On maintenance optimization for offshore wind farms

Elforsk report 13:11

François Besnard

February 2013

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Preface

A large amount of the cost of energy from wind power is attributed to the operating cost such as cost of maintenance and repair. Consequently, much is to be gained by using good strategies and methods for maintenance.

In order to deepen the knowledge on this subject and to develop methods and strategies for maintenance a PhD-project was started in the research program Vindforsk II program and this project has further continued within the Vindforsk research program Vindforsk III as project V-327.

The project has now come to end with the dissertation of the Phd student François Besnard under the supervision of Professor Lina Bertling Tjernberg at Chalmers.

The work in the project has been carried out in collaboration with Vattenfall Vindkraft which has contributed with real operational data. The work at Vattenfall has been led by Thomas Stalín

This report consist a summary of the results of the project as a non-academic complement to the Phd-thesis. The work has been carried out at Chalmers Division of Electric Power Engineering, Department of Energy and Environment in close cooperation with the utility Vattenfall.

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Summary

The maintenance cost is known to be an important part of the levelized cost of energy generated by wind parks. Operational costs can be significantly reduced by optimizing decisions for maintenance strategies, maintenance support organization and maintenance planning. This is especially important for offshore wind power systems to reduce the high economic risks related to the uncertainties on the accessibility and reliability of wind turbines.

In this project, decision models for cost efficient maintenance for offshore wind power systems were developed. The results show that maintenance costs can be significantly reduced through optimizing the maintenance strategies, the maintenance support organization and the maintenance planning.

Maintenance strategies

Two models investigate the economical benefits of condition based maintenance strategies for the drive train and for the blades of wind turbines, respectively. The results indicate that condition monitoring of the drive train could reduce the total cost of maintenance and production losses by 26% over the lifetime and that it decreases the risk of high maintenance costs.

The cost-benefit of condition based maintenance techniques or continuous monitoring for blades is much dependent on failure rate and deteriorate rate. The results indicate that online condition monitoring is the optimal solution in case of high failure rate, or short deterioration time.

Maintenance support organization

Two models are proposed to perform a cost benefit analysis of the maintenance support organization by evaluating the benefit of the location of the maintenance base, logistic and personnel planning on availability. The results from a case study for a wind farm of 100 wind turbine with 5MW rated capacity indicate that an economic benefit in the range of 0.6 M€-5.2 M€ per year can be achieved by selecting the optimal maintenance support organization as compared to alternative support organizations. This corresponds to 4-30% savings of the costs of the logistic and production losses.

Maintenance planning

One model is proposed to optimize the maintenance planning of service maintenance activities by taking advantage of opportunities arising at low wind or when corrective maintenance activities are necessary. The results from a case study indicate that an cost saving of 32% of the costs of the transportation and production losses could be achieved as compared to a classic time based planning approach.

Sammanfattning

Det är allmänt känt att underhållskostnader utgör en stor del av kostnaden för el genererad från vindturbiner. Kostnader för drift och underhåll kan minskas markant genom att använda systematiska metoder för underhålls-planering vilka baseras på optimeringsmodeller för underhållsstrategier, organisation för underhållssupport och underhållsplanering. Detta gäller speciellt för havsbaserad vindkraftverk med hög ekonomisk risk relaterad till osäkerhet för tillgänglighet och tillförlitlighet för vindturbiner.

I detta projekt har beslutsmodeller för kostnadseffektivt underhåll för havsbaserade vindkraftsystem utvecklats. Resultat visar att underhålls-kostnader kan minskas signifikant genom optimering av strategier för underhåll, organisationer för underhåll och underhållsplaner.

Underhållsstrategier
Två modeller presenteras för analys av ekonomisk vinst av tillståndskontroll-baserade underhållsstrategier för drivlina och turbinblad. Resultaten visar att tillståndskontroll för drivlinan kan reducera total kostnad för underhåll och produktionskostnader upp till 26% över livstiden, och minska risken för höga kostnader för underhåll. Kostnaden för tillståndskontrollmetoder eller för kontinuerlig övervakning för blad är starkt beroende av felintensitet och försämringsintensitet. Resultat visar att online tillståndskontrollövervakning är optimal lösning i fall med hög felintensitet eller kort försämringsintensitet.

