Maintenance strategies for deep sea offshore wind turbines

Abstract

The objective of this article is to outline a guiding framework to be used when developing maintenance strategies and policies for deep sea offshore wind turbines. Design, development, installation and operation of offshore wind farms are topics on the agenda in many countries. An important problem to be solved is reducing the high operation and maintenance costs in order to make offshore wind a viable energy production source. In Norway, offshore wind energy production faces additional challenges, as the most feasible locations are remote, at water depths of > 30 m, and in a very harsh marine environment. The framework proposed in the article is based on systems engineering principles, and facilitates integration of fragmented, but valuable knowledge and results from different disciplines. In addition, the framework may be used to identify knowledge gaps with respect to maintenance of deep sea offshore wind turbines, and areas for further research.

Keywords

Offshore wind turbines, Maintenance management, Maintenance models, Systems engineering

1 Introduction

Offshore wind power is a prospective energy production source, especially in these times of global focus on climate change. Energy produced from offshore wind does not emit greenhouse gases, and it reduces society's dependence on non-renewable fossil fuel sources (EWEA, 2009). In Norway, as in many other countries, offshore wind energy production is on the agenda (NOWITECH, 2009), but the future most feasible locations are remote, at water depths of > 30 m, and in a harsh marine environment. In addition, the general development goes towards larger turbine sizes of 8-10 MW to achieve better cost efficiency. These challenges call for implementation of new concepts, such as floating structures (Eggen *et al.*, 2008), which will make operation and maintenance even more demanding and costly, due to increased corrosion, excessive wear on the constructions , reduced accessibility and fewer opportunities for carrying out maintenance (Wiggelinkhuizen *et al.*, 2008; Wilkinson *et al.*, 2006). Some estimations show that offshore operation costs will be 5-10 times higher than work onshore (Eggen *et al.*, 2008).

In the literature, there is a vast number of general maintenance methods and models available (Wang, 2002; Nicolai and Dekker, 2007; Van Noortwijk, 2009; Jardine *et al.*, 2006; Dekker, 1996; Dekker and Scarf, 1998; Valdez-Florez and Feldman, 1989; Garg and Deshmukh, 2006). In recent years, various maintenance methods and strategies have been proposed for wind energy production systems, e.g., (Andrawus *et al.*, 2006; Andrawus *et al.*, 2008; Brandão *et al.*, 2008; Guo *et al.*, 2009), and for offshore wind production, e.g., (McMillan and Ault, 2007; Besnard *et al.*, 2009; Wilkinson *et al.*, 2006; Wiggelinkhuizen *et al.*, 2008; Sørensen, 2009; Nilsson and Bertling, 2007; Krokoszinski, 2003; Amirat *et al.*, 2009; Hameed *et al.*, 2009). These articles may give valuable input to maintenance planning of wind turbines; however, novel deep sea offshore wind turbines face even tougher challenges than onshore and shallow water systems. In addition, many of the above mentioned articles address very specific, theoretical, and detailed parts of maintenance modeling.

When working on operation and maintenance aspects of deep sea offshore wind turbines and trying to reduce costs, complex issues soon arise. There is limited information and data available; due to only a few offshore wind farms in operation (in shallow water). Most of the existing knowledge is based on onshore concepts and experiences. The design and construction of the offshore wind turbines determine operation and maintenance features, but current deep sea offshore concepts are under development. In addition, the location sites of the deep sea offshore wind farms are often not established. Still, reducing operation and maintenance costs is necessary to make deep sea offshore wind projects viable in the first place.

The objective of this article is to propose a framework that can be used to guide the complicated process when developing maintenance strategies and policies for deep sea offshore wind farms; from need analyses, to implementation, and operation. In addition, the principles in the framework may be used to identify areas for further research. Even though there exist some suggestions on decision-making methods for developing maintenance organizations and including stakeholders, for example, Emblemsvåg and Tonning (2003) and Söderholm *et al.* (2007), they seem to focus more on the management and organizational level, than on relevant maintenance methods for the specific system (or asset) at hand.

The article is structured as follows: The first part discusses the systems approach and systems engineering principles related to maintainability, maintenance management, and maintenance. Then the framework is presented, with sequential sections discussing related tasks and topics on deep sea offshore wind turbines, and suggestions for further research.

