Ocean Engineering 176 (2019) 118–133

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

A systematic Failure Mode Effects and Criticality Analysis for offshore wind turbine systems towards integrated condition based maintenance strategies

Matti Niclas Scheu[a,*], Lorena Tremps[b], Ursula Smolka[a], Athanasios Kolios[c], Feargal Brennan[c]

[a] Ramboll Energy, Burchardstrasse 13, 20095, Hamburg, Germany
[b] ScottishPower Renewables, 1 Tudor St, London, EC4Y 0AH, United Kingdom
[c] Department of Naval Architecture, Ocean & Marine Engineering, University of Strathclyde, Henry Dyer Building, 100 Montrose Street, Glasgow, G4 0LZ, United Kingdom

ARTICLE INFO

Keywords:
Offshore wind energy
Failure Mode Effects and Criticality Analysis
Availability
Operations and maintenance
Condition monitoring
Risk assessment

ABSTRACT

Condition-based maintenance is applied in various industries to monitor and control critical assets and to optimize maintenance efforts. Its applicability to the offshore wind energy industry has been considered for almost 20 years and has resulted in the development and implementation of solutions that have contributed to lower cost of maintenance and increased asset availability. However, there is currently no public domain guidance available that provides the information required to (i) prioritize systems for which condition monitoring would generate highest value and to (ii) understand the parameters that need to be monitored by a specific system from failure cause to failure mode. Both items are addressed in this paper, providing a clearly structured, risk-based assessment methodology and corresponding results for state-of-the-art offshore wind turbines. A total of 337 failure modes have been identified and analysed by experts representing approximately 70% of the European offshore wind market to assess potential benefits of condition monitoring systems. Results may be used to target the development of condition monitoring systems focusing on critical systems and to find optimal O&M strategies by understanding failure paths of main offshore wind turbine systems resulting in a lower cost of energy and a more optimal risk-return balance.

1. Introduction

Deployment of offshore wind power plants for electricity generation is becoming more and more competitive in various regions around the globe (Pineda and Pierre Tardieu, 2017). Its increasing contribution to the overall energy mix emphasises the requirement to comply with standards ensuring energy security at a price of electricity acceptable for a society (European Commission, 2014), and produced in a safe and environmentally sensitive manner. In the early years of offshore wind deployment, this demand was often not met. Examples are the Barrow, North Hoyle, Scroby Sands or Kentish Flats wind farms (WFs) in the United Kingdom (UK) that only delivered approximately 60–80% of the electricity that could have been produced had the assets continuously fulfilled the desired function (Feng et al., 2010). The main reasons for this shortcoming were identified in early studies and are mainly: (i) a low reliability of the wind turbines (WTs) (P. Tavner, 2012), (ii) underestimation of access restrictions for conducting maintenance activities (GJW Van Bussel and Zaaijer, MB, 2001), (iii) non-availability of specialised vessels for the aforementioned activities (Gerard Van Bussel and Schöntag, 1997) and (iv) the application of corrective maintenance – i.e. the initialization of maintenance activities in a reactive manner after the fault of a component or part within the WT system (Jannie Jessen Nielsen and Sørensen, 2011). Application of such strategies and corresponding effects on WT availability have been investigated in several publications. Availability is defined as the fraction of time the WT is producing electricity over the full duration of a certain time interval or the electricity produced over the theoretically producible electricity during a time interval (Elena Gonzalez, et al., 2017b). Studies presented in (Scheu, 2012) or (Rademakers, L and Braam, H 2003) quantify the impact of production losses due to downtime following a corrective maintenance strategy to around 12 m€ annually for a 500 MW wind farm with the direct cost for corrective maintenance around four times the cost for preventive activities. It was understood that preventing failures from occurring has a positive effect on WT availability and accordingly on the cash flow returning from the electricity sold. Significant efforts have therefore been made to keep WTs in an operational state to reliably produce electricity. Availability figures rose in the following years reaching values of 95% for wind farms located close to shore (Offshore Renewable Energy Catapult, 2016) to 98% based on the authors' industry experience. Availability depends

* Corresponding author.
E-mail address: matti.scheu@gmail.com (M.N. Scheu).

https://doi.org/10.1016/j.oceaneng.2019.02.048
Received 1 October 2018; Received in revised form 5 January 2019; Accepted 10 February 2019
Available online 23 February 2019

on, amongst other things, the WT site conditions and technical characteristics as presented in (Feng et al., 2010).

The efforts made to achieve those availability figures are comprised of preventive maintenance activities, such as scheduled replacements of wear parts, oil or grease and responsiveness to unforeseen scenarios, such as WT faults, by for example, having a suitable means of access through different types of vessels and/or helicopters as well as having spare parts, tools and technicians readily available; a situation that is well-known also for other offshore applications such as wave energy converters (A. Gray et al., 2017). As the industry is maturing, the maintenance strategies as such are further developed and concepts such as condition-based maintenance (CBM) are investigated. According to ("EN 13306: Maintenance Terminology" 2017), CBM is a form of "preventive maintenance which includes assessment of physical conditions, analysis and the possible ensuing maintenance actions". CBM strategies allow for failure prevention by understanding the physics of failure and, subsequently, the corresponding initiation of targeted maintenance activities. Implementation of CBM requires installation of sensors and application of analysis tools for various WT operational signals which adds complexity and cost to the operation of a Wind Farm. To exploit the benefits of CBM, a strategy needs to be developed that is based on a (i) thorough understanding of physics of failure and (ii) a subsequent prioritization of WT systems.

There is yet no published literature containing an inclusive overview about the most critical failure modes of state-of-the-art OWTs, that includes the rotor nacelle assembly (RNA), substructures and foundations as well as their corresponding failure causes and mechanisms based on operating track records of existing assets and design information. This information is essential for prioritization of WT systems to assess their suitability and feasibility for incorporation of condition monitoring systems (CMS).

This paper presents a systematic methodology for prioritization of WT systems for the application of CBM strategies commensurate with the most critical WT, substructure and foundation failure modes, as well as their respective causes and failure mechanisms. The contents are based on twelve Failure Mode Effects and Criticality (FMECA) workshops involving experts from companies representing more than 70% of the total installed capacity of offshore wind energy in Europe. The operating experience includes assets with a total capacity of more than 9 GW supplied from over 2500 single WTs.

The following section presents a literature review concerning CBM and risk prioritization in the wind industry. This is followed by an explanation of relevant terminology, then a methodology and a results section including critical discussion and conclusions.

2. Literature review

2.1. Condition based maintenance in offshore wind

The first widely accepted publications concerning Operations and Maintenance (O&M) optimization by condition monitoring date back to the late 1990s. A comprehensive report published out of the WT-Ω Project (Verbruggen, 2003) presented the state-of-the-art of O&M for onshore wind applications at that time. It describes the different monitoring techniques applicable for pitch systems, gear boxes, main bearings and blades as well as global monitoring systems, the latter referring to an analysis of system data and alarms for detecting a developing fault. This is described later on in this section in more detail as the applied techniques are still used today in the context of artificial intelligence (AI). Offshore wind O&M optimization was presented for the first time in 2005 (Caselitz and Giebhardt, 2005). This paper specifically focuses on the rotor as critical system within the wind turbine assembly. Later, (Wilkinson et al., 2007) presented an in-depth analysis regarding the use of condition monitoring systems on the drive train assemblies with a particular focus on the generator. Results of the European Union (EU) funded Condition Monitoring for Offshore Wind Farms (CONMOW) project were presented by (Wiggelinkhuizen et al., 2008). The CONMOW project ran from 2002 to 2007 and is the successor of the WT-Ω project. It described the use of direct and indirect measurement techniques for early fault detection and includes on-site application and testing of different techniques. The application of condition monitoring techniques has been described in a review paper published in 2009 (Lu et al., 2009). This was followed by (Sørensen, 2009) who firstly included the factor of risk. This work was followed in (J J Nielsen and Sørensen, 2009) focusing on the application of Bayesian theory as well as damage and uncertainty modelling. Like the other referenced works, this paper underlines the potential cost savings by moving from a corrective to a preventive maintenance approach. The state-of-the art of acceleration- and strain-based measurement techniques and algorithms is described in (Hameed et al., 2009) with a focus on onshore applications but outlining potential benefits for offshore turbines due to accessibility restrictions. More practical aspects related to installation and testing of CMS are described in (Hameed et al., 2010). They point out that particularly the usage of multiple interacting solutions is a complex undertaking requiring extensive system understanding and programming skills. Their focus is on wind energy in general i.e. on- and offshore applications. An attempt to understand root causes and failure prevention strategies for electrical and electronic assemblies is presented by (Peter Tavner et al., 2010). The motivation for this study were the high failure rates of the systems at the time causing long periods of downtime, particularly offshore. An indirect CMS, using generator power and rotational speed signals, was investigated by (Wenxian Yang et al., 2010). This paper addresses again the need for lowering complexity of analysing simultaneously various signals such as direct measurements of vibrations, strains or lubrication analyses in order to efficiently monitor the condition of the WT and its systems. Calculating the remaining useful lifetime of a system by deriving a damage function from operating conditions and/or direct signals is described by (C. S. Gray and Watson, 2010). They suggest that real-time damage calculation is feasible for various systems; however, the analysis presented was only focused on the gearbox. Over the following years the topic of CMS received increased attention and can be summarized in four research areas:

(1) Literature focusing on advanced O&M strategies through risk and condition-based strategies in general;
(2) Literature focusing on the technical description of specific CMS based on direct measurements;
(3) Literature focusing on the use of indirect signals through Supervisory Control and Data Acquisition (SCADA) systems;
(4) Review papers presenting the state-of-the-art in specific research developments and applications.

Papers of high relevance within (1) are (El-Thalji and Jantunen, 2012), who describe challenges for implementation of CMS from an academic and industrial perspective. The potential benefit of CMS is described by (Maples et al., 2013), who assume that 50% of the WT faults may be detected well in advance by monitoring systems which in turn have the potential to raise availability by 1.2%. The value of CBM strategies was also addressed by (Van Horenbeek et al., 2013). They conclude that CMS offers cost saving potential even for onshore WTs. However, when assessing the correlations in more detail it can be seen that the commercial benefits depend strongly on the ability of the CMS to reliably predict a developing fault. As a follow up to their previous papers, (J. S. Nielsen and Sørensen, 2014) propose the use of monitoring information to be fed in a maintenance decision logic based on Bayesian networks in order to refine accuracy of predictions and consequently optimize maintenance decision making from a risk perspective. A recent publication (Leimeister and Kolios, 2018) describes a generic framework of qualitative and quantitative methods for fault path investigation from a reliability perspective, providing information of high relevance for the evaluation of the suitability of CMS.

Work published in (2), i.e. those focusing on direct measurements, mainly contain specific technical assessments of the applicability of systems for monitoring the condition of (i) RNA or (ii) structural components such as towers, substructures and foundations. Relevant publications for components in (i) are: (Sheng et al., 2011), (Tian et al., 2011), (Kostandyan and Sorensen, 2012), (Matthews et al., 2015), (Romero et al., 2018), (González-González et al., 2018), (Artigao et al., 2018a). In category (ii), focusing on substructures and foundations, the following relevant publications have been identified (Smolka and Cheng, 2013), (Devriendt et al., 2014), (Ziegler and Muskulus, 2016), (Martinez-Luengo et al., 2016), (Ziegler et al., 2017), (Weijtjens et al., 2017), (Ziegler et al., 2018). It should be noted that these papers refer to the term 'Structural Health Monitoring' (SHM) which is often used as a synonym of CMS for structural items. These references mainly address the challenge of determining the remaining useful lifetime of offshore wind turbine (OWT) substructures and foundations with a focus on (i) reducing the required number of inspections by maintaining an acceptable confidence in structural integrity and (ii) enabling the operation of an OWT longer than its intended service life, generally referred to as Life Time Extension (LTE).