Underhållssupportorganisation
Två modeller föreslås för kostnadsanalys för underhållssupportorganisationer genom att studera inverkan av: placering av bas för underhållsverksamheten, logistik och tillgänglighet av personal Resultat från en fallstudie, för en vindkraftpark med 100 vindturbiner med kapacitet av 5 MW, indikerar att en ekonomisk vinst kring 0.6 till 5.2 miljoner € per år kan erhållas genom att optimera organisationen för underhåll. Detta motsvarar 4-30% besparingar i kostnader för logistik och bortfall i produktion.

Underhållsplanering
En modell föreslås för att optimera underhållsplaneringen för underhålls-aktiviteter genom att utnyttja situationer vid låg vind, eller när avhjälpande underhållsaktiviteter är nödvändiga. Resultat från en fallstudie visar en möjlig kostnadsbesparing om 32% för kostnader för transport och produktionsbortfall jämfört med en klassiskt schemalagd underhållsplanering.

List of contents

Abbreviations

CBM	Condition Based Maintenance
CM	Corrective Maintenance
CMS	Condition Monitoring System
CTV	Crew Transfer Vessel
LCC	Life Cycle Cost
MTTF	Mean Time To Failure
O&M	Operation and Maintenance
PM	Preventive Maintenance
SCADA	Supervisory Control And Data Acquisition
TBM	Time Based Maintenance
WT	Wind Turbine

1 Introduction

1.1 Problem background

In the last decades, an increased awareness of the impact of human living on the environment has emerged in the world. In January 2007, the European Commission presented an independent commitment in a report titled “Energy Policy for Europe" [1]. The proposal aims at reducing the gas emission by 20% relative to the 1990 levels (previously 8% in the Kyoto protocol), with an obligatory target for at least 10% bio-fuel and 20% of renewable energy. A resource is said to be renewable if it is replaced by natural processes at a rate comparable or faster than its rate of consumption by humans. Sources of renewable energy are e.g. biomass, hydroelectric, wind, photovoltaic, concentrated solar or geothermal energy. Wind energy has been the strongest growing renewable source of energy in the world this last decade, particularly in Europe where wind energy accounted for 6.3% of the electricity generated, and 21,4% of the generating capacity installed in 2011 [2].

Despite high capital cost and operation and maintenance costs, the installed capacity of offshore wind power has increased rapidly in Europe from 800 MW installed at the end of 2006 to 3.8 GW at the end of 2011 and many offshore wind farms are expected to be built in the near future, especially in the UK, Germany, Denmark and the Netherlands [2]. The reasons for this trend are high wind resources, the availability of space, low visual and noise impact, better understanding of the economic risks and high financial incentives [3]. The target of the European Wind Energy Association is to reach 230 GW of installed wind power in Europe by the end of 2020, of which 40 GW shall be generated by offshore wind power plants [4].

The maintenance cost is known to be an important part of the levelized cost of energy generated by wind parks. In particular offshore, operation and maintenance contributes between 15-30% of the cost of energy [5]. At the 160MW Horns Rev offshore wind farm located 20 km off the coast of Esbjerg in Denmark, the maintenance was estimated to contribute to as much as 40% of the life cycle cost due to early serial failures, as well as low investment costs compared to the current market. The main drivers of the maintenance costs were identified as being the major component replacements, major retrofits and refurbishment of major components and the logistic as depicted in Figure 1-1. While the major retrofit can only be tackled by reliability improvements, the maintenance strategy of the major components has a major influence on the costs of replacement and refurbishment.