2 Maintenance in the system life cycle

A deep sea offshore wind farm will consist of many wind turbines with several subsystems and components. Determining optimal maintenance strategies and policies for such complex systems with conflicting requirements and many operating constraints may benefit from using a systems approach.

A systems approach is characterized by considering the whole as more than just the sum of its constituent parts, and may be facilitated through the multidisciplinary systems engineering process (Utne, 2006). Crucial in the systems engineering process is the emphasis on all life cycle phases and their interconnectedness, from need analyses, design, development, construction, operation to disposal. The operation phase of a system's life cycle include maintenance processes (INCOSE, 2006), i.e., the process of executing maintenance management. Thus, the utilization and support phases give valuable inputs to system requirements and architectural design, for example, with respect to maintainability (INCOSE, 2006; Blanchard *et al.*, 1995). Maintainability is determined in the design phase, but has to be catered for through all life cycle phases (Knezevic, 2009). Figure 1 shows the interconnectedness between the system life cycle phases, maintainability, maintenance, and maintenance strategies.

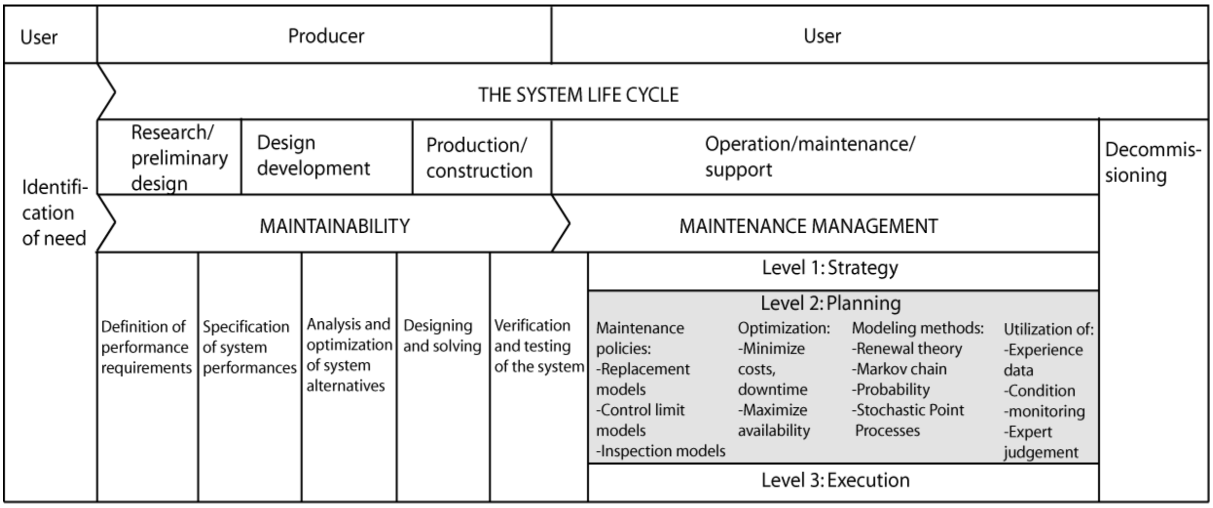

Figure 1. The system life cycle, the systems engineering process, maintainability, and important constituent parts of maintenance management. Extracted from (Blanchard and Fabrycky, 1998; Marquez, 2007; Wang, 2002; Kobbacy and Murthy, 2008; Utne, 2006).

The overall objective of carrying out maintenance is to reduce production losses and achieve high availability. The average availability can be defined as (Rausand and Høyland, 2004; MIL STD 1388, 1991):

$$A_{av} = \frac{MTTF}{MTTF + MTTR + LDT} \qquad (1)$$

MTTF is Mean Time to Failure, which is related to the failure rate λ, MTTR is Mean Time to Repair after failure, and LDT is logistics downtime (Mean downtime (MDT) = MTTR + LDT). Obviously, an increase in MTTF or a decrease in MTTR and LDT will increase the system availability. Thus, Eq. 1 illustrates the relationship between reliability, maintainability (maintenance), and system performance in terms of availability (Williams et al., 1994).