The topic of using SCADA data for maintenance purposes (3) was first introduced by (Verbruggen, 2003). In recent years, from 2010 onwards, this topic has gained increased attention. These indirect data analysis techniques are today often referred to as predictive maintenance. The concept was introduced to offshore wind CMS by (Garcia, Sanz-Bobi, and del Pico, 2006) and subsequently by (Kusiak and Li, 2011), (Lapira et al., 2012) and (Wenxian Yang, Court, and Jiang, 2013). From 2015 onwards, the topic has gained even more momentum underlined by recent publications such as (Reder et al., 2016), (E Gonzalez et al., 2016), (Colone et al., 2017), (Elena Gonzalez et al., 2017a), (Nabati and Thoben, 2017), (E Gonzalez et al., 2018), (Dao et al., 2018) (Arcadius Tokognon et al., 2017). First results presented show promising potentials even though some challenges are still to be addressed in current and futuree research. Outstanding challenges, amongst others, are the limited number of components on which the respective machine learning techniques are applicable to and a challenging system identification process that potentially requires linking SCADA data with direct measurements stemming from strain gauges or accelerometers. On the other hand, the suggested techniques make efficient use of already available measurements instead of requiring transmission, handling, storage and analysis of new data which would ultimately result in increased and expensive data management. This overall trend is further reflected by current research activities such as the project from which this paper has been developed ("Romeo Project" 2018).

In (4), review papers concerning CMS are presented. On average, one paper per year is published that either focuses on one specific aspect or monitoring in general. The most recent are (Sharma and Mahto, 2013), (Nie and Wang, 2013), (Tchakoua et al., 2014), (Coronado and Fischer, 2015), (Tautz-Weinert and Watson, 2017), (Wang et al., 2018), (W. Yang, 2016). Two publications that link the aspect of risk in the form of a Failure Mode and Effect Analysis with offshore wind O&M optimization and CMS are (Shafiee and Dinmohammadi, 2014) and (Zhou et al., 2015). The most comprehensive review of developments in the field of wind turbine reliability considering the potential value of CMS is presented in (Artigao et al., 2018b). The latter two papers are most relevant for this research as they investigate the problem of the value of CMS from a risk perspective rather than on the pure technological feasibility. In other words, they investigate the likelihood and consequence of the fault of a certain WT component or system in order to make a judgement concerning the potential value of implementing a certain monitoring system.

It has been shown that a great amount of work has been done to develop, test and implement CMS/SHM systems over the past years. The focus lies on "critical systems", which cause long cause long periods of downtime and high costs of failure. Furthermore, for all systems investigated there are records of actual single or serial faults from the field. Thus, it can be concluded that the natural prioritization of systems is reasonable as it focuses on systems whose failure is known to have severe consequences, considering the view of an offshore wind developer or operator. However, one may argue that a prioritization solely based on observed scenarios may be incomplete requiring a greater cohesive and complete system analysis for prioritization of CMS developments; therefore offering improvement potential for operating performance and maintenance efficiency.

One approach of doing this is to apply the concept of risk, which is explained in more detail in the following section.

2.2. Risk prioritization and FME(C)A

The concept of risk helps to prioritize systems by assessing which scenarios may occur (for instance, a component failure), how likely is this to happen and what the associated consequences are. Consequences may be evaluated in different categories depending on the purpose of the risk assessment. Often, they include cost and asset value implications, asset availability (as a main performance indicator), considerations towards health and safety of personnel and environmental impact (NORSOK STANDARD Z-008 2001).

Several qualitative and quantitative methods may be applied to prioritize a system or failure scenario for further investigation. A widely applied reference for risk assessment methodologies is the ISO 31000 series of standards (ISO31000, 2009), (ISO31010, 2010). From these standards, the Failure Mode and Effect Analysis (FMEA) is one of the most relevant techniques for creating transparency of the failure scenarios with the highest relevance in the context of the operation of physical assets. This thesis is supported by the various publications referred to below.

A FMEA is a logical qualitative risk assessment process aimed at evaluating failure modes (FMs) of a process, procedure or system, their causes and effects. When extended by "Criticality Analysis" (CA) for failure modes classification by including estimates of the likelihood and the severity of each failure mode, it is known as Failure Mode Effects and Criticality Analysis (FMECA), which is classified as a semi-quantitative reliability method. It is commonly defined as 'a systematic process for identifying potential design and process failures before they occur, with the intent to eliminate them or minimise the risk associated with them' (Juhaszova, 2013). By quantitatively assessing each of the FMs it is possible to measure their criticality, enabling their prioritization and subsequent identification of appropriate mitigation measures. FME(C)A is an accepted risk assessment technique for functional analysis as per (ISO31010, 2010), which can be applied throughout the complete life-cycle of a physical asset from design to decommissioning. The FMECA discipline was originally developed in the United Sates Military and was first formally formulated in 1949 with MIL-STD-1629A which is reflected in the document referred to in (Reliability Analysis Centre, 1993). It was used as a reliability evaluation technique to assess the effect and consequences of system or equipment failures towards financial and non-financial aspects such as safety or the reputation of an organization. The technique has been in use for a long period of time, especially in the aerospace industry with the development of the SMC Regulation 800-31 (Jackson et al., 1995) and the automotive industry with SAE J1739 (Surface Vehicle Standard, 2009). However, the most widely used standard is MIL-STD-1629A which has been applied in many industries for general failure analysis. At present, the standards that are usually referred to when carrying out an FME(C)A include BS EN 60812:2006 (EN 60812, 2006) and BS EN 5760-5:1991 (British Standards Institution. 1991). For more practical guidance see (Moubray, 1992).

Specifically, in the wind industry, (Shafiee and Dinmohammadi, 2014) presented a systematic review of maintenance optimization methods and strategies within the offshore wind industry over the past few decades. The FMEA technique was used by (Arabian-Hoseynabadi

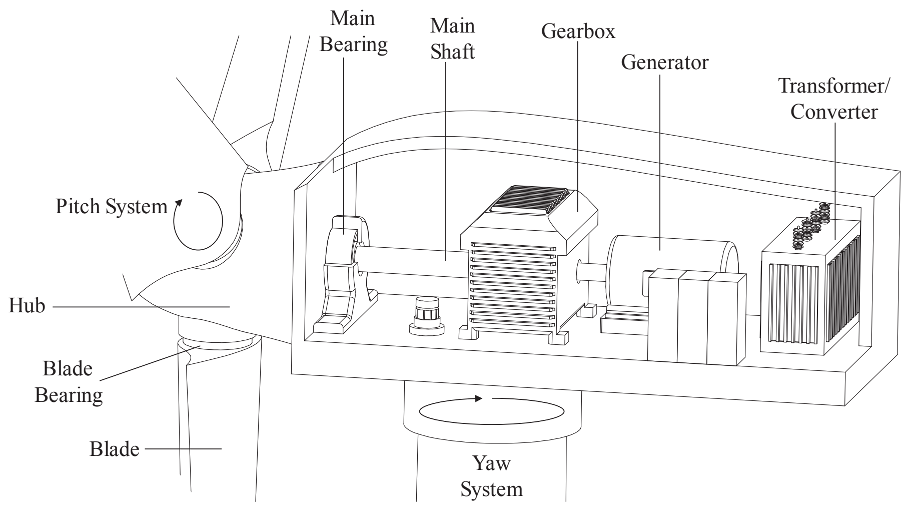

Fig. 1. Main systems of offshore wind turbines.

et al., 2010) in evaluating an existing design of a 2 MW wind turbine with a Doubly Fed Induction Generator (DFIG) against a hypothetical Brushless Doubly Fed Generator (BDFG), within the EU FP7 RELIAWIND Project (Peinke et al., 2007). It concluded that the FMEA is a technique that could significantly contribute to achieving long-term cost-effective systems. This project identified more than 150 different types of components for a wind turbine, which have been used as the basis for WT breakdown in upcoming studies. This is similar to the work conducted by (Gauravkumar Bharatbhai, 2015) who presented a reliability analysis of Repower 5 MW WT by means of different tools such as FME(C)A. The study concluded that the overall reliability of the 5 MW WT was very low, identified areas susceptible of failure and highlighted those with the need and potential to have condition monitoring systems fitted. (K. Fischer et al., 2012) applied the concept of RCM in the form of a FMECA workshop with the owner, operator and industry experts to assess two wind turbine models Vestas V44-600 kW and V90-2 MW.

(Kahrobaee and Asgarpoor, 2011) elaborated the limitations of a traditional FMEA or FMECA when applied to the assessment of wind turbines. They presented a quantitative approach called Risk-Based-FMEA based on failure probabilities and incurred failure costs and applied this to a direct drive wind turbine case study. Similarly, (Dinmohammadi and Shafiee, 2013) developed a fuzzy failure mode and effects analysis (FMEA) approach for risk and failure mode analysis of offshore wind turbine systems.

Most recently, (Kang et al., 2017) applied the FMEA method to conduct a reliability analysis of floating offshore wind turbines (FOWT). Contrary to onshore wind turbines or bottom-fixed offshore wind turbines FOWTs are characterised by a complex structure formed by interdependent sub-systems. For this reason, an alternative FMEA method named correlation FMEA was applied. Interestingly, the study revealed that the foundation structure and mooring system were high-relevance systems as a result of the many dimensions associated with potentially severe consequence of failure. Furthermore, (Luengo and Kolios, 2015) presented a comprehensive list of failure modes of OWT with particular focus on end-of-life considerations.

The literature review in this section has shown that significant research has been conducted in the area of risk prioritization and risk-based maintenance optimization. There are also some distinct papers specifically addressing the problem of prioritizing CMS based on the risk profile of a specific system. (Zhou et al., 2015) applied an FMECA for prioritization of CMS. They focus on representing FMECA information in an ontology in order to enable sophisticated fault diagnosis. The paper has a strong emphasis on information technology (IT) and the applicability of using actual fault diagnosis techniques in operation. This is also shown by the baseline scenario in which a 1 MW (Mega Watt) onshore WT is used as example. It includes failure modes and causes for the main WT systems; however, the data provided is limited to an onshore WT, hence does not represent the latest technological state-of-the-art and likewise does not contain information about OWT substructures. In summary, this paper provides good insights into how to efficiently use information (e.g. from an FMECA) in order to implement fault diagnosis in an operational wind farm, but it lacks assessing typical failure modes of latest offshore wind turbines. A highly relevant work was also published by (Artigao et al., 2018b). They use reliability statistics and maintenance track records for assigning criticality levels to WT systems in order to prioritize scenarios for CMS. This paper is the most comprehensive literature available describing in detail asset reliability of wind turbines. The study reveals however, that availability of reliability data for offshore wind is much more limited than for onshore wind. In fact, it only refers to one study providing reliability data for a portfolio of wind farms rather than a single array. This study was published by (Carroll et al., 2016) and contains highly relevant information for all those stakeholders involved in offshore wind O&M. Artigao condenses the information from Carroll's study, including in addition twelve other publicly available reliability statistics to identify the top five contributors to asset downtime (i.e. systems with a high failure rate and/or long durations for repair or replacement). The study concludes with the recommendation to focus development efforts for CMS on five systems. However, a detailed overview concerning which failure modes any particular system should focus upon is not included. Their study also omits the element of the foundation and substructures. In offshore wind, those items are subject to a very harsh environment and achieving long-term integrity whilst minimising the inspection and maintenance costs is crucial for increasing the overall cost-efficiency. In order to assess the applicability of CMS, this information is essential and it is therefore desirable to link CMS to the failure rates and downtimes of the systems they refer to.

3. Methodology

3.1. Wind turbine system description

This paper addresses the applicability of CMS for main OWT systems in the RNA as shown in Fig. 1 below and foundation and substructure items. It should be noted that modern OWT often use direct drive generators instead of a gearbox configuration as shown below. For further information on this see (Polinder et al., 2006) and (T. Fischer,

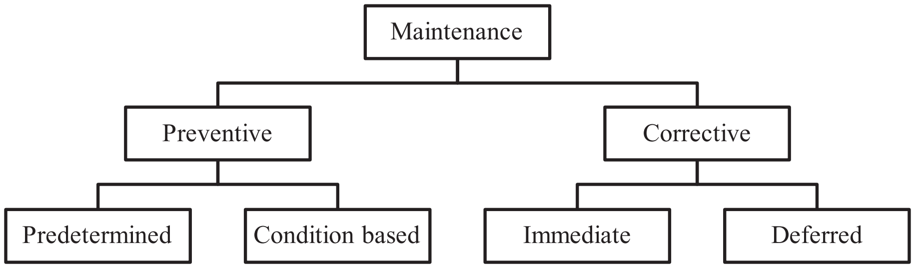

Fig. 2. Maintenance types (“EN 13306: Maintenance Terminology” 2017).

