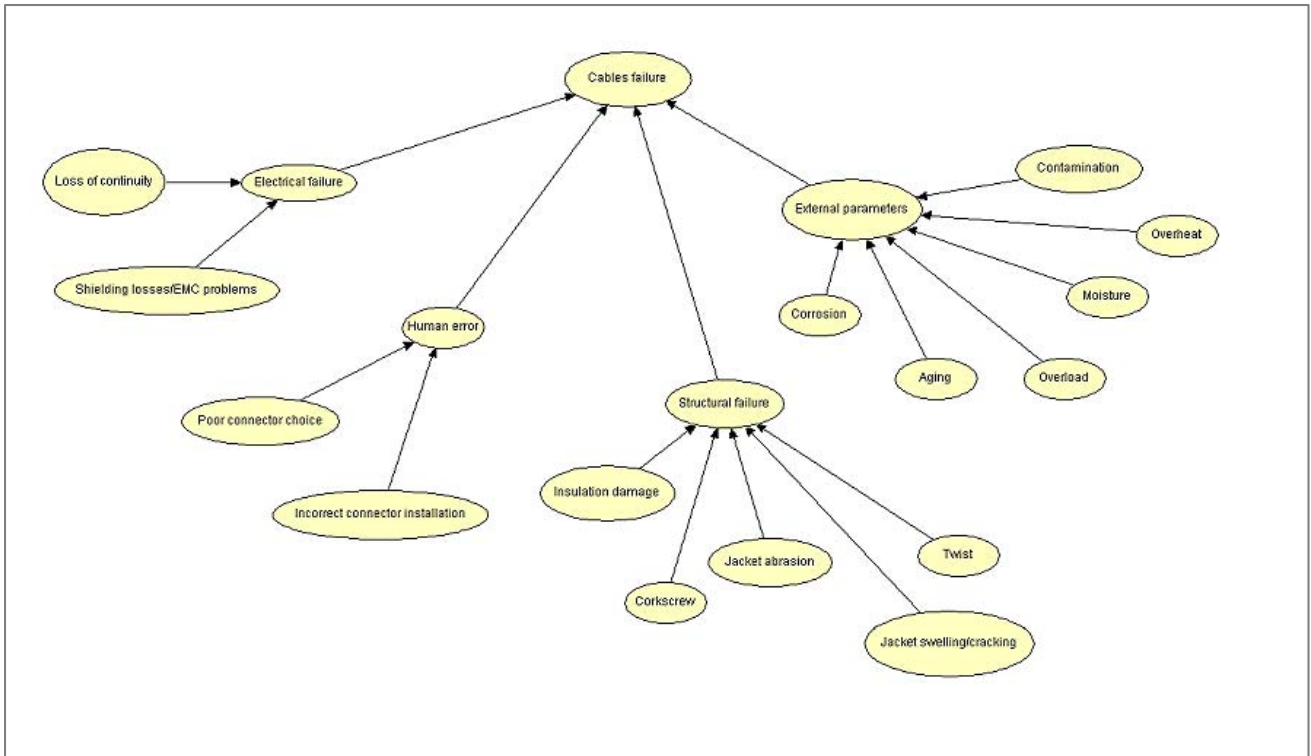
Figure 8. BBN diagram showing possible failure causes of a wind turbine's cables.

Table 8. Failure probabilities of failure causes for Pitch system [29].

Undesired event/Hazard	Cause	Failure probability
Pitch system failure	Friction (excessive wear, getting stuck) causing fatigue	0,1680
	Maximum rpm due to internal lubrication and lubricant film	0,1680
	Oil leakage	0,0297
	Overheat	0,2019
	Structural failure of link due to excessive loads	0,1680
	Support beam failure or ovalization due to excess load	0,1680
	Actuator sleeve failure due to excess load	0,1680
	Breakup of rollers and raceway surface of pitch change bearing due to excess load	0,1680
	Thrust ring failure due to excess loads	0,1680
	Pitch brake electric system malfunction	0,2019
	Pitch motor overloading	0,5000

Table 9. BBN analysis-Failure probabilities of the components.

Ranking of components	Failure probability
Yaw system	0.4336
Rotor blades	0.336
Power generation system	0.3074
Gearbox	0.2937
Foundation	0.2895
Pitch system	0.2687
Main frame	0.2547
Transformer	0.2146
Rotor hub	0.1585
Cables	0.1405
Tower	0.136

After implementing below cost data for the components into the BBN network:

Table 10. Annual cost estimate for an offshore 3MW turbine [53].

Component	Component cost in $1000
Foundation	1114
Rotor blades	319
Rotor hub	69
Pitch system	83
Nacelle	38
Shaft	59
Bearings	32
Gearbox	408
Brake system	6
Generator	211
Electronics	266
Yaw system	46
Main frame	168
Electrical connections	150
Hydraulics	41
Tower	415

For the Wind turbine as a total we can summarize the following:

Table 11. Summarized wind turbine results.