Maintenance management in the operation phase should be constituted at three levels, as shown in Figure 1 (Kobbacy and Murthy, 2008): The top level (i) dealing with establishing a maintenance strategy and evaluating maintenance constraints; the intermediate level (ii) consisting of planning, optimizing, and implementing maintenance policies; and the bottom level (iii) where maintenance tasks are executed and failure and lifetime performance data collected.

The levels of maintenance management have similarities to the top-down and bottom-up approaches in systems engineering. Top-down basically means moving from the strategy level; dealing with the overall objectives related to maintenance at system level; decomposing and allocating sub-objectives and detailed requirements down to subsystem and component level at the bottom of the system hierarchy where maintenance is executed and data can be collected. Bottom-up means that the maintenance actions and data/information gathered give further input to development and adjustments of the maintenance planning and strategy moving up through the hierarchy, in an iterative process.

The merging of the maintenance management levels of Kobbacy and Murthy (2008) with the systems engineering process is illustrated in Figure 2. The systems engineering process related to maintenance management and developing strategies and policies for offshore wind turbines consists of six steps:

1. Identification of stakeholders and needs
2. Definition of performance requirements
3. Specification of system performances
4. Analysis and modeling
5. Solving and optimization
6. Execution and data collection

These steps are further discussed in subsequent sections.

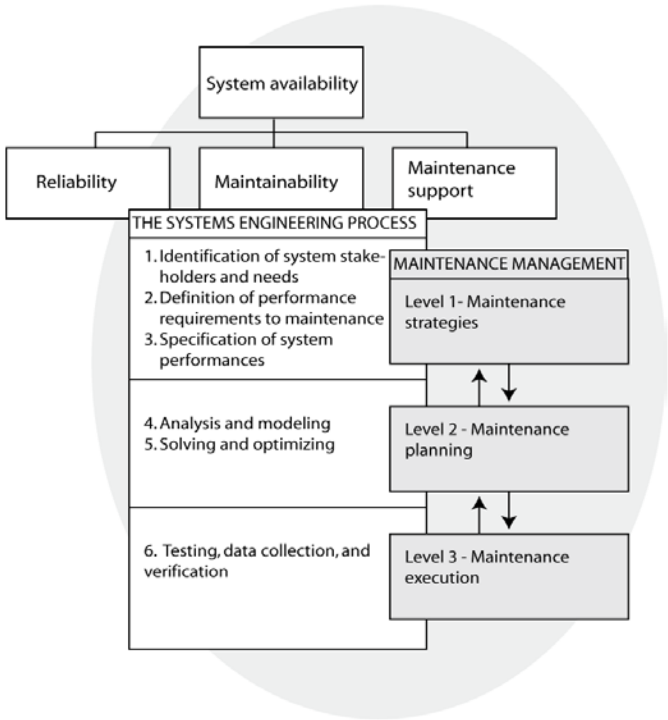

Figure 2. An iterative framework for developing maintenance strategies and policies.

2.1 Maintenance strategies

Achieving the desired system performance, e.g., availability, is determined in system design and development, but also through implementation of feasible maintenance strategies. The first steps of the framework are analyzing the stakeholders and their needs for maintenance and specifying these needs into requirements and specifications. Specification of system performances constitutes an important basis for maintenance modeling and optimization.

1. **Identification of system stakeholders and needs**

Identifying stakeholders and their needs is the first step of the systems engineering process (Blanchard and Fabrycky, 1998), but it is also found, for example in Total Productive Maintenance (TPM) (Söderholm *et al.*, 2007). Several stakeholders are involved regarding offshore wind turbines, e.g., the system owner, the operator, the authorities, service providers, and customers needing energy supply (Kobbacy and Murthy, 2008). The stakeholders' needs constitute the basis specifying relevant requirements to the system.

2. Definition of performance requirements

Requirements to wind turbines, for example to inspection intervals, can be found in the *DNV Offshore Standard DNV-OS-J101 Design of Offshore Wind Turbine Structures* (DNV, 2004): The interval of periodical inspections of the wind turbine, the structural and electrical systems above water should not exceed one year, in addition to following the requirements in the wind turbine service manual. The structures below water and the sea cables should be inspected at least every fifth year so that the whole wind farm is inspected at least once during a five-year period.