2012) for illustration and explanations of the offshore substructure concepts relevant to this study, i.e. monopile and jacket structures.

For detailed descriptions of the main wind turbine systems, subassemblies and components see (Burton et al., 2001).

3.2. O&M terminology

The main WT components are subject to preventive and corrective maintenance activities (see Fig. 2); preventive measures are intending to avoid any fault occurrence whilst corrective measures are those activities taking place subsequent to a component failure (“EN 13306: Maintenance Terminology” 2017).

CMS can in general terms allow for condition-based maintenance which in a more sophisticated approach can be translated to a predictive maintenance strategy. Predictive maintenance is defined as ‘condition-based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item’ (“EN 13306: Maintenance Terminology” 2017). This form of maintenance offers inherent optimization potential for both, preventive and corrective maintenance activities.

A corrective maintenance strategy has the advantage that the useful lifetime of the item is always fully utilized. This means that there is no ‘waste’ of resources caused by, e.g., a preventive replacement of the item or parts of it. On the other hand, the disadvantages of a corrective maintenance strategy are that (i) it relies on a quick reaction time to avoid significant production losses during downtime and (ii) it can potentially cause indirect costs, e.g. if secondary damages are caused when the item fails. The offshore wind industry is moving more and more towards preventive maintenance strategies as long periods of inaccessibility can cause substantial financial losses in case a wind turbine is out of production and cannot be brought back into an operational state.

A preventive maintenance strategy has the advantage of keeping the asset delivering in a more constant and reliable manner electricity and thus ensures a stable financial income. The disadvantage of a preventive maintenance strategy is that it comes (at least initially) at a higher cost. Any preventive equipment check, overhaul, replacement or testing campaign has a cost associated with it. A practicable balance must be found between the efforts put into a preventive maintenance campaign and the risk of the component to fail. Depending on the details of the preventive maintenance strategy, there is a possibility of over-maintaining. This means that for example a component is replaced far earlier than the end of its useful lifetime, which is the type of scenario that can be avoided by applying a corrective maintenance strategy.

A way to mitigate the disadvantages of each of the above strategies is to apply a condition-based or predictive maintenance approach. Within either of these approaches maintenance activities are only carried out when they are actually required, i.e. the item is not unnecessarily over-maintained, but it will also not fail unexpectedly. This is only possible if accurate information on the condition of the item and the associated degradation mechanisms are obtained at any time.

Condition based strategies rely on information based on data gathered by continuous or periodic, online or offline condition monitoring systems. It must be distinguished between diagnosis and prognosis systems. The following definition can be used to differentiate between the two: ‘Diagnosis is an assessment about the current (and past) health of a system based on observed symptoms, and prognosis is an assessment of the future health’ (Mathur et al., 2001).

3.3. Failure assessment and risk prioritization

While the potential benefits of a CBM strategy appear obvious, a certain effort is required to develop and implement the required systems to reliably provide information about an items' current condition. It is therefore desirable to prioritize certain components and failure modes with respect to a potential CBM strategy rather than trying to implement it for the entire system. A risk-based approach is deemed as the most suitable technique for such prioritization based on the author's industry experience and the literature review conducted on this topic. An approach based on the FMECA methodology has been developed and applied as explained below.

In order to gather the relevant information, a total of twelve FMECA workshops were held involving more than 40 technical experts (mechanical, electrical, structural, O&M, reliability) from leading European offshore wind developers, wind turbine manufacturers, expert consultancies and universities. Where applicable, data from the wind turbine manufacturer's and structural design documentation, the developers or WT manufacturer's operating track-record as well as any other relevant experience from the participants was fed into the process for generation of the most optimal and representative results covering the different viewpoints of the stakeholders. The process followed is presented in Fig. 3 below. The first author of this paper has acted as workshop leader, i.e. the workshop preparation and moderation were in his responsibility. The participants of the workshops were selected in accordance with the requirements for experience within each field. Relevant industry experience of 5 + years was the general requirement; but most of the participants were significantly more experienced. Due to privacy protection reasons, further detail on the participant's profiles is omitted.

The ***first step*** was to divide the assets under consideration into systems and components. An RDS-PP (Reference Designation System for Power Plants (“VGB-Standard RDS-PP ® Application Guideline Part 32: Wind Power Plants” 2014)) structure was used to organize the system breakdown in accordance with the equipment's functional location (FLOC). This process was conducted considering the wind turbine manufacturer and end user requirements.

In ***step 2*** the description of the main function was added to each item. This description reflects the main design intention and helps at a later stage to assess effects and consequences of a functional failure.

The failure mode, as documented in ***step 3***, contains information about the event which causes a functional failure. In basic terms it answers the: “what happens” question (not to be confused with the failure cause) (European Standard 14224 2006).

The failure cause describes what made the failure mode to occur (not to be confused with the failure mechanism) (European Standard

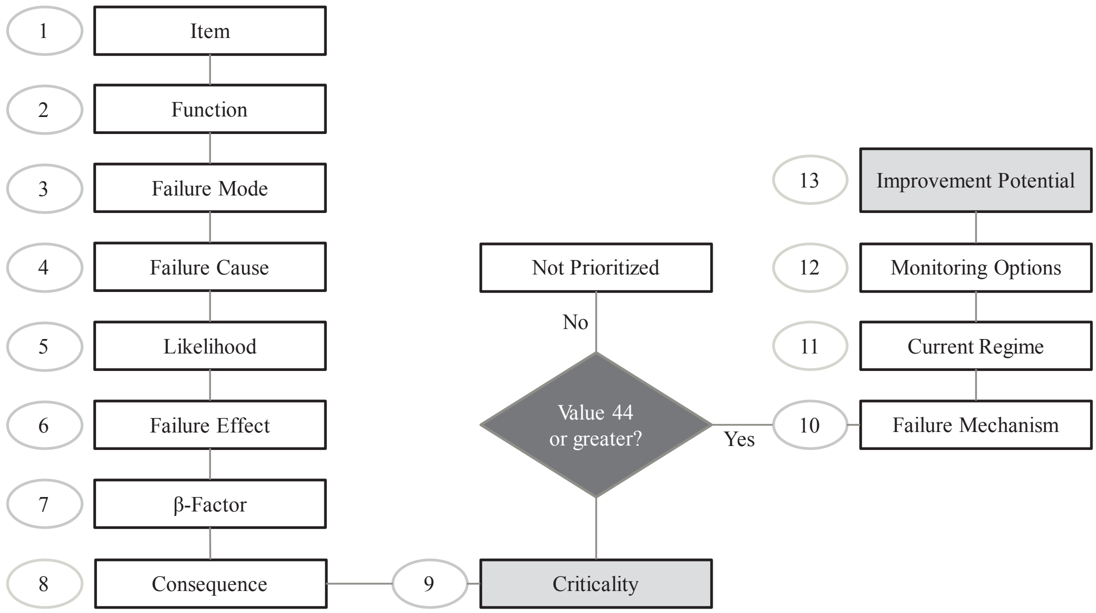

Fig. 3. Process for FMECA and prioritization of CMS.

14224 2006). This is documented in ***step 4*** in order to be able to document the likeliest root causes of the failure mode under consideration.

In the next question, answered in ***step 5***, the information about the likelihood of a failure scenario to occur is documented. The likelihood of occurrence assessment is a vital part of any risk assessment. Generally, the likelihood of occurrence (or probability of occurrence) can be assessed quantitatively, semi-quantitatively or qualitatively. Quantitative and semi-quantitative approaches are applicable if there is an operating track record available of the item under consideration providing statistically viable information; i.e. the information about an items' reliability can be obtained from actual data records. This approach is not applicable for items which have been in operation for a short period of time. Therefore, qualitative engineering judgment was used for the assessment of the likelihood of occurrence of the given scenarios. The mentioned judgments were supported by numerical calculations, other modelling techniques, or experience from other fields of application of a similar technology where possible. Within this research project, the assets under consideration are of differing ages; i.e. for some assets, an operating track record of several years is available, whereas others have been in operation only for a relatively short period of time or not even built. Due to this differing characteristic, a qualitative assessment approach has been chosen for the likelihood of occurrence evaluation. Table 1 summarizes the three levels that have been used:

The failure end effect, documented in ***step 6***, describes what happens when a failure mode occurs (not to be confused with failure consequence) (Moubray, 1992). It is this scenario which is assessed in terms of consequence in subsequent steps. The failure effect description shall consider the realistic worst-case scenario.

In ***step 7***, the β-factor is analysed and documented. The β-factor represents the conditional probability of the failure end effect (described in step 6) to materialize, given that the failure mode has already occurred. It is used to account for the failure progression mitigation measures which would prevent the end effect to occur in case of failure mode occurrence. The categories that have been considered in the course of the ROMEO project are presented in Table 2.

In ***step 8***, the consequence of the described failure end effect is assessed. This step describes why and how a scenario matters. Different consequence categories were defined in accordance with the project requirements and industry-standard practices; they encompass 'Safety', 'Environment', 'Spare Part Cost', 'Production Availability' and 'Type of Intervention'. Three consequence levels were introduced in each category, representing their respective severity categorization; 'Marginal', 'Medium' and 'Critical'.

Consequences are assessed per individual asset; i.e. per one wind turbine and its individual systems. Park (array/full-system) effects, scale effects, etc. are not considered in this assessment.

Economic consequences are split into direct and indirect cost, with the latter referring to production losses. This split allows for the identification of items which may be repairable at low cost, but potentially having a significant influence on availability vice versa. In addition, there is a distinction between the types of intervention required in order to account for the impact of specialised resources and logistics required to carry out certain activities.

The realistic failure end effect of a scenario is assessed with respect to the consequence levels; each carrying the same weight in the assessment (weighted factoring is omitted here, i.e. eventual weighting shall be reflected by the categorization). Consequence groups and levels were agreed upon in the expert forum involved in this project, as referred to earlier. They reflect the particular risk appetite of this specific group of experts and, therefore, have potential for adjustment. Risk analysis consequence groups and levels are summarized in Table 3 below.

Table 1
Likelihood of occurrence categorization.

Category	Description	Factor
Not expected	The occurrence of the described failure mode is not expected throughout the planned lifetime of the asset and under consideration of the current inspection or maintenance regime.	1
Possible	The failure mode could occur throughout the planned asset lifetime but it is not certain.	2
High	This failure mode would, under the given inspection and maintenance regime, certainly occur.	3

Table 2
β-factor categorization.

Category	Description	Factor
Low	The described failure end effect will most likely not materialize if this failure mode occurs. There are several mitigation or detection measures in place which will prevent the fault to progress to the worst-case effect.	1
Medium	The failure mode could progress to the described failure end effect, but it is not certain. In most cases, the end effect will not materialize.	2
High	The failure mode described will certainly lead to the described failure end effect.	3

The criticality value is calculated in ***step 9***. The criticality value provides a quantified result combining the earlier collected information about the potential failure mode, the likelihood of occurrence and β-factor as well as the consequences of the effect. The formula used for the calculation of the criticality is given below. This formula relies on the values denoted as 'Factor' as listed in the tables above, i.e. a value of 1–3 representing the likelihood of occurrence, the β-factor and the severity summation.

$$Criticality = Likelihood * \beta * (\sum Severity)$$

The combined result is a value between 5 and 135. For risk evaluation purposes, the following categorization, presented in Table 4, was discussed among the forum of industry experts and reflects the common understanding of acceptable boundaries. It should be noted however, that these values or classes ultimately depend on the risk appetite of stakeholders and therefore may change (see Table 5).

All failure modes which were either in the medium or high-risk category were prioritized and have been further assessed as part of steps 10 to 13.

In ***step 10***, the failure mechanisms of any prioritized failure mode were analysed by in-depth evaluation of the physical, chemical or other processes leading to the failure. This information forms the basis for establishing a list of desirable monitoring systems and their requirements.