Wind turbine	
Total probability of failure	0.6098
Total annual cost in case of failure	115,398.75$
Total annual gain in case of not failure	67,985.37$

For the calculation of the wind turbine failure probability the data used for each component's failure are not absolute failure probabilities of each subsystem but percentage contribution to the overall failure of a turbine as actual figures are hard to find in the newly established wind energy industry. On the other hand the figures of the failure causes of each component are taken from OREDA oil & gas handbook and are actual. Thus there is also a parameter of uncertainty and error in the calculations.

That is most likely the main reason for obtaining such a high probability of failure. The total annual cost in case of failure is 115398.75$, that is relatively low comparing to the cost of the components respectively, since the top critical subsystems are relatively inexpensive.

Here we present the ranked failure modes for first three critical components as an example of failure:

Table 12: Failure modes and probabilities for the yaw and rotor blades system.

Yaw system	
Insufficient torque to drive motor from internal leakage or valve failure	0.425
Failure to pinion rotation from blockage or foreign object between gear teeth, sheared shaft or cracked pinion housing and bearing	0.0424
Rotor blade	
Rotor lightning	0.34
Power generation system	
Slipring failure due to misalignment, pearing stuck, lightning or dirty insulation	0.0614
Incorrect signal on stabilizer circuit due to sensor failure	0.0555
Unauthorized entry due to vandal, thief or curiosity seeker	0.0422
Excitation incorrect output due to age or circuit deterioration	0.0341
Closure failure on line ground current relay due to loss of CT signal, relay mechanical or electrical failure	0.001

As mentioned above the values used in the calculations are taken from the OREDA Handbook that it is more specifically for oil and gas industry. Since offshore wind turbines are a relatively new way of producing energy there is a lack of accurate data regarding risk and criticality analysis so there is a parameter of error in the calculations although we compare similar equipment types and operational conditions.

Despite this, results have an adequate level of accuracy and can be verified by past studies. The system with the highest failure probability is yaw system and is followed by rotor blades and power generation system. At some point this is justified as all of them are electrical systems and they are more sensitive to failures than mechanical systems.

The overall failure probability of the wind turbine is relatively high. This can be due to data error since the values used as failure probabilities of failure causes are taken from the OREDA handbook which is more specifically used for oil and gas industry. Another parameter of error is inserted with the use of percentage contribution of each subsystem to the overall failure of a turbine instead of absolute failure probabilities.

The overall cost of the wind turbine in case of failure is relatively low comparing to the components' costs respectively, since the top critical subsystems are relatively cheap.

Verification of present study can also be achieved by comparing the results of BBN to the ones from FMECA. The ranking of the critical components deriving from of the HUGIN program is up to a satisfactory level similar to the results from FMECA analysis. Yaw system, power generation system and gearbox are in both ranking amongst the first places. One major difference is the position of pitch system that is on the top of one list and rather low at the other.

Conclusions and recommendations for future research

Reliability prediction is considered as a crucial measure to understand system performance for minimizing maintenance cost and mitigate unnecessary downtime. In addition, imperfect maintenance is identified as one of the typical drawbacks in operation and maintenance practices that reduce system reliability. In this work we used a combined research

methodology for the risk analysis and the prediction of the long-term reliability of an offshore wind turbine's sub-systems. The key elements presented in this report are as follows:

- Review of risk analysis and risk assessment methods in renewables, maritime and oil & gas sector, as well as their tools and softwares.
- Presentation of a risk analysis and decision making methodology for implementation of the offshore wind turbine sector
- A novel technique for predicting system reliability is provided through this approach by combining HAZID, FMECA and BBN analysis.
- Development of a detailed risk matrix to be used for all activities of the wind turbine as well as for the critical components.
- Identification of the hazards in all activities in the lifetime of the turbine.
- Identification of the high-ranked hazardous areas in all activities in the lifetime of the turbine and its components.
- Identification of the most costly components of a wind turbine.

Additionally, the research study conducted here provides a tread for expanding into further research in risk analysis. The main recommendation that may enhance the proposed methodology is a further investigation in order to gather more accurate information about the offshore industry since implementation of the onshore data can lead to significant errors. Furthermore, more maintenance details could be implemented in the BBN networks so that more informative and proper decisions can be made on behalf of the decision makers about the maintenance strategy. In order to obtain more realistic reliability result it is also suggested that the different kinds of maintenance strategy (i.e. planned, preventive, corrective, breakdown) is taken into consideration. A sensitivity study on the conditional probability tables could also be a part of future research for accurate verification of the results.

Also, BBN analysis could be implemented for the HAZID analysis as well, so that the costs, in case the most critical operations occur, could be calculated. Finally, Future research could include a more elaborate, sophisticated risk based analysis considering the explicit formulation of a numerical optimization problem to be solved for the global minimum (optimal solution). Further, the time dependent character of the problem would be explicitly considered by modeling the involved dynamics via non- stationary stochastic processes[54, 55, 56].

The above recommendations can improve reliability and criticality analysis that are beneficial for obtaining optimum maintenance strategy and prevent risks and hazards of an offshore wind turbine.

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