Experiences from current offshore wind turbines indicate a need for planned maintenance activities 1-2 times a year, each activity requiring 2-3 working days for 2 engineers. Corrective maintenance (CM) is expected 1-4 times a year, with MDT per failure of 2-4 days. Every fourth year a major overhaul will be needed, and after 10-12 years in operation, replacement of major components may need to be replaced (Van Bussel, 2009; Eggen *et al.*, 2008). However, for remote deep sea offshore wind turbines, the MDT can be expected to be much longer certain during time periods of the year (Oct-April), due to limited windows of opportunities for executing maintenance.

The specific nature of the maintenance requirements depends on the design of the wind turbines and the external conditions, and should be balanced towards requirements of reliability. The detailed specifications emerge as the wind turbine and wind farm concepts materialize, and are therefore part of the iterative system development process.

3. Specification of system performances

Krokoszinski (2003) categorizes the production losses related to wind energy converters into external and technical losses, and further into downtime, speed, and quality losses. The external losses are due to both planned and unplanned occurrences, such as preventive maintenance (PM) activities and weather conditions, for example too low or too high wind speeds. The technical losses may be due to failures in main components, cables and substations.

According to van Bussel (2009), the availability of some existing offshore wind farms vary, from 81% to 97%. Amirat *et al.* (2009) state that most failures of Swedish, Danish, and German wind turbines are related to the electric system, followed by sensors, and blade/pitch components. The variable availability implies that it is likely to be even poorer for remote deep sea locations due to the more challenging operational conditions.

In general, the availability of a wind turbine can be measured by:

$$A_{\%} = \frac{T_p + T_s + T_{pr}}{T_p + T_s + T_{pr} + T_d + T_r + T_g} \qquad (2)$$

where T_p is the time the turbine is producing power, T_s is the time the turbine is in standby mode, and T_{pr} is the time the turbine is parked due to e.g., weather conditions, T_d is logistics delay, T_r is inspections, failures, service and repairs, and T_g is production time lost due to grid loss. Sometimes, T_g is not included.

2.2 Maintenance planning

Based on the performance requirements and system specifications, more specific maintenance planning can be carried out to develop the maintenance policy. The analysis and optimization step of the systems engineering process, shown in Figure 2, covers partly the maintenance planning level and partly maintenance execution. This is due to the need for data collected during operation of the relevant systems or components, as well as the iterations needed to improve the modeling and specifications.

4. Analysis and modeling

Maintenance modeling requires specific knowledge of system, subsystems and components, their functions, failure modes and deterioration processes. Reliability centered maintenance (RCM) may be a useful approach to determine the maintenance requirements of any physical asset in its operating context. The main outcome of RCM is a greater understanding of how the asset or system works, how it may fail, and how it may be maintained, which again may lead to improved operating performance and maintenance cost effectiveness (Moubray, 1991). The logic and structure of RCM is, as such, part of a systems approach and should therefore not be left until after the wind farm has been constructed, but should be used to analyze the functions of the turbines during the development process, for example, to find out how different system configurations influence failure modes and the need for maintenance.

There are different types of maintenance, of which the main types are preventive maintenance (PM) and corrective maintenance (CM). PM can further be divided into two main categories; (i) time based, age based, and condition based, which means that the system has to be taken out of operation, and (ii) opportunistic maintenance, which means that the system is repaired or replaced when the system is down for some other reason. Condition-monitoring is already an integral part of the condition-based maintenance (CBM) strategy of existing onshore wind farms and is assumed to be cost-effective for offshore wind farms, due to higher loss of energy (revenue), longer downtimes (due to harsh weather and long transport distances), and larger, heavier and more costly components for larger capacity rated turbines (Amirat *et al.*, 2009; McMillan and Ault, 2007). However, a wind farm may consist of many turbines, and instrumentation of every turbine will be costly. One possibility may be to use some few turbines ("flight leader turbines") with full instrumentation in representative positions, where loads and probability of failure are higher than for other turbines.