Steps 10 to 13 were carried out separately for structures and RNA. This is because structures (here monopile and jacket substructures) are handled differently to the turbine main systems (here blades, pitch system, yaw system, main shaft, gearbox, generator, transformer and converter) during the operational phase of a wind farm. In general terms, structures are subject to an inspection and monitoring regime aimed to verify their structural integrity is maintained throughout the intended lifetime of the asset. Wind turbine RNA components are, on the other hand, predominantly subject to regular maintenance campaigns which ensure that the components and systems are fit for their desired purpose. This main difference is respected by following specific measures in the course of the FMECA process.

Table 4
Risk evaluation categories.

Category	Range
Low	5–43
Medium	44–90
High	90–135

3.4. Benchmarking of wind turbine RNA component monitoring options

A common method to evaluate the performance of a monitoring system is the PF-interval. This is defined as the time interval between the detection of a developing fault and the failure occurrence, as illustrated in Fig. 4 below. This example shows a fictitious component with a certain performance requirement. As soon as the performance falls below the required value, the component is considered to be in a failed state. This represents the *F* of the PF-interval. *A* and *B* represent measurements derived from condition monitoring systems. In this particular example, A is capable of detecting the fault development at time *P1* and *B* is capable of detecting the failure at time *P2*. The interval between the potential fault detection *PX* and the actual fault *F* is defined as PF-interval.

The PF-interval is used as a performance indicator for condition monitoring systems. The longer this interval is and the more accurately the exact point in time of failure occurrence can be estimated, the more benefits can be obtained by applying the system. For prioritization of monitoring systems for main turbine components, the PF-interval achievable with contemporary commercially available monitoring systems has been compared with the potential PF-interval of any imaginable monitoring system. This is done by following the process shown below.

- Describe any currently used monitoring system for the failure mechanism under consideration.
- Estimate the PF-interval achievable with the monitoring system applied today.
- Describe how a future monitoring system could look like and what its performance criteria are.

Table 3
Consequence categories and levels for criticality analysis.

	Consequence		
	Marginal	Medium	Critical
Production Availability	< 3 days	3 day < downtime < 7 days	7 days < downtime
Personal Safety	No potential for injuries. No effect on safety systems.	Potential injuries requiring medical treatment. Limited effect on safety systems.	Potential for serious personnel injuries or fatality.
Environment	No impact. Contained release requiring only simple clean up. No need for reporting to local environmental agencies.	No impact. Contained release requiring response from trained team. No need for reporting to local environmental agencies.	Impairment of ecosystems function. Uncontained release. Event needs to be reported to local environmental agencies.
Spare Part Cost	0–7.5 k€	7.5–100 k€	> 100 k€
Type of Intervention	Minor campaign – 1 CTV, SOV or helicopter mobilization and use for up to 1 day, 3 or less technicians	Medium campaign – 1 CTV, SOV or helicopter mobilization and use for up to 7 days, 6 or less technicians	Major campaign – 1 CTV, SOV or helicopter mobilization and use for more than 7 days, 1 jack-up vessel mobilization and use for min 1 day
Factor	1	2	3

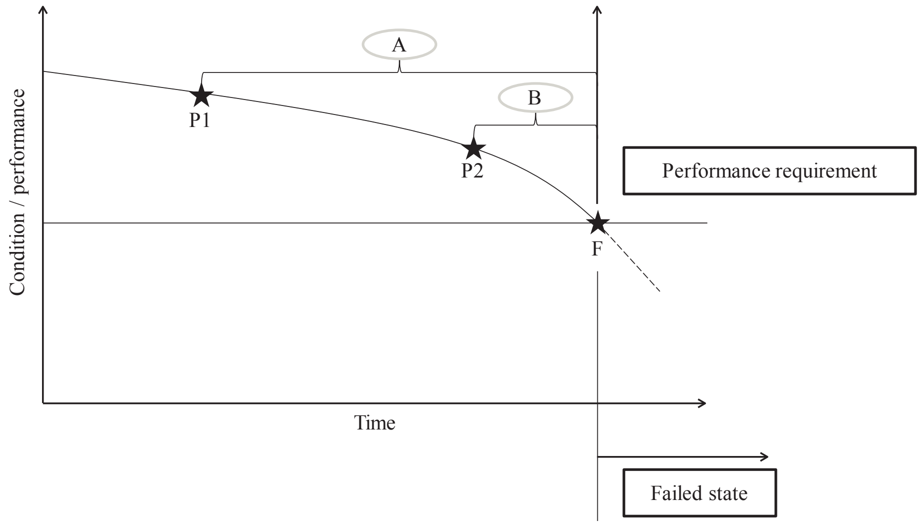

Fig. 4. PF-Interval example.

- Estimate the potential cost savings achievable by applying the new monitoring system.
- Estimate the expected downtime reduction by applying the new monitoring system.

Points (4) and (5) are assessed based on the same levels used in ***step 8*** of the criticality assessment, i.e. three levels for cost savings and three levels for downtime reduction.

A second prioritization is then performed based on the calculated benefits for the specific monitoring system. The respective categories used in the context of this project are provided in Table 6 below and reflect the judgement of the industry experts involved in this research project (see Tables 7-11).

Any evaluation of the 'medium' and 'high' categories represents an improvement over the current status. It should be noted that not all critical failure modes have been assessed in such level of detail. This caveat applied in those cases where the respective scenario was already covered by another measure or for those where the failure mechanism did not show any degradation pattern (sudden failure) and, therefore, was not considered suitable for monitoring.

3.5. Benchmarking of substructure structural monitoring options

An alternative method to assess the potential of a substructure monitoring system is proposed as the PF-interval concept used for the wind turbine RNA components has limited applicability for this particular system and components. Firstly, the FMECA results were reviewed and all relevant failure modes extracted. The next step consisted of an analysis of these failure modes and a review of the failure mechanism from root cause to failure mode, with the objective of assessing the potential for monitoring based on known damage mechanisms prior to failure.

A benchmark study of substructure monitoring systems was then performed. This study focused on those mechanisms that take sufficient time before a failure materialises, hence allow sufficient time to react and plan for maintenance mobilization/failure prevention or mitigation. A number of five core questions were formulated to assess the suitability of monitoring systems for each of the previously identified structural failure modes and mechanisms. The questions are:

- Can the inspection frequency be reduced?
- Can the inspection depth/extent be reduced?
- Is it possible to defer unplanned maintenance activities?
- Is an update of structural capacity enabled?
- Can secondary damages be mitigated or prevented by applying a monitoring system?

The scope of the study was narrowed down to cover primary structural items, i.e. the main items with the function to provide structural integrity and load bearing capacity throughout the lifetime. Also, the scope focused on the submerged section of those primary structural items. This is the area of most interest as any inspection activity in this environment is very costly and generally poses an increased risk to personal safety (particularly if divers are used. The five questions listed above were answered by the forum of technical experts during the workshops by a simple 'yes' or 'no'. A 'yes' infers an improvement compared to the current situation while a 'no' refers to no improvement. If a monitoring system was judged to not improving the situation compared to today, it did not qualify for further assessment.

Table 5
Benefits of monitoring categorization.

	Level		
	Low	Medium	High
Downtime Reduction	< 3 days	3 day < downtime < 7 days	7 days < downtime
Cost Savings	0–7.5 k€	7.5–100 k€	> 100 k€
Factor	1	2	3

Table 6
Monitoring benefit categories.

Category	Range
Low	2
Medium	3–4
High	5–6

4. Results

4.1. Overview

A presentation of the main observations made during the implementation of the FMECA process outlined above is provided in this section. Fig. 5 shows an overview of the overall distribution of identified failure modes for each of the main systems within the scope of the project. The largest proportion is related to the substructure, i.e. approximately one third of the 337 failures identified fall into this

Table 7
Prioritized failure modes of blades.

Failure Mode	Cause	Mechanism	Benefit
Cracks and delamination	Manufacturing error	Material failure - Crack opening/delamination/local stress concentrations/ out-of-plane loading conditions	High
Cracks/de-bonding on bonding line	Incorrect adhesive application (lack, inclusion, porosity) – related to manufacturing	Not assessed	N/A
Top coat damage	Underestimation of impact by objects (e.g. birds). Also during transport and installation handling (design error)	Mechanical failure - Crack opening/delamination/local stress concentrations/out-of-plane loading conditions	Medium
Delamination	Insufficient lightning protection (design error)	Material failure - Sudden delamination/crack (similar to impact). Thermal expansion (very fast). Failure mechanism of lightning guidance system is degradation of material.	Medium

category. One reason for this may be that the analysis has been done for the specific purpose of identifying areas that would potentially profit from the application of monitoring systems. Looking deeper into the failure modes assessed for substructures, it can be seen that all of them are related to submerged items. Those items are by nature rather difficult to be inspected so that a tendency for prioritizing them for monitoring can be interpreted as the natural reaction of the experts involved. The second most common failure modes are related to the transformer; both systems together make up almost half of all failure modes. The remaining main systems carry each a comparable weight with values of 16–30 failure modes per item. The pitch system is the smallest contributor of the investigated failure modes with only 5 failure modes. This can be justified by the fact that this system was initially not part of the scope of work; therefore, the focus was rather limited if compared to the predominating failure modes of the rotor system.

The distribution of the overall system criticality is shown in Fig. 6 below. The graph shows the number of failure modes rated with the corresponding criticality value on the horizontal axis. Most of the failure modes are in the medium region (approx. 30); a peak of critical items can be observed towards the right of the figure, from 54 onwards.

As described in the methodology section, only those failure modes with criticality values greater or equal than 44 have been prioritized. Fig. 7 shows the proportion of criticality numbers per system in this criticality region. The overall result looks comparable to Fig. 6; however, the transformer system, the converter and the blade bearings show now a slightly higher number of critical failure modes when compared to the other systems.

The critical failure modes (FM), including a description of their likely cause and mechanism and potential benefit for monitoring category, are presented in the following sections. Since several failure causes may lead to the same failure mode, some of the tables presented contain repetitions of the same failure mode. Since the presentation of all potential failure paths needs to be assessed for evaluating the suitability of a monitoring system, also the paths resulting to the same failure modes have been included and are presented.

4.2. Blades

Four of the blade system failure modes have been prioritized for further investigation of monitoring systems. One FM is related to incorrect application of adhesives and is therefore not assessed in more detail with respect to a possible CBM strategy. Of the remaining three, monitoring of cracks and delamination could provide high value, whereas top coat damage and delamination caused by design errors would not be relevant and therefore, be prevented by the application of monitoring during operation.

Table 9
Prioritized failure modes of pitch system.

Failure Mode	Cause	Mechanism	Benefit
Wear out of gear	Design error	Material failure, wear out	Low

4.3. Blade bearings

Five out of six identified critical failure modes could benefit from the application of monitoring systems. All of them are related to material failures that show a time dependency: fatigue and wear. Several monitoring techniques may be investigated to detect developing failures based on those mechanisms well in advance, respecting the different potential main causes.

4.4. Pitch system

Only one critical failure mode, namely “wear of the pitch gears”, has been identified. A potential monitoring system was, however, not assessed. The current most common maintenance strategy is run-to-failure and a monitoring system was not deemed beneficial.

4.5. Main shaft

A large number of failure modes have been identified for the main shaft, where also the main bearing is considered. The bearing assessment is similar to the blade bearing assessment; i.e. a significant improvement over present practice can be achieved by the use of monitoring systems. Other potential failure modes of the main shaft, such as excessive vibration, leakages or fabrication issues are not expected to have an improvement over the current situation.

4.6. Gearbox

Four monitoring systems would potentially improve the PF-interval

Table 8
Prioritized failure modes of blade bearings.

Failure Mode	Cause	Mechanism	Benefit
Fatigue fracture of raceways	Microgeometry (load zones not properly designed), local overload	Material failure, local overload causing fatigue	High
Fatigue fracture of ball	Microgeometry (load zones not properly designed), local overload	Material failure, local overload causing fatigue	High
Wear of ball	Insufficient material quality (fabrication related)	Material failure, wear out	High
Wear of cages	Shape/roughness inadequately designed	Material failure, wear out	High
Loss of structural integrity	Insufficient material quality (fabrication related)	Material failure causing fatigue	High
Wear of raceways	Lack of grease (O&M related)	Material failure caused by wear out	Low

Table 10
Prioritized failure modes of main shaft.