A challenging aspect of offshore wind farms is the logistic that needs to be planned according to the distance from shore and weather conditions at site. The transportation of maintenance technicians to the wind turbines must be performed by workboats, which are constrained by the wave height and may lead to poor accessibility resulting in long downtimes, or by a helicopter. Both alternatives are costly. The logistic and maintenance support organization for offshore wind farms will become even more crucial for the new projects being installed further from shore, in deeper water depth and harsher environment.

The reliability of onshore wind turbines has been reported in e.g. [7]-[10]. The availability of onshore wind turbines is typically in the range of 93-99% while for early offshore projects an availability as low as 60% has been observed at some wind farms due to serial failures and harsh weather conditions [11], [12]. This can also be observed in Figure 2-1. An interesting aspect of wind power compared to conventional electricity sources is the variability in the power production. In this respect, the energy-based availability is more representative of the actual production losses, and the planning of the scheduled maintenance activities should aim to maximize the energy-based availability.

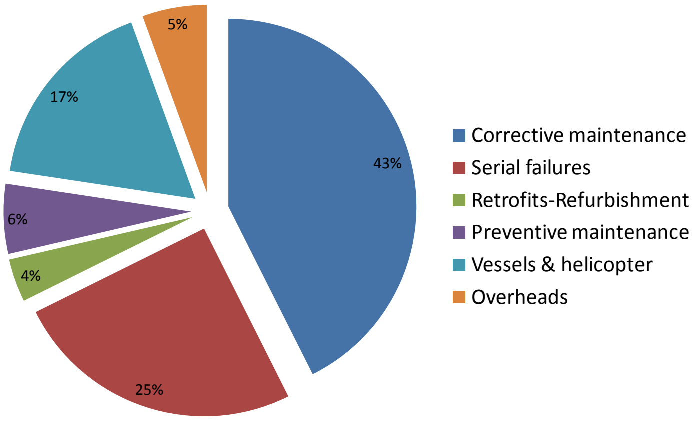

Figure 1-1: O&M life cycle cost at Horns Rev wind farm estimated by the author with a modified version of the ECN O&M tool [6].

1.2 Project objective

The objective of this project has been to develop mathematical models for supporting decision making related to maintenance of wind farms, with a particular focus on offshore wind farms. In order to achieve the objective, the model have been developed based on industry needs and achievable reliability and cost data, and supported with case studies.

1.3 Structure of the report

This report consist a summary of the Vindforsk III project V-327 which is carried out as PhD project. The report shall be read as a summary of the project accessible for a broader target group than that of a PhD thesis.

The work of the project mainly focuses only the three topics:

- Maintenance strategies,
- Maintenance support organization,
- Maintenance planning.

The subsequent chapters follow to a large extent the structure of the PhD thesis. The work of the project is further reported in nine papers referred to as paper I to paper IX in the list of publications of the project.

2 Life cycle cost analysis of offshore wind farms

2.1 Introduction

The life cycle cost of offshore wind farm is of much interest for a wind farm developer. A collaboration with Vattenfall was initiated in order to develop a life cycle cost model based on real operational data. The objective was to determine the cost driving factors for the operation and maintenance costs, to estimate the life cycle costs and profits, and levelized cost of offshore wind energy, and to be able to compare the economic benefits of maintenance concept alternatives.

The model is a further development of a commercial model developed by the ECN to evaluate yearly average maintenance costs [6]. The ECN O&M model was extended by considering the full life cycle cost of a wind farm and lifetime models, possibility to model retrofits, evaluation of combination of multiple vessels (e.g. boat and helicopter), by taking into account warranty, maintenance contracts and insurances and electricity scenario. A case study was done based on real data from the offshore wind farm Horns Rev. The model that was developed can be used for evaluating new projects or analyzing current wind farms.

2.2 Main results

One of the main results was to estimate the contribution of the operation and maintenance costs to the life cycle cost of an offshore wind farm, and to identify the main cost drivers for the operation and maintenance costs as presented in Figure 1-1.