Access to the offshore wind turbines will be limited, and most of the maintenance activities have to be carried out from May to September. This implies that use of condition-monitoring techniques, implemented with fault detection systems (FDS), will be even more important for remote deep sea offshore wind turbines than for onshore turbines. If potential failures are detected early enough, it is possible to plan for the maintenance action when the component is still operational (Hameed *et al.*, 2009). However, due to the limited window of opportunity for doing maintenance on the remote offshore wind turbines, planning ahead implies a rather long time horizon. When deterioration and faults are detected during the summer season, decisions have to be made whether to replace and repair immediately, or wait until next summer.

Hard life and soft life are two concepts used in maintenance of aircraft. Hard life is defined as the age at which a component has to be replaced (age based preventive maintenance). When a component has reached its soft life, it will be replaced the next time the system it belongs to is recovered (age based opportunistic replacement) (Crocker and Kumar, 2000). Regarding offshore wind turbines, this means that components which have reached their soft lives, determined by a life distribution or condition-monitoring, may be replaced during overhauls of other failed turbines during the summer season.

In order to utilize the information from condition-monitoring into maintenance decision-making, it is necessary to establish a relationship between the state of the item (or system) and one, or more, (condition-) monitored state variables, denoted $Y(t)$. The relationship between the item and $Y(t)$ can be determined by using mathematical models or expert judgements to predict the behaviour of the deterioration process. It is often of further interest to find the probability of failure based on the value of $Y(t)$.

Different subsystems and components of a wind turbine will have different deterioration processes and measures, depending on their construction, materials, usage, and exposure to external conditions. Deterioration (or ageing) may be modeled by a failure rate, but if information about the deterioration of a component is available, the failure model can be based on physics of failure and characteristics of the operating environment; i.e., modeling deterioration in terms of a time-dependent stochastic process (Van Noortwijk, 2009). Relevant models are, for example, the P-F interval (Moubray, 1991), proportional hazard modelling (PHM) (Jardine *et al.*, 2006; Jardine and Tsang, 2006; Rausand and Høyland, 2004; Ebeling, 1997), and Markov-processes (Jardine and Tsang, 2006; Vatn and Drøpping, 2008). Since, the operation of deep sea offshore wind turbines implies condition-based maintenance strategies and temporal variability of deterioration, stochastic process models, such as Markov processes, may be more applicable.

Useful Markov processes for modeling stochastic deterioration may be Markov chains having a finite or countable state space, and Markov processes with independent increments, for example, the Wiener process and the gamma process (Van Noortwijk, 2009). In a Markov model, an item's condition is modeled in one of a few states, usually 3-6 states (Welte, 2008). The probability of an item deteriorating into another state is only dependent on the two states involved, and the process is memoryless meaning that the future development of the item is regardless of what has happened in the past (Rausand and Høyland). Often, such assumptions may be too rough compared to the real life situations. Seasonal variations may cause more severe degradation of the offshore wind turbines during winter time than during summer, implying higher transition rates during winter than summer. An alternative to the general Markov model is to use semi-Markov models with a general life distribution, such as Weibull or Gamma distributions, instead of the exponential distribution.

A problem with the Wiener process is that $Y(t)$ may increase and decrease, which is rather unlikely for systems with increasing deterioration, like wind turbines. The gamma process is, according to Noortwijk (2009), feasible for modeling gradual damage monotonically accumulating over time, occurring in a sequence of tiny increments, for example, wear, fatigue, corrosion, crack, growth, erosion, consumption, creep, swell, degrading health index, etc. The gamma process can be stationary and non-stationary. In a stationary gamma process, the expected deterioration is linear with time, whereas in a non-stationary process the deterioration is non-linear or non-constant. If the gamma process is to be used for deep sea offshore wind turbines, it may be assumed that the non-stationary gamma process is more suitable than the stationary gamma process. This is due to the heavy impact from the marine environment, as well as the floating structure that might introduce additional wear on the constructions.