Failure Mode	Cause	Mechanism	Benefit
Fatigue of raceways or roller	Microgeometry (load zones not properly manufactured), local overload	Material failure, local overload causing fatigue	High
Wear of roller or raceways	Microgeometry (load zones not properly designed), local overload	Material failure, wear out	High
Wear of raceways	Lack of lubrication oil (O&M related)	Material failure, wear out	High
Excessive vibration	Insufficient material quality (general)	Material failure, micro pitting	Low
Excessive vibration	Standstill marks due to long downtime (O&M related)	Mechanical failure, stress concentrations, vibrations, false brinelling	Low
Fatigue of rollers, raceways or cages	Insufficient material quality of items (fabrication related)	Material failure, local overload causing fatigue	Low
Wear (structural deficiency of rollers, raceways or cages)	Insufficient material quality of items (fabrication related)	Material failure, wear out	Low
Wear (structural deficiency of rollers, raceways or cages)	Lightning protection system undermaintained (O&M related)	Mechanical, burn marks on rollers and raceways due to current flow, increased wear	Low
Wear (structural deficiency of rollers, raceways or cages)	Standstill marks on the raceways (O&M related)	Mechanical - Stress concentrations, vibrations, false brinelling	Low
Leakage of lubrication system	Failed couplings (design related)	Mechanical failure, breakage	Low
Failure to start on demand (no grease supply or broken pump)	Electrical failure (O&M related)	Electrical failure	Low

of the prioritized FMs of the gearbox compared to today. The failure mechanisms to be detected cover different fatigue and wear processes as well as various temperature related effects.

4.7. Generator

Significant improvements in the current operation and maintenance of the generator system can be achieved by means of monitoring. Nine mechanisms have been assessed in detail and all of them rank the highest when assessing their impact on PF-intervals. The failure mechanisms cover material degradation and overheating as well as mechanical failures related to vibration and electrical faults related to isolation. Specifically, monitoring the latter electrical failure mechanisms is considered a great improvement to today.

4.8. Transformer

The largest number of failure modes has been identified and prioritized for transformer systems. The failure modes and mechanisms are to a large extent comparable to those identified for the generator, i.e. related to material and electrical faults. However, there are limited possibilities to monitor specific failure modes of the transformer, which leads to further consideration of only two failure modes as having large improvement potential.

4.9. Converter

Improvement potential is expected for three out of the seven identified failure modes in the converter system. Two are related to material failure mechanisms which are expected to have detectable degradation patterns over time. The other one relates to an electrical short circuit, which could also be detected early by analysing simultaneously temperature, current and voltage signals.

4.10. Yaw system

Only one out of the seven identified and prioritized failure modes of the yaw system is deemed to offer a significant improvement potential. This relates to defects in the yaw motor or yaw gear, which may be detected remotely by automatic data analysis methods. Other failure

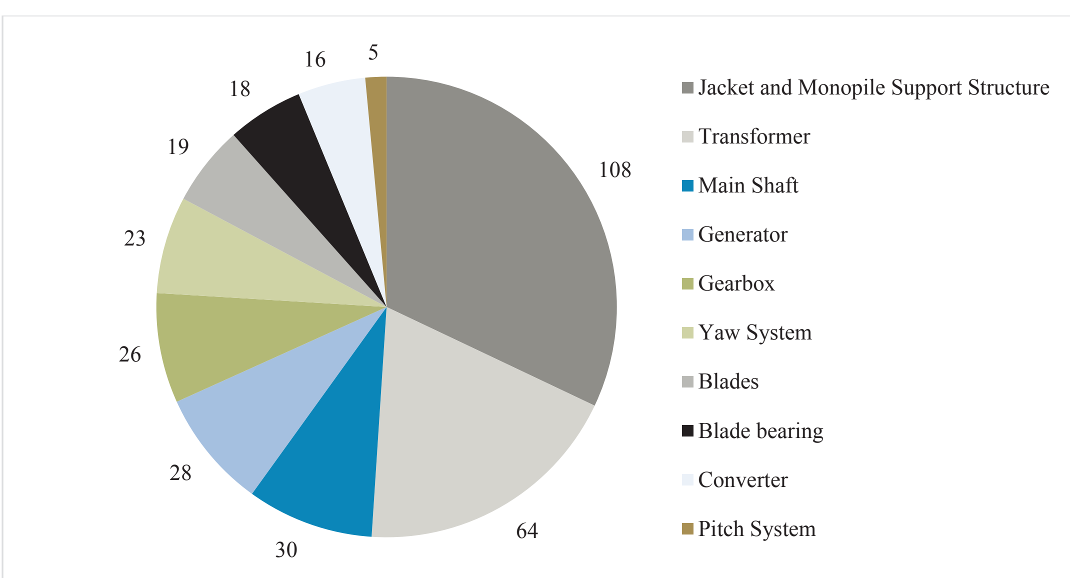

Fig. 5. Number of failure modes for identified for main systems.

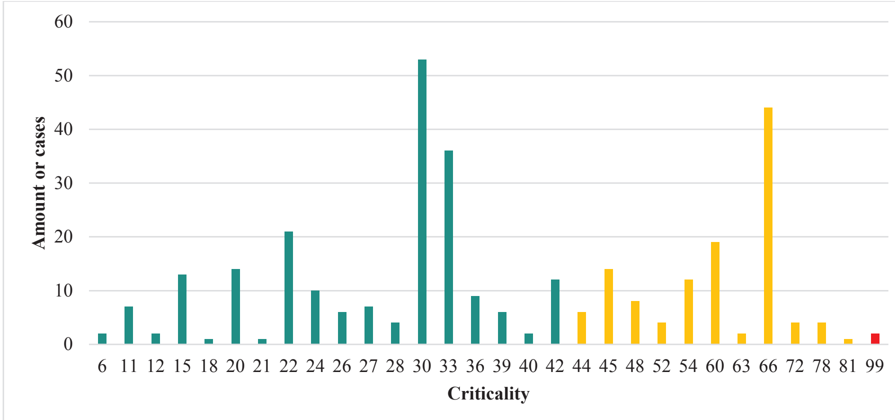

Fig. 6. Distribution of criticality numbers throughout all systems.

mechanisms may also be monitored; however, the impact in respect to PF-interval improvement is deemed limited.

4.11. *Jacket and monopile support structure*

The results show that all assessed and prioritized failure modes in the substructure system have the potential for improvement if compared to their current situation as of today in the event monitoring systems are applied successfully. The total benefit-rating for each failure mode gives an indication on the overall impact and benefit of the monitoring application for the assessed failure mechanism.

Generally, the greatest impact resulting from the application of monitoring systems is deemed to be achieved in the mitigation or prevention of secondary damages (84%). This is followed by the possibility of providing the basis structural capacity update (68%) and deferment of unplanned maintenance activities (64%). Approximately 50% of the assessed failure modes will benefit from a reduction in the substructure inspection frequency and the inspection extent (refer to section 3.5 for further details).

5. Discussion

A risk-based approach has been applied to prioritize OWT systems for analysing the potential value of implementing a CBM strategy. This is based upon extensive expert experience but also long-term operating track records of a large proportion of all wind farms located in European seas.

A comparison study with different other publicly available risk-prioritization studies for WT systems has been carried out to enable investigation of any possible differences that could arise from the particular focus of study, the different data and knowledge bases.

Table 17 shows risk priority of the different studies. For this paper, study (1), the number of critical failure modes identified for each system has been documented. This number reflects the focus for CMS developments, which has been the main objective of the FMECA conducted for achieving those results. In (Kang et al., 2017), study (2), the focus is on system reliability of floating OWTs. The authors intend to identify interconnections between systems to improve overall system reliability. In (Gauravkumar Bharatbhai, 2015), study (3), the focus is somewhat similar, except that this study is specifically done for a 5 MW OWT on a bottom-fixed substructure. A risk analysis and failure mode prioritization is presented in study (4) by (Kougioumtzoglou and Lazakis, 2015), looking at the optimization of O&M of offshore WT systems. Study (5), presented in (Dinmohammadi and Shafiee, 2013), attempts to solve some weaknesses of conventional FMEAs by introducing fuzzy logic. The final aim of this study was to improve system

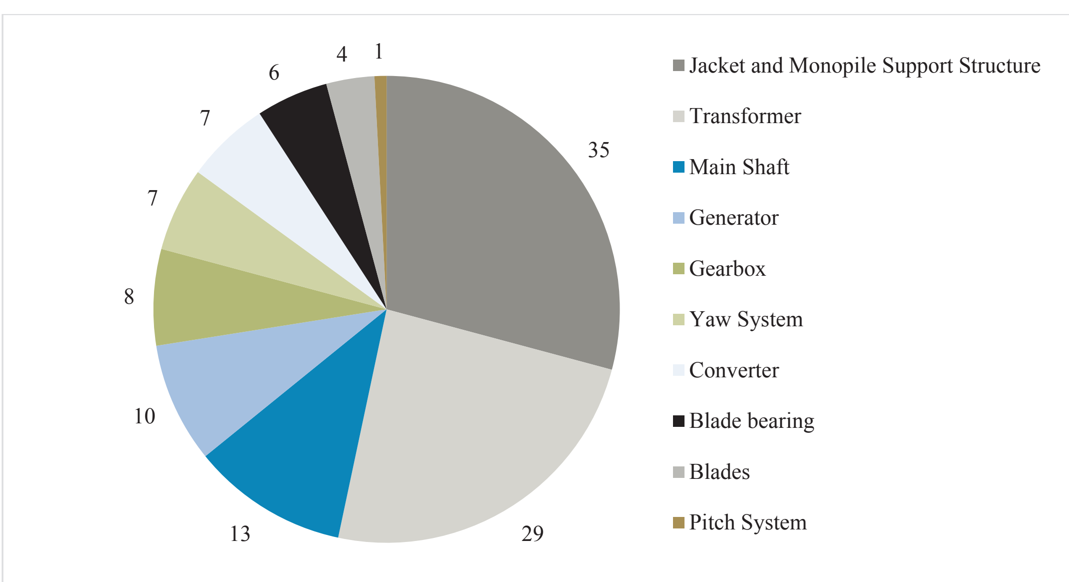

Fig. 7. Number of prioritized failure modes (criticality > 44) for main systems.

Table 11
Prioritized failure modes of gearbox.

Failure Mode	Cause	Mechanism	Benefit
Wear of raceways	Lack of lubrication oil	Material failure, fatigue	Low
Wear of roller	Microgeometry (load zones not properly designed), local overload	Material failure, fatigue	High
Blockage	Lack of lubrication on that local area	Material failure, wear out	High
Cracks in gear	Material inclusion, flaws	Material failure, fatigue	High
Cracking	Insufficient material quality of items	Material failure, micro pitting, cracking, crack development	Low
Insufficient oil cooling	Multiple causes (pump, valve, etc.)	Miscellaneous Various temperature-related effects	Medium

Table 12
Prioritized failure modes of generator.

Failure Mode	Cause	Mechanism	Benefit
Too low magnetization-demagnetized	Underestimation of operating temperature (design related)	Material failure, overheating	High
Too low magnetization-demagnetized	Overestimation of magnet performance lifetime (design related)	General material failure	High
Magnet detachment	General fabrication error	Not assessed	N/A
Loss of insulation in the winding	Insufficient retainment capacity of the winding (design related)	Electrical failure, earth/isolation fault	High
Loss of insulation in the winding	Insulation degradation due to manufacturing/installation quality issues	Electrical failure, earth/isolation fault	High
Loss of insulation in the winding	Insulation degradation due to off design service (e.g.: power throughput too high)	Electrical failure, earth/isolation fault	High
Electrical failure of windings (loss of insulation)	Ageing of insulation material due to insufficient design	Material failure, degradation	High
Electrical failure of windings (loss of insulation)	Vibration in structural elements supporting the coils is underestimated (design related)	Mechanical failure, vibration	High
Electrical failure of windings	Manufacturing quality insufficient	Material failure, accelerated aging	High
Insufficient cooling	Multiple causes (ventilator, etc.). Random electrical failure (fabrication related)	Miscellaneous - Overheating	N/A

Table 13
Prioritized failure modes of transformer.