The downtime per system at the Horns Rev offshore wind farm is depicted in Figure 2-1. Note that this excludes all serial failures that occurred during the first years of operation. The yearly availability is currently 95-97% and the aggregate failure rate per wind turbines is approx. 5 failures per year.

It has been observed that the main contributors to the failure rates are the power electronics, gearbox oil system, hydraulic and control systems. Similar results have been found for wind turbines at onshore sites [7]-[9]. For these sub-systems, the availability can be improved by implementing redundancy, time based replacement (if the sub-system is ageing) or by improving the maintenance support organization.

The replacement of the major components, such as the gearbox, is responsible for the longest downtime per failure, as well as for 80% of the cost of corrective maintenance in Figure 2-1. The downtime results from the long lead time for the spare parts and crane ship. The availability and maintenance costs for the major components can be minimized by use of condition based maintenance (CBM) e.g. with Condition Monitoring Systems (CMS).

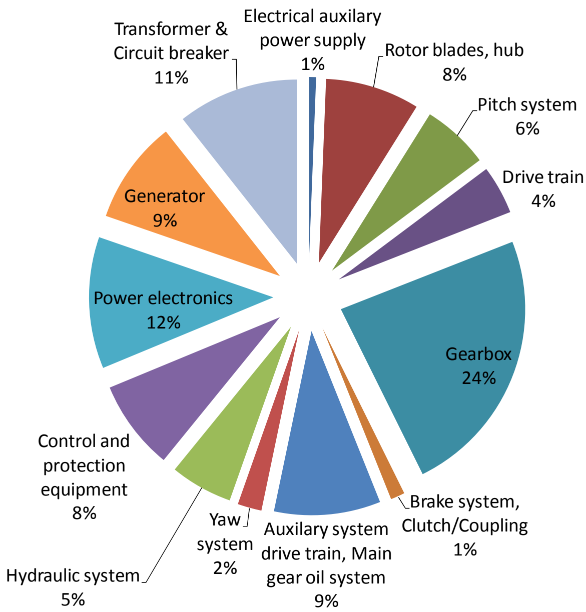

Figure 2-1: Downtime per system at Horns Rev estimated by the author with a modified version of the ECN O&M tool [6] based on maintenance reports for years 2009-2010.

A main result from the investigation was also to identify modeling factors that were not considered directly in the ECN O&M model, such as the possibility to use alternative transportation means, the possibility of queuing of maintenance activities due to a lack of maintenance technicians, and the effect of the efficiency condition monitoring. This was the basis to develop the models developed by the author in Papers IV and V

Another result was to identify some gap in the procedure for data collection. The first finding was that there was the need for an incentive for the technicians to record all maintenance activities. Moreover, there was a need to connect the work orders with the SCADA data and material orders in order to relate the failures with their associated downtimes and spare part costs.

3 Optimization of maintenance strategy

3.1 Introduction

Maintenance is defined as the combination of all technical and corresponding administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function [13]. Figure 3-1 shows a common classification of maintenance strategies which is based on the standard SS-EN 13306.

Corrective Maintenance (CM) is carried out after a failure has occurred and is intended to restore an item to a state in which it can perform its required function [1]. It is typically performed when there are no cost-effective means to detect or prevent a failure.

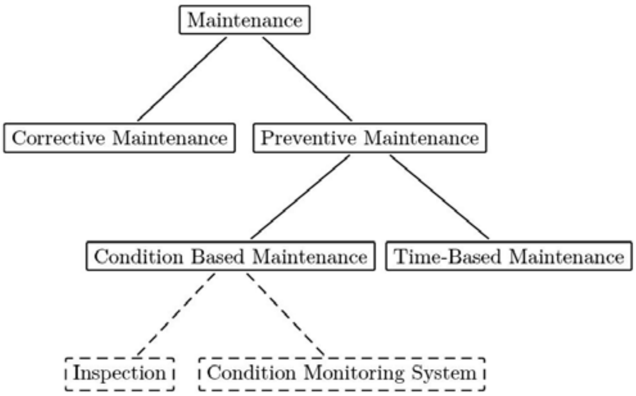

Figure 3-1: Types of maintenance strategies, partly adapted from [14].