In order to use the gamma process in maintenance optimization, threshold levels are often introduced, which is related to the so called control-limit maintenance policy. This means that an operation is planned when the degradation level crosses a predefined alarm threshold. A single threshold level may be effective when the system is only exposed to one mode of degradation (Saassouh *et al.*, 2007). However, degradation of a system may suddenly change after a random time and due to a change in its environment. Saassouh *et al.* (2007) therefore propose a maintenance model with a defined "activation zone", in which a maintenance action can be planned in accordance to a decision rule. The decision rule is based on available information about the level of degradation and its current mode, either M1 (nominal degradation mode) or M2 (accelerated degradation mode). The modes can be modeled by two stochastic processes under the same law, but with different parameters. This means that when the system is in mode M1, the increments $Y_{t+\Delta t} - Y_t$ $(t \geq 0, \Delta t > 0)$ follows a Gamma law with parameters $\alpha_i \Delta t$ and β_i. After a random time, the system switches to mode M2, where the deterioration rate is greater than in the first mode $(\alpha_i/\beta_1 < \alpha_2/\beta_2)$. When the system exceeds a given level L , $Y_t > L$, the system is failed.

5. Solving and optimization

Optimizing costs related to maintenance of wind turbines may be related to the wind turbine subsystem's or component's effective failure rate, $\lambda_E(\tau_i, \xi_i)$ as a function of the inspection intervals and the threshold values. For wind turbines, the interval between inspections most likely would decrease when different threshold values are passed. Still, for deep sea offshore wind turbines, the window for performing inspections and maintenance will be limited and it will be difficult to inspect the turbines during long time periods of a year. Thus, opportunity maintenance may be economically feasible.

According to Walford (2006), the operation and maintenance cost elements of a wind turbine consist of operation costs, preventive maintenance (PM) costs, and failure related (corrective) maintenance (CM) costs. The operation costs are related to scheduling site personnel, monitoring turbine operation (through SCADA), responding to turbine fault events, etc. PM costs include periodic inspections of the equipment, oil and filter changes, calibration of sensors, and replacement of consumables, such as seals and brake pads. The frequency of the PM tasks is usually recommended by the turbine supplier. The direct costs related to CM are associated with the labor and equipment required to repair and replace, component costs. Indirect costs are due to lost revenue due to turbine downtime. The downtime depends on the repair time, including detection, getting access to the turbine, diagnosis, labor and spare part mobilization, and weather conditions. Costs of major overhauls and major component replacement over the life of a wind turbine constitute an additional cost element.

Figure 3 shows important factors influencing the system performance (availability), operation and maintenance costs, and thereby maintenance management. The factors have to be taken into consideration over the system's entire life cycle. Assuming that the activities in the diagram to some extent are sequential (but not static), and that CM is more expensive to carry out than PM ($C_{pm} < C_{cm}$), PM and CBM are advantageous compared to strategies merely based on CM actions.

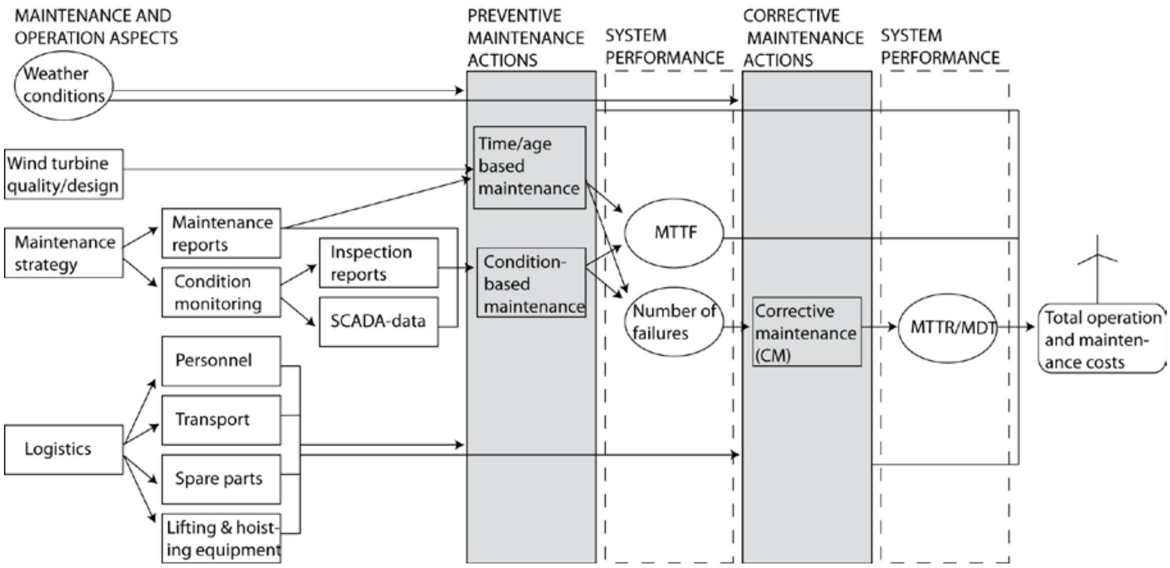

Figure 3. Influence diagram illustrating factors influencing system availability and the operating and maintenance costs.