Failure Mode	Cause	Mechanism	Benefit
Broken	Material not properly selected – design error	Not assessed	N/A
Broken	Insufficient isolating distance – design error	Not assessed	N/A
Broken	Incorrect loading assumption – design error	Not assessed	N/A
Broken	Installation error	Not assessed	N/A
Loss of insulating properties	Maintenance error	Not assessed	N/A
Broken tank	Underestimation of oil pressure – design error	Material failure, overload and breakage	N/A
Broken tank	Fabrication error	Material failure, overload and breakage	N/A
Broken tank	Operated out of service	Material failure, overload and breakage	N/A
Compromised structural integrity to keep the core in place	Insufficient capacity to deal with static and dynamic loads	Material failure, local overload causing fatigue	Medium
Compromised structural integrity to keep the core in place	Out of tolerance manufacturing	Material failure, local overload causing fatigue	Medium
Loss of insulation in the winding	Insulation degradation due to manufacturing/installation quality issues	Electrical failure, earth/isolation fault	Medium
Loss of insulation in the winding	Insulation degradation due to off design service (e.g.: power throughput too high)	Electrical failure, earth/isolation fault	Medium
Loss of insulation in the winding	Overestimation of insulation performance lifetime	Electrical failure, earth/isolation fault	Medium
Compromised structural integrity to keep the core in place	Insufficient capacity to resist static and dynamic loads	Material failure, local overload causing fatigue	High
Compromised structural integrity to keep the core in place	Out of tolerance manufacturing	Material failure, local overload causing fatigue	High
Insufficient cooling	Multiple causes (ventilator, etc.). Random electrical failure	Miscellaneous failures, overheating	N/A

Table 14
Prioritized failure modes of converter.

Failure Mode	Cause	Mechanism	Benefit
Degradation	General fabrication errors	Material failure, chemical composition inside capacitor changes	Medium
Degradation	Fabrication errors/polluted microchips	Electrical failure, short circuit	Medium
Broken soldering of parts to the PCB	Fabrication errors/bad soldering	Electrical failure, open or short circuit	N/A
Failed deionization	Expected wear and tear	Material failure, electrochemical corrosion	N/A
Electrical failure	Fabrication error (e.g.: polluted microchips, etc.)	Electrical failure, short circuit	N/A
Electrical failure	Fabrication error	Material, failure in component behaviour	Medium
Insufficient cooling	Multiple causes (ventilator, etc.). Random electrical failure	Miscellaneous failure, overheating	Low

reliability and to optimize maintenance by using any possible data input, such as expert opinions but also SCADA data. Study (6), presented in (Kahrobaee and Asgarpoor, 2011), focuses on failure effect mitigation by thorough understanding of system failure modes and causes. This study was applied to an onshore WT system. Study (7), presented in (Arabian-Hoseynabadi et al., 2010) focuses on system

Table 15
Prioritized failure modes of yaw system.

Failure Mode	Cause	Mechanism	Benefit
Leakages of the hydraulic system	Specification of fittings insufficient (design related)	Not assessed	N/A
Leakages of the hydraulic system	Fittings installed out of tolerance	Not assessed	N/A
Electrical failure	Overheating (O&M related)	Degradation accelerated by overheating, decrease insulation aging, wearing	Low
Electrical failure	Overheating (O&M related)	Overheating due to high continuous load on the yaw motor due to wind loads	N/A
Leakage of lubrication system	Failed couplings	Breakage	Low
Electrical failure	Currently unclear	Defect Motor and/or yaw gear	Medium
Faulty signal	Undesired misalignment of the sensor during maintenance works	External impact on the sensor	Low

Table 16
Prioritized failure modes of substructure.

Failure Mode	Cause	Mechanism	Benefit
Excessive Corrosion	Design	Insufficient cathodic protection (electric potential),	Medium
Fatigue	Design	Underestimation of wind turbine loads, environmental conditions and operational conditions e.g. extreme events, grid faults (Jacket)	High
	Design	Underestimation of marine growth	Medium
	Fabrication and Installation	Earlier crack initiation and crack growth/propagation through cyclic loading (acoustic)	Medium
	Operation and Maintenance	Scour protection damage, scour depth increased, degradation excessive loading	Medium
	Operation and Maintenance	ICCP system reference cell is broken and gives wrong values, under protection, corrosion (hot redundancy of reference cell provides correct electrical potential)	Medium
	Design	ICCP system in place, ventilation system for compartment faulty, H2 is exceeding allowed concentration, material becomes brittle, crack initiation and growth accelerated.	Medium
	Design	Underestimation of wind turbine loads, environmental conditions and operational conditions e.g. extreme events, grid faults (Monopile)	Medium
	Fabrication and Installation	Excessive fatigue life consumption/loading during handling at fabrication site, during shipping and during installation (CMS in place before operational phase)	Low
Deformation, Buckling, Displacement of steel	Design	Overestimation of soil capacity, soil degradation, pile displacement rotation	High
	Design	Underestimation of environmental and operational condition, excessive loading, buckling, crack formation	Medium
	Operation and Maintenance	Scour degradation, scour depth increased, excessive displacement of scour material	Medium
Grouted Connection MP/TP	Fabrication and Installation	Loss of hard material, water ingress in porous material, sliding (LVDT) of grout against steel	High
	Design	Loss of hard material, water ingress in porous material, sliding of grout against steel	High
	Design	Excessive loads and displacement, de-bonding/lack of contact between steel and grout, sliding	High
	Fabrication and Installation	Failed grout seal, leakage/over spilling, volume of grout is insufficient, reduced capacity in connection, global dynamics changed	Medium
	Fabrication and Installation	Improper thermal environment during installation/curing process, reduced capacity of grout, global dynamics changed	Medium
	Fabrication and Installation	Eccentricity during installation caused reduced capacity at one side of the MP/TP connection. global dynamics changed	Medium
Broken bolted connection	Design	Poorly specified pretension force, loosening of connection at one bolt, more bolts to loosen	Medium
	Operation and Maintenance	Internal climate control broken, high humidity, corrosive environment	Low

reliability improvement of future designs of onshore WTs (see Tables 12-16).

It should be noted that system topology is not consistent throughout the studies. This is reflected by zeros in the table below, meaning that a specific item may have been included in study X but not in study Y. The items were grouped into subassemblies and systems as appropriate and in accordance with industry practice. In all cases, the total sum of individual contributors totals 100%.

Towers and substructures account for almost one third of all critical failure modes identified in the course of this paper. This number is unprecedented in the context of the literature available in this subject area. In studies (2), (3), (6) and (7), this category contributes less than 10% of the critical FMs, whereas the contribution is rather significant in studies (4) and (5) which have a strong focus on O&M optimization of OWT. Studies (2) and (3) focus on system reliability; studies (6) and (7) deal with onshore wind applications and therefore do not contain the critical submerged area that is mostly associated with the critical FMs identified in this study. It can therefore be concluded that studies focusing on O&M and condition monitoring account more for structural FMs than those focused on system reliability or onshore wind applications.

The second highest priority for CMS developments is related to the transformer system. This system is identified as somewhat critical in study (2), however not at the magnitude reported in this present paper. The other studies either did not include the transformer in their assessment, or this system did not contribute significantly to the most critical FMs. It should be noted that some studies refer to converter and transformer in one system. But even if this would be the case for all studies, this assembly would not be in the foremost position of risk priority.

A particular observation is made for the generator system of study (2). With more than 40%, this system is the most significant in study (2). From the original paper, it appears that this is due to the specific nature of FOWT application (Kang et al., 2017). Interestingly, the generator is a top risk also for the onshore-specific studies number (6) and (7). Furthermore, main shaft and bearing are included in the

Table 17
Risk priority comparison between this study (1) and others available in the literature.

System	1	2	3	4	5	6	7
Blades	3,33%	0,00%	2,01%	0,00%	12,87%	7,38%	17,81%
Blade Bearings	5,00%	0,00%	0,00%	9,28%	2,94%	0,00%	0,00%
Pitch System	0,83%	0,00%	14,88%	20,62%	6,86%	6,46%	7,66%
Main Shaft	10,83%	0,00%	9,36%	6,19%	9,07%	6,46%	2,72%
Gearbox	6,67%	0,00%	16,22%	9,28%	12,87%	0,00%	10,06%
Generator	8,33%	40,72%	6,69%	6,19%	8,58%	12,31%	13,33%
Transformer	24,17%	12,68%	0,00%	6,19%	7,35%	0,00%	0,00%
Converter	5,83%	12,93%	3,01%	0,00%	10,29%	9,23%	0,00%
Yaw System	5,83%	0,00%	12,54%	12,37%	1,96%	3,69%	9,00%
Tower & Substructure	29,17%	6,98%	6,02%	14,43%	17,40%	8,62%	5,62%
Auxiliary Systems	0,00%	11,41%	7,53%	0,00%	0,00%	6,15%	0,00%
Controls	0,00%	15,27%	4,01%	0,00%	0,00%	10,77%	10,24%
Grid & Electrical	0,00%	0,00%	0,00%	9,28%	0,74%	9,23%	9,65%
Hydraulics	0,00%	0,00%	5,69%	0,00%	0,00%	5,54%	10,19%
Mechanical Brake	0,00%	0,00%	6,02%	0,00%	3,43%	9,69%	3,72%
Nacelle Housing	0,00%	0,00%	6,02%	0,00%	0,74%	0,00%	0,00%
Rotor Hub	0,00%	0,00%	0,00%	6,19%	4,90%	4,46%	0,00%
Sum	100,00%	100,00%	100,00%	100,00%	100,00%	100,00%	100,00%

generator assembly in Kang's study which explains the rather high risk priority number. With around one quarter of the critical FMs, the drive train components consisting of main shaft, main bearing, gearbox and generator are still deemed a critical assembly in this study which is in accordance with earlier studies.

The blade assembly does not contribute significantly to the critical failure modes in this study; however, it carries some weight in the onshore studies (6) and (7) as well as in a former offshore study (5). It appears as if the respective FMs are well covered by O&M technology, such as sensors, in more recent applications. The same reasoning applies to the pitch system, which is less of a focus in this study, but contributes significantly to critical FMs in earlier studies, particularly number (3) and (4), which relate to improved O&M and system reliability.

Overall, the referred studies have a similar profile; however, this paper in particular emphasises the potential of CMS developments for substructures and foundations as well as transformer systems and the main shaft (including main bearing). It is found that the proposed methodology ensures that (i) expert knowledge, (ii) operating track records and (iii) design information is used collectively – enabling a comprehensive all-encompassing transparent system analysis. Development efforts for condition monitoring systems can in this manner be targeted towards the most critical systems.

It may be argued, however, that costs for developing and implementing monitoring systems are not included in this study which makes it difficult to assess the cost-effectiveness in the long-term of such systems. It may also be argued that the results presented only compare the state-of-the-art (i.e. what is currently been done) and the application of condition monitoring. Other strategies, such as increased efforts for predetermined preventive maintenance for instance, are not considered in the assessment. Such strategies may lead to a different risk prioritization that could eliminate or mitigate some of the failure modes prioritized in this study. Regarding both points, it should be noted that the objective of this study is to provide an un-biased and realistic risk analysis of wind turbine systems. For each specific failure mode, a number of different ways forward can be considered based on the results obtained in the analysis. This study has considered the development of a monitoring solution for specific, prioritized failure modes. Such a development should be preceded by a comprehensive evaluation of the opportunities and limitations of all possible options for failure mode treatment. This should be supported by a thorough cost analysis in order to assess the impact of each of the options in a fully transparent manner.

6. Conclusion

This paper presents the most critical failure modes of state-of-the-art offshore wind turbine systems. Each failure mode is investigated considering the opportunity to optimize O&M (less inspections or higher PF-interval) through the application of condition monitoring systems. Failure causes and mechanisms are evaluated in order to establish the degradation patterns that may be potentially identified by a monitoring system. A total of 337 individual failure modes have been identified and analysed by a consortium representing more than 70% of the total offshore wind capacity installed in Europe today. Results were to some extent in accordance with other studies; however, a particular potential for monitoring of substructures and foundations as well as transformer systems and the main shaft (including main bearing) has been identified. Further work involves the prioritization of all failure modes to be followed by the development of diagnosis and prognosis tools to be implemented in pilot tests at the Teesside, Wikinger and East Anglia Offshore Wind Farms.