Preventive Maintenance (PM) is carried out at predetermined intervals or corresponding to prescribed criteria, and intended to reduce the probability of failure or the performance degradation of an item [1]. There are two main approaches for preventive maintenance strategies:

- Time Based Maintenance (TBM) is preventive maintenance carried out in accordance with established intervals of time or number of units of use but without previous condition investigation [14]. TBM is suitable for failures that are age-related and for which the probability distribution of failure can be established.

- Condition Based Maintenance (CBM) is preventive maintenance based on performance and/or parameter monitoring [14]. CBM consists of all maintenance strategies involving inspections or permanently installed Condition Monitoring Systems (CMS) to decide on the maintenance actions. Inspection can involve the use of human senses (noise, visual, etc.), monitoring techniques, or function tests. CBM can e.g. be used for non-age related failures if the activity has the ability to detect/diagnose the degradation in time in a cost-effective manner.

A CBM strategy is effective if it can observe the deterioration sufficiently in advance and ideally give a prognosis of the time to failure, in order to schedule a repair/replacement of the component before failure. This has the advantage to minimize downtime cost and often reduce further consequential damages.

Two models are presented in this Chapter to optimize the maintenance strategies for the drive train (consisting of main bearing, gearbox, generator) and for the blades.

3.2 Cost benefit of condition monitoring systems

3.2.1 Introduction

Failures of the major components of the drive train are expensive due to the high costs for the spare parts, the logistic and maintenance equipment, and energy production losses. Vibration and oil CMS are available for the components of the drive train in WTs [15], [16]. The CMS may identify incipient failures far before major maintenance is required. If a failure is suspected, an inspection is performed, and either minor maintenance is performed to prevent the failure, or the replacement of the component is planned. In this condition, both the cost of the maintenance activity itself and the costs for production losses may be reduced.

The economic benefit of CMS depends on the probability of failure of the component in the drive train, the efficiency of CMS, and damage and logistic time advantages provided by the use of CMS. An economic analysis is presented in Paper I. The proposed model is based on a stochastic Life Cycle Cost (LCC) with random variables for the occurrence of failure of the components of the drive train.

3.2.2 Main results

The benefit of CMS is evaluated as the difference between the LCC with and without CMS. A case study based on 3MW wind turbines was performed and a sensitivity analysis was used to investigate the influence of some parameters. The CMS was assumed to have an efficiency of 90%, which means that 90% of the failure can be corrected with preventive repair, preventing from production losses and lowering consequential damages by 50% in cost. Moreover, the cost for the CMS was assumed to be 100,000 € which is high compared to solutions proposed today and thus a conservative assumption regarding the cost benefit.

In the base case, the LCC is 710,000€ without CMS and 520,000€ with a CMS. The cost benefit of using CMS is therefore 190,000 € over the lifetime which corresponds to 26% cost savings. The sensitivity of the results to the lifetime of the gearbox is shown in Figure 3-2. The gearbox is the most critical component of the drive train with respect to its impact on maintenance costs. It can be observed that the reliability of the gearbox has a large impact on the economic benefit of the CMS. Even under the conservative assumption made regarding the CMS investment cost, the CMS is expected to be beneficial if the Mean Time To Failure (MTTF) of the gearbox is lower than 18 years, which is clearly the case in the majority of wind turbine gearboxes in operation today. Moreover, it could be shown that the use of CMS reduces the probability of high maintenance costs, as depicted in Figure 3-3.