A maintenance optimization model for deep sea offshore wind turbines can be used to achieve costs savings in the maintenance strategy program. A deep sea offshore wind farm will consist of several wind turbines, which to a large extent will be similar with respect to design, construction, age, and stress. The possible advantages related to *grouping* of maintenance activities, i.e., maintaining several wind turbines and/or several components within the wind turbine at the same time, should be taken into consideration.

Assuming that two types of maintenance can be carried out (PM and CM), and that the set up costs S, such as preparation and closure of the maintenance activities, is shared among n turbines, a simple model of the total maintenance costs per time unit $C_{tot}(\tau)$ is:

$$C_{tot}(\tau) = \frac{S}{\tau} + \sum_{i=0}^{n} \left(\frac{C_{pm,i}}{\tau} + \left(C_{cm,i} + PL_i\right) \cdot \lambda_E(\tau) \right) \qquad (3)$$

PL_i are costs due to production loss (related to the turbine's availability) and $\lambda_E(\tau)$ is the effective failure rate, depending on the maintenance interval, τ, for the turbine. Assuming static grouping (the grouping of wind turbines is fixed), the total costs for operation and maintenance can be calculated by Eq. 3. Optimization would be to minimize $C_{tot}(\tau)$ for n wind turbines maintained at the same time.

In reality, not all components in a wind turbine will be maintained at the same time, but for example at $k_i\tau$, where τ is the maintenance interval (e.g., 6 months), and k_i is an integer. This means that for example component 1 may be maintained at $k_1 = 1$, which means every 6 months, whereas component 2 may be maintained at $\mathrm{k_i} = 4$, which means every second year. A standard indirect grouping strategy is one way to dealt with this type situation. A more realistic grouping approach may be dynamic grouping, which takes into account changing information, such as varying deterioration (see Wildeman (1996)).

2.3 Maintenance execution

Maintenance modeling and optimization are dependent on available data. Even though these may be hard to collect systematically before the system is in operation, data collection is very important in order to verify that the chosen maintenance tasks are well suited, and that the desired system performance is acceptable.

6. **Verification, data collection, and feedback**

Data gathering from operational experience and expert judgments are essential for establishing valid maintenance models; for testing of the system, verification, and for improving maintenance strategies. Currently, there is little operational experience with full scale deep sea offshore wind turbines, except Statoil's Hywind, which is the world's first floating deep sea turbine, installed 10 km off the south-western coast of Norway. The Hywind concept extends 100 metres beneath the sea's surface and is attached to the seabed by a three-point mooring spread (Statoil ASA, 2010). Hywind was installed in the summer of 2009, and will be tested during a two-year period to find out how wind and waves affect the structure.

The limited amount of data available poses a major challenge to the development of optimal maintenance strategies and models for deep sea offshore turbines to reduce operation and maintenance costs. Thus, it would be beneficial to establish a database with participation from industry, similar to the OREDA database (2009).

3 Discussion and conclusions

There are different ways of reducing the operation and maintenance costs, for example, by reducing the need for maintenance. This can be achieved, for example, by designing the wind turbine simpler, reducing the number of components, and using components of very high reliability (Van Bussel *et al.*, 2001). Nevertheless, even with a very reliable wind turbine, maintenance will be necessary.

Developing new concepts for deep sea offshore wind turbines, and at the same time finding ways to reduce operation and maintenance costs, is a complex process involving many people with different backgrounds and expertise. Typically, the design of the different parts of an offshore wind turbine is carried out in separate work groups from those people working on maintenance and operational issues. This separation imposes challenges to the information flow between the groups on current status and exchange of knowledge. In addition, the different specialists speak different "languages", and uses different analytical methods and computer programs which are difficult to understand for people outside the specific domain. It is therefore hard to assess what impact different design concepts and decisions have on maintainability and maintenance costs.