This study provides the reader with a structured and transparent, risk-based assessment methodology that helps optimize O&M and to minimise operational expenditure. It further provides detailed information about the paths leading to critical failure modes. Those paths must be understood in order to properly design targeted and useful condition monitoring systems. As a first of its kind, this paper draws upon extensive operating experience, making the methodology and results highly applicable to the industry.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 745625 (ROMEO) ("Romeo Project" 2018). The dissemination of results herein reflects only the author's view and the European Commission is not responsible for any use that may be made of the information it contains. Furthermore, this work was supported by grant EP/L016303/1 for Cranfield University and the University of Oxford, Centre for Doctoral Training in Renewable Energy Marine Structures - REMS (http://www.rems-cdt.ac.uk/) from the UK Engineering and Physical Sciences Research Council (EPSRC)" and Ramboll Energy (http://www.ramboll.com\energy).

References

Arabian-Hoseynabadi, H., Oraee, H., Tavner, P.J., 2010. Failure Modes and Effects Analysis (FMEA) for Wind Turbines. Int. J. Electr. Power Energy Syst. 32 (7), 817–824. https://doi.org/10.1016/J.IJEPES.2010.01.019.

Arcadius Tokognon, C., Gao, Bin, Tian, Gui Yun, Yan, Yan, 2017. Structural health monitoring framework based on internet of things: a survey. IEEE Internet Things J. 4 (3), 619–635. https://doi.org/10.1109/JIOT.2017.2664072.

Artigao, Estefania, Koukoura, Sofia, Honrubia-Escribano, Andrés, Carroll, James, Mcdonald, Alasdair, Gómez-Lázaro, Emilio, 2018a. Current signature and vibration analyses to diagnose an in-service wind turbine drive train. Energies. https://doi.org/10.3390/en11040960.

Artigao, Estefania, Martín-Martínez, Sergio, Honrubia-Escribano, Andrés, Gómez-Lázaro, Emilio, 2018b. Wind turbine reliability: a comprehensive review towards effective condition monitoring development. Appl. Energy 228 (October), 1569–1583. https://doi.org/10.1016/J.APENERGY.2018.07.037.

British Standards Institution, 1991. Reliability of Systems, Equipment and Components. Pt. 5, Guide to Failure Modes, Effects and Critically Analysis (FMEA and FMECA). BSI. https://shop.bsigroup.com/ProductDetail/?pid=000000000000256425.

Burton, Tony, Sharpe, David, Jenkins, Nick, Bossanyi, Ervin, 2001. Wind Energy Handbook. John Wiley & Sons, Ltd, Chichester, UK. https://doi.org/10.1002/0470846062.

Bussel, Gerard Van, Schöntag, Chr, 1997. Operation and Maintenance Aspects of Large Offshore Windfarms Wind Turbine Wake Studies Using Simple Vortex Methods View Project Dutch Offshore Wind Energy Convertor, DOWEC View Project Operation and Maintenance Aspects of Large Offshore Windfarms. http://www.ct.tudelft.nl/windenergy/ivwhome.htm.

Bussel, GJW Van, Zaaijer, M.B., 2001. Reliability, availability and maintenance aspects of large-scale offshore wind farms, a concepts study. 113 1–1.

Carroll, James, McDonald, Alasdair, McMillan, David, 2016. Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines. Wind Energy. https://doi.

org/10.1002/we.1887.
Caselitz, Peter, Giebhardt, Jochen, 2005. Rotor condition monitoring for improved operational safety of offshore wind energy converters. J. Sol. Energy Eng. 127 (2), 253. https://doi.org/10.1115/1.1850485.
Colone, L., Reder, M., Tautz-Weinert, J., Melero, J.J., Natarajan, A., Watson, S.J., 2017. Optimisation of data acquisition in wind turbines with data-driven conversion functions for sensor measurements. In: Energy Procedia, . https://doi.org/10.1016/j.egypro.2017.10.386.
Coronado, Diego, Fischer, Katharina, 2015. CONDITION MONITORING OF WIND TURBINES: STATE OF THE ART, USER EXPERIENCE AND RECOMMENDATIONS. Fraunhofer IWES Publication.
Dao, Phong B., Staszewski, Wieslaw J., Barszcz, Tomasz, Uhl, Tadeusz, 2018. Condition Monitoring and Fault Detection in Wind Turbines Based on Cointegration Analysis of SCADA Data. Renew. Energy 116 (February), 107–122. https://doi.org/10.1016/J.RENENE.2017.06.089.
Devriendt, Christof, Magalhães, Filipe, Weijtjens, Wout, De Sitter, Gert, Cunha, Álvaro, Guillaume, Patrick, 2014. Structural health monitoring of offshore wind turbines using automated operational modal analysis. Struct. Health Monit.: Int. J. 13 (6), 644–659. https://doi.org/10.1177/1475921714556568.
Dinmohammadi, F., Shafiee, M., 2013. A Fuzzy-FMEA Risk Assessment Approach for Offshore Wind Turbines. Int. J. Prognostics Health Manag 4 (4), 1–10.
El-Thalji, Idriss, Jantunen, Erkki, 2012. On the development of condition based maintenance strategy for offshore wind farm: requirement elicitation process. Energy Procedia 24, 328–339. January. https://doi.org/10.1016/J.EGYPRO.2012.06.116.
EN 13306: Maintenance Terminology, 2017. European Standard. www.ds.dk.
EN 60812, 2006. Analysis Techniques for System Reliability - Procedure for Failure Mode and Effects Analysis (FMEA).
European Commission, 2014. Energy Economic Developments in Europe. https://doi.org/10.2765/72195.
European Standard 14224, 2006. Petroleum, Petrochemical and Natural Gas Industries-Collection and Exchange of Reliability and Maintenance Data for Equipment. European Standard, pp. 14224.
Feng, Y., Tavner, P.J., Long, H., 2010. Early Experiences with UK Round 1 Oshore Wind Farms. Proc. Inst. Civ. Eng.: Energy 163 (4), 0–1. https://doi.org/10.1680/ener.2010.163.0.1.
Fischer, Tim, 2012. Mitigation of Aerodynamic and Hydrodynamic Induced Loads of Offshore Wind Turbines. Shaker. https://www.shaker.de/de/content/catalogue/index.asp?lang=de&ID=8&ISBN=978-3-8440-1501-0.
Fischer, Katharina, Francois, Besnard, Bertling, L., IEEE Transactions on Energy, Undefined 2012, Lina Bertling, 2012. Reliability-centred maintenance for wind turbines based on statistical analysis and practical experience. IEEE Trans. Energy Conv. 27 (1), 184–195. https://doi.org/10.1109/TEC.2011.2176129.
Gauravkumar Bharatbhai, Mehta, 2015. Failure mode and effect analysis of repower 5M wind turbine. Int. J. Adv. Res. Eng. 2.
Garcia, Mari Cruz, Miguel, A., Sanz-Bobi, Javier del Pico, 2006. SIMAP: Intelligent System for Predictive Maintenance: Application to the Health Condition Monitoring of a Windturbine Gearbox. Comput. Ind. 57 (6), 552–568. https://doi.org/10.1016/J.COMPIND.2006.02.011.
Gonzalez, E., Reder, M., Melero, J.J., Journal of Physics: Conference, and Undefined 2016, 2016. SCADA Alarms Processing for Wind Turbine Component Failure Detection. Iopscience.Iop.Org.. http://iopscience.iop.org/article/10.1088/1742-6596/753/7/072019/meta.
Gonzalez, Elena, Julio, J Melero, González, E., Melero, J.J., 2017a. Wind Turbine Component Fault Detection by Monitoring Its Performance Using High-Resolution SCADA Data Performance Monitoring Techniques for the Operation and Maintenance of Wind Turbines View Project Wind Farm Management Cost Optimization View Project Win. https://www.researchgate.net/publication/316473396.
Gonzalez, Elena, Emmanouil, M. Nanos, Helene, Seyr, Laura, Valldecabres, Nurseda, Y. Yürüşen, Ursula, Smolka, Michael, Muskulus, Julio, J. Melero, 2017b. Key performance indicators for wind farm operation and maintenance. In: Energy Procedia, . https://doi.org/10.1016/j.egypro.2017.10.385.
Gonzalez, E., Tautz-Weinert, J., Melero, J.J., Watson, S.J., 2018. Statistical evaluation of SCADA data for wind turbine condition monitoring and farm assessment. 32038. https://doi.org/10.1088/1742-6596/1037/3/032038.
González-González, Asier, Cortadi, Alberto Jimenez, Galar, Diego, Ciani, Lorenzo, 2018. Condition monitoring of wind turbine pitch controller: a maintenance approach. Measurement 123, 80–93. July. https://doi.org/10.1016/J.MEASUREMENT.2018.01.047.
Gray, Christopher S., Watson, Simon J., 2010. Physics of failure approach to wind turbine condition based maintenance. Wind Energy. https://doi.org/10.1002/we.360.
Gray, Anthony, Dickens, Beth, Bruce, Tom, Ashton, Ian, Johanning, Lars, 2017. Reliability and O&M Sensitivity Analysis as a Consequence of Site Specific Characteristics for Wave Energy Converters. Ocean Eng. 141, 493–511. September. https://www.sciencedirect.com/science/article/pii/S0029801817303359.
Hameed, Z., Hong, Y.S., Cho, Y.M., Ahn, S.H., Song, C.K., 2009. Condition monitoring and fault detection of wind turbines and related algorithms: a review. Renew. Sustain. Energy Rev. 13 (1), 1–39. https://doi.org/10.1016/J.RSER.2007.05.008.
Hameed, Z., Ahn, S.H., Cho, Y.M., 2010. Practical aspects of a condition monitoring system for a wind turbine with emphasis on its design, system architecture, testing and installation. Renew. Energy 35 (5), 879–894. https://doi.org/10.1016/J.RENENE.2009.10.031.
Horenbeek, Adriaan Van, Van Ostaeyen, Joris, Duflou, Joost R., Pintelon, Liliane, 2013. Quantifying the added value of an imperfectly performing condition monitoring system—application to a wind turbine gearbox. Reliab. Eng. Syst. Saf. 111, 45–57. March. https://www.sciencedirect.com/science/article/pii/S0951832012002104.
ISO31000, 2009. Risk Management-Principles and Guidelines.
ISO31010, 2010. Risk Management-Risk Assessment Techniques.
Jackson, Tyrone, Warren, Bruce, Marietta, Martin, San Diego, 1995. Standardizing the FMECA Format: A Guideline for Air Force Contractors.
Juhaszova, Darina, 2013. Quality innovation prosperity/kvalita inovácia prosperita XVII/2-2013 failure analysis in development & manufacture for customer. https://doi.org/10.12776/QIP.V17I2.203.
Kahrobaee, Salman, Asgarpoor, Sohrab, 2011. Risk-based failure mode and effect analysis for wind turbines (RB-FMEA). In: North American Power Symposium (NAPS), 2011. https://doi.org/10.1109/NAPS.2011.6025116.
Kang, Jichuan, Sun, Liping, Sun, Hai, Wu, Chunlin, 2017. Risk assessment of floating offshore wind turbine based on correlation-FMEA. Ocean Eng. 129, 382–388. January. https://doi.org/10.1016/J.OCEANENG.2016.11.048.
Kostandyan, Erik E., Sorensen, John D., 2012. Physics of failure as a basis for solder elements reliability assessment in wind turbines. Reliab. Eng. Syst. Saf. https://doi.org/10.1016/j.ress.2012.06.020.
Kougioumtzoglou, Maria A., Iraklis, Lazakis, 2015. Developing a Risk Analysis and Decision Making Strategy for an Offshore Wind Farm. https://pure.strath.ac.uk/portal/en/publications/developing-a-risk-analysis-and-decision-making-strategy-for-an-offshore-wind-farm(ffd0b46e-7f81-40c5-acdc-495a72b27f31).html.
Kusiak, Andrew, Li, Wenyan, 2011. The prediction and diagnosis of wind turbine faults. Renew. Energy 36 (1), 16–23. https://doi.org/10.1016/J.RENENE.2010.05.014.
Lapira, Edzel, Brisset, Dustin, Ardakani, Hossein Davari, Siegel, David, Lee, Jay, 2012. Wind turbine performance assessment using multi-regime modeling approach. Renew. Energy 45, 86–95. September. https://doi.org/10.1016/J.RENENE.2012.02.018.
Leimeister, Mareike, Kolios, Athanasios, 2018. A Review of Reliability-Based Methods for Risk Analysis and Their Application in the Offshore Wind Industry. Renew. Sustain. Energy Rev. 91, 1065–1076. August. https://doi.org/10.1016/J.RSER.2018.04.004.
Lu, Bin, Li, Yaoyu, Wu, Xin, Yang, Zhongzhou, 2009. A review of recent advances in wind turbine condition monitoring and fault diagnosis. In: In 2009 IEEE Power Electronics and Machines in Wind Applications. IEEE, pp. 1–7. https://doi.org/10.1109/PEMWA.2009.5208325.
Luengo, Maria, Kolios, Athanasios, 2015. Failure mode identification and end of life scenarios of offshore wind turbines: a review. Energies 8 (8), 8339–8354. https://doi.org/10.3390/en8088339.
Maples, B., Saur, G., Hand, M., Van De Pietermen, R., Obdam, T., 2013. Installation, Operation, and Maintenance Strategies to Reduce the Cost of Offshore Wind Energy. www.nrel.gov/publications.
Martinez-Luengo, Maria, Kolios, Athanasios, Wang, Lin, 2016. Structural health monitoring of offshore wind turbines: a review through the statistical pattern recognition paradigm. Renew. Sustain. Energy Rev. 64 (October), 91–105. https://doi.org/10.1016/J.RSER.2016.05.085.
Mathur, Amit, Cavanaugh, Kevin F., Pattipati, Krishna R., Willett, Peter K., Galie, Thomas R., 2001. Reasoning and modeling systems in diagnosis and prognosis. In: Willett, Peter K., Kirubarajan, Thiagalingam (Eds.), In *SPIE - The International Society for Optical Engineering*, pp. 194–203. https://doi.org/10.1117/12.434239.
Matthews, Peter C., Chen, Bindi, Tavner, Peter J., 2015. Automated on-line fault prognosis for wind turbine pitch systems using supervisory control and data acquisition. In: IET Renewable Power Generation, . https://doi.org/10.1049/iet-rpg.2014.0181.
Moubray, John, 1992. Reliability-Centered Maintenance. Industrial Press.
Nabati, Elaheh Gholamzadeh, Thoben, Klaus-Dieter, 2017. Data driven decision making in planning the maintenance activities of off-shore wind energy. Procedia CIRP 59, 160–165. January. https://doi.org/10.1016/J.PROCIR.2016.09.026.
Nie, Mengyan, Wang, Ling, 2013. Review of condition monitoring and fault diagnosis technologies for wind turbine gearbox. Procedia CIRP 11, 287–290. January. https://doi.org/10.1016/J.PROCIR.2013.07.018.
Nielsen, Jannie Jessen, Dalsgaard Sørensen, John, 2011. On Risk-Based Operation and Maintenance of Offshore Wind Turbine Components. Reliab. Eng. Syst. Saf. 96 (1), 218–229. https://doi.org/10.1016/J.RESS.2010.07.007.
Nielsen, Jannie Sønderkær, Dalsgaard Sørensen, John, 2014. Methods for risk-based planning of O&M of wind turbines. Energies. https://doi.org/10.3390/en7106645.
Nielsen, J.J., Sørensen, J.D., 2009. Risk-Based Operation and Maintenance of Offshore Wind Turbines. pp. 61–64.
NORSOK STANDARD Z-008, 2001. Criticality Analysis for Maintenance Purposes. Norwegian Technology Centre. www.nts.no/norsok.
Offshore Renewable Energy Catapult, 2016. "Portfolio Review." *System Performance, Availability and Reliability Trend Analysis*. Own Publication.
Peinke, J. Joachim, Peter, Schaumann, Barth, Stephan, 2007. Wind Energy : Proceedings of the Euromech Colloquium. Springer. https://cordis.europa.eu/result/rcn/55560_en.html.
Pineda, Iván, Pierre Tardieu, WindEurope, 2017. Key Trends and Statistics 2016 The European Offshore Wind Industry WindEurope Business Intelligence Andrew Ho (Construction Highlights) Ariola Mbistrova (Financing Highlights) Courtesy of ScottishPower Renewables Offshore Wind Farm: West of Duddon Sands.
Polinder, H., Van Der Pijl, F.F.A., De Vilder, G.-J., Tavner, P.J., 2006. Comparison of direct-drive and geared generator concepts for wind turbines. IEEE Trans. Energy Convers. 21 (3), 725–733. https://doi.org/10.1109/TEC.2006.875476.
Rademakers, L., Braam, H., 2003. O&M Aspects of the 500 MW Offshore Wind Farm at NL7. In: Ecn.Nl DOWEC 10090 Rev 1, . https://www.ecn.nl/fileadmin/ecn/units/wind/docs/dowec/10090_001.pdf.
Reder, M.D., Gonzalez, E., Melero, J.J., 2016. Wind turbine failures - tackling current problems in failure data analysis. J. Phys. Conf. 753 (7) 072027. https://doi.org/10.1088/1742-6596/753/7/072027.
Reliability Analysis Centre, 1993. "Failure Mode, Effects and Criticality Analysis (FMECA)" CRTA-FMECA.
Romeo Project." 2018. 2018. https://www.romeoproject.eu/documents/.