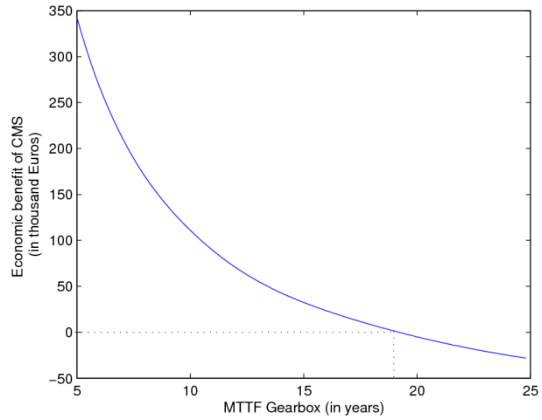

Figure 3-2: Expected economic benefit of vibration CMS for a wind turbine as a function of the Mean Time To Failure (MTTF) for the gearbox

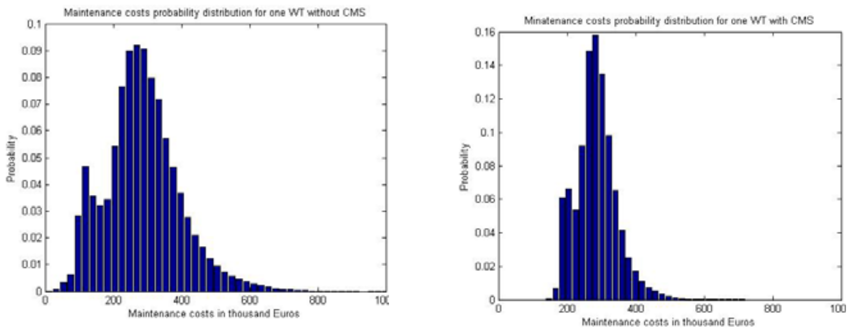

Figure 3-3: Probability distribution of the LCC costs without CMS (left) and with CMS (right).

3.3 Optimal condition based maintenance for blades

3.3.1 Introduction

Another component being critical for the reliability, availability, and profitability of wind turbines is the rotor, today usually consisting of three rotor blades. The size of blades for the wind turbines has generally been increasing rapidly during these last decades and they are subject to high stress. Wind turbine blades are usually inspected once a year at service maintenance and at additional occasions e.g. after a lightning strike detected by lightning detectors.

Condition monitoring can be used in order to detect cracks and delamination, either at inspection or continuously. Inspection monitoring devices consist of infrared or ultrasound sensors installed on an inspection robot scan and examine the inner material of the blade [17]. On-line condition monitoring systems can be achieved by inserting fiber optical sensors, whose emission frequency is modified by measured properties i.e. strain or temperature, mounted on an optical line in the material of the blades [17].
The objective of the model describe in Paper I are:

1. to compare the expected maintenance costs for the three maintenance strategies (a) only visual inspection, (b) inspection using condition monitoring technique, and (c) continuous monitoring with condition monitoring system (inspection are carried on only if a failure is detected);
2. to optimize the inspection interval for the inspection based strategies.

The model consists of a LCC model for the life time of the wind.. A Markov chain is used for the deterioration and maintenance model of the blades. The model takes into account sudden failures that could be caused e.g. by to lightning impact.

3.3.2 Main results

The base case for the case study assumed a crack initiation rate of λ_{init} =0.01 per year, average deterioration time $T_{\det}$ of 1 year and the lightning rate λ_l of 0.01 per year. The cost parameters are provided in Paper II

The central result of this analysis is shown in Figure 3-4, where the expected maintenance costs for the different maintenance strategies are plotted as a function of the inspection interval. Note that in case of the application of a condition monitoring system, the resulting cost is independent of any inspection interval. It can be observed that the optimal strategy among the alternatives (a-c) named above is to install a condition monitoring system (c), followed by inspection with condition monitoring techniques every 6 months (b) and, as least cost-effective solution, the visual inspection of blades every 3 months (a).

However, the benefit of the different maintenance strategies depends strongly on the dynamics of the failure as it can be observed in Figure 3-5. The figure presents the expected maintenance costs for the three maintenance strategies a-c (with optimal inspection intervals in the cases (a) and (b)) as a function of the crack time to failure, i.e. the time between a crack is initiated until it leads to a fault. The shorter this time is, the less probably is the detection of a crack by offline inspection and the more beneficial are thus condition monitoring systems. This is due to the need for short inspection intervals for inspection strategies to be efficient, and the resulting high inspection costs.