The field of operation and maintenance is broad, and researchers work on various topics, such as investigating specific degradation processes, finding improved means for reduced corrosion and wear on the tower structures, deriving formulas for calculating life cycle profit (LCP), and optimizing costs for specific nacelle components. A lot of new knowledge is produced, but this knowledge is fragmented, and it is difficult to fit the fragments into an overall maintenance strategy for deep sea wind turbines that actually will work in the real life situation.

The proposed framework in this article is an attempt to pull the threads together to enable the important overview of "what is needed", "why is it needed", and "how is the need going to be fulfilled" with respect to operation and maintenance of deep sea offshore wind turbines. Without this overview, it is hardly possible to investigate and analyze the gaps in the existing knowledge, and to evaluate how the produced research work contributes to the overall objective of developing reliable and maintainable turbines and offshore wind farm concepts.

The framework is divided into three main levels; strategy, planning, and execution. These levels are interconnected through the systems engineering process, shown in Figure 2. The first step is to identify the needs for maintenance and maintainability; then these needs are specified and analyzed so that models can be developed for optimized planning and execution of maintenance actions. Data collected through operational experience and/or through testing may be used to verify that the operation and maintenance costs are reduced; at the same time as the overall availability level is achieved. The framework is iterative; for example, optimization of costs (or inspection intervals etc.) may require changes to the maintenance policy and the strategies. These changes may again alter the optimization procedure until the system performance requirements, for example related to system availability, are achieved.

The framework may be feasible for identifying important areas to focus research effort, since it integrates the produced knowledge with the overall objectives of the research. In this article, the framework is used to address the importance of a life cycle perspective on maintenance, and that condition-monitoring and condition-based maintenance, related to deep sea offshore wind turbines, should be subject to further research:

- If advanced condition-monitoring techniques are to be utilized, costs may be high, and RCM may be used to assess and identify the most critical systems to which the most advanced methods should be applied. Since wind farms will consist of similar turbines, the analyses can be generic and carried out for one turbine, and then the results can be transferred onto other turbines. This means that single unit maintenance models may be sufficient. Most existing models are considering single units and not multi-component systems.
- There are many theoretical models and methods related to condition-monitoring and deterioration modeling, but few real cases in which stochastic processes have been assessed empirically (one exception is Nicolai *et al.* (2007)). Since deep sea offshore turbines will be remote controlled, effective utilization of condition-monitoring data have to be implemented. In addition, data from condition-monitoring has to be reliable, which implies that redundancy of condition-monitoring equipment also is an issue to consider. Above all, a major challenge is to balance between developing and implementing methods easily understood by non-experts, and requirements to model

validity. There exist great many theoretically advanced mathematical models, but few are applied to solve real life problems.

- Optimizing maintenance with respect to costs is challenging, due to the need for effective grouping strategies. The different subsystems and components of the wind turbines have different failure modes and different requirements to maintenance. In addition, it is reasonable to believe that more failures will occur during high load periods during the winter time, when access to the turbines are difficult. This may cause increased down-times, and reduced availability. Due to limited access to the turbines, utilization and optimization of opportunity based maintenance so that efforts spent to access the turbines are efficient, is a major challenge to address. In addition to the site specific constraints, logistics remains to be solved, such as crew size, spare parts planning, transportation and accommodation.
- There are several issues related to factors influencing the maintenance and operation costs of wind turbines. The costs of CM may give opportunities for doing preventive maintenance and reducing set up costs. The costs of PM may vary greatly depending on external conditions, such as time of the year and the weather on site. Redundant systems may be implemented in a wind farm, meaning that some of the most critical components may be duplicated, reducing the costs related to production loss. Another option is to design a wind farm with a system configuration so that production from one wind turbine can be replaced by another turbine. The MDT of the wind turbines are influenced by the weather conditions on site and seasonal variation. Calm weather increases the feasibility of doing maintenance. However, calm weather (low wind speed) may cause reduced power production from the wind turbines; thus minimizing the production loss due to maintenance.

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