Romero, Antonio, Soua, Slim, Gan, Tat-Hean, Wang, Bin, 2018. Condition monitoring of a wind turbine drive train based on its power dependant vibrations. Renew. Energy 123, 817–827. August. https://doi.org/10.1016/J.RENENE.2017.07.086.
Scheu, Matti, 2012. Maintenance Strategies for Large Offshore Wind Farms. https://doi.org/https://doi.org/10.18419/opus-8779.
Shafiee, Mahmood, Dinmohammadi, Fateme, 2014. An FMEA-based risk assessment approach for wind turbine systems: a comparative study of onshore and offshore. Energies 7 (2), 619–642. https://doi.org/10.3390/en7020619.
Sharma, Sachin, Mahto, Dalgobind, 2013. Condition Monitoring of Wind Turbines: A Review. Int. J. Sci. Eng. Res. 4 (8). http://www.ijser.org.
Sheng, Chenxing, Li, Zhixiong, Qin, Li, Guo, Zhiwei, Zhang, Yuelei, 2011. Recent progress on mechanical condition monitoring and fault diagnosis. Procedia Eng. 15, 142–146. January. https://doi.org/10.1016/J.PROENG.2011.08.029.
Smolka, Ursula, Cheng, Po Wen, 2013. On the Design of Measurement Campaigns for Fatigue Life Monitoring of Offshore Wind Turbines. June. https://www.onepetro.org/conference-paper/ISOPE-I-13-041.
Sørensen, John Dalsgaard, 2009. Framework for risk-based planning of operation and maintenance for offshore wind turbines. Wind Energy 12 (5), 493–506. https://doi.org/10.1002/we.344.
Surface Vehicle Standard, 2009. "SAE-J-1739: Potential Failure Mode and Effects Analysis in Design (DFMEA), Manufacturing and Assembly Processes (Process FMEA)." *Surface Vehicle Standard*.
Tautz-Weinert, Jannis, Watson, Simon J., 2017. "Using SCADA Data for Wind Turbine Condition Monitoring – a Review. IET Renew. Power Gener. 11 (4), 382–394. https://doi.org/10.1049/iet-rpg.2016.0248.
Tavner, P., 2012. Offshore Wind Turbines: Reliability. Community.Dur.Ac.Uk. https://community.dur.ac.uk/supergen.wind/docs/presentations/2011-03-24_Session4_OffshoreReliabilityExperience_PJT.pdf.
Tavner, Peter, Faulstich, S., Hahn, B., van Bussel, G.J.W., 2010. Reliability & availability of wind turbine electrical & electronic components. EPE J. https://doi.org/10.1080/09398368.2010.11463777.
Tchakoua, Pierre, Wamkeue, René, Ouhrouche, Mohand, Slaoui-Hasnaoui, Fouad, Tommy Andy, Tameghe, Gabriel, Ekemb, 2014. Wind turbine condition monitoring: state-of-the-art review, new trends, and future challenges. Energies. https://doi.org/10.3390/en7042595.
Tian, Zhigang, Jin, Tongdan, Wu, Bairong, Ding, Fangfang, 2011. Condition Based Maintenance Optimization for Wind Power Generation Systems under Continuous Monitoring. Renew. Energy 36 (5), 1502–1509. https://doi.org/10.1016/J.RENENE.2010.10.028.
Verbruggen, T.W., 2003. "Wind turbine operation & maintenance based on condition monitoring WT-Ω final report. In: Wind Turbine Operation and Maintenance Based on Condition Monitoring (WT_OMEGA) Project Report.
VGB-Standard RDS-PP ® Application Guideline Part 32: Wind Power Plants." 2014. www.vgb.org.
Wang, Peng, Tian, Xinliang, Peng, Tao, Luo, Yong, 2018. A review of the state-of-the-art developments in the field monitoring of offshore structures. Ocean Eng. 147, 148–164. January. https://doi.org/10.1016/J.OCEANENG.2017.10.014.
Weijtjens, Wout, Tim Verbelen, Capello, Emanuele, Devriendt, Christof, 2017. Vibration based structural health monitoring of the substructures of five offshore wind turbines. Procedia Eng. 199, 2294–2299. January. https://doi.org/10.1016/J.PROENG.2017.09.187.
Wiggelinkhuizen, Edwin, Verbruggen, Theo, Henk Braam, Rademakers, Luc, Xiang, Jianping, Watson, Simon, 2008. Assessment of condition monitoring techniques for offshore wind farms. J. Sol. Energy Eng. 130 (3), 031004. https://doi.org/10.1115/1.2931512.
Wilkinson, Michael R., Spinato, Fabio, Tavner, Peter J., 2007. Condition monitoring of generators & other subassemblies in wind turbine drive trains. In: 2007 IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives. IEEE 388–92. https://doi.org/10.1109/DEMPED.2007.4393125.
Yang, W., 2016. Condition Monitoring of Offshore Wind Turbines. *Offshore Wind Farms*, January, pp. 543–572. https://doi.org/10.1016/B978-0-08-100779-2.00018-0.
Yang, Wenxian, Tavner, Peter J., Crabtree, Christopher J., Wilkinson, Michael, 2010. Cost-effective condition monitoring for wind turbines. In: IEEE Transactions on Industrial Electronics, . https://doi.org/10.1109/TIE.2009.2032202.
Yang, Wenxian, Court, Richard, Jiang, Jiesheng, 2013. Wind turbine condition monitoring by the approach of SCADA data analysis. Renew. Energy 53 (May), 365–376. https://doi.org/10.1016/J.RENENE.2012.11.030.
Zhou, Anmei, Yu, Dejie, Zhang, Wenyi, 2015. A research on intelligent fault diagnosis of wind turbines based on ontology and FMECA. Adv. Eng. Inf. 29 (1), 115–125. https://doi.org/10.1016/J.AEI.2014.10.001.
Ziegler, Lisa, Muskulus, Michael, 2016. 2016 EAWE PhD Seminar 12 Th EAWE PhD Seminar on Wind Energy in Europe LIFETIME EXTENSION OF OFFSHORE WIND MONOPILES: ASSESSMENT PROCESS AND RELEVANCE OF FATIGUE CRACK INSPECTION.
Ziegler, Lisa, Ursula, Smolka, Cosack, Nicolai, Muskulus, Michael, 2017. Brief communication: structural monitoring for lifetime extension of offshore wind monopiles: can strain measurements at one level tell us everything? Wind Energy Sci. 2 (2), 469–476. https://doi.org/10.5194/wes-2-469-2017.
Ziegler, Lisa, Gonzalez, Elena, Tim Rubert, Ursula, Smolka, Julio, J., Melero, 2018. Lifetime extension of onshore wind turbines: a review covering Germany, Spain, Denmark, and the UK. Renew. Sustain. Energy Rev. 82, 1261–1271. February. https://doi.org/10.1016/J.RSER.2017.09.100.