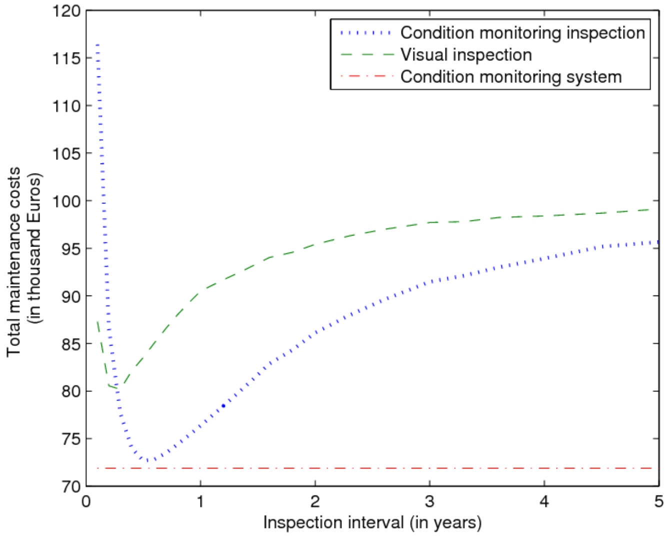

Figure 3-4: Expected maintenance costs of one blade over the lifetime of a WT for different maintenance strategies as a function of inspection interval.

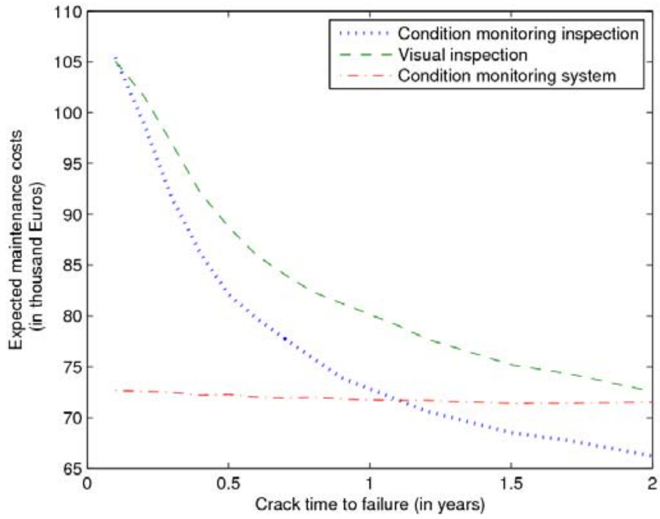

Figure 3-5: Expected maintenance costs of one blade over the lifetime of a WT for different maintenance strategies as a function of the crack time to failure.

4 Optimization of maintenance support organization

4.1 Introduction

The maintenance support organization can be defined as all the resources required to perform maintenance activities. The following aspects of support organizations have been identified as critical for offshore wind farms:

(1) Location of maintenance accommodation,
(2) Number and type of crew transfer vessels,
(3) Use of helicopter,
(4) Work shift organization,
(5) Number of maintenance teams per work shift,
(6) Spare part stock management,
(7) Technical support,
(8) Buy or contract of crane ship.

For safety reasons, the nacelle of a WT should not be accessed individually and the maintenance is generally performed teams of at least 2 technicians supervised by a site and maintenance manager. The work is organized in work-shifts which for offshore wind farms without offshore accommodation would consist of day shifts. For wind farms further from shore, an offshore based maintenance organization (with an accommodation platform or accommodation vessel) enables to have night work-shift and 24 hours 7 days a week response to failure. The maintenance teams may be complemented in order to perform specific maintenance activities such as service maintenance activities or major component replacements (for which maintenance expert are generally required). The driver to optimize the number of technicians and work-shift arrangement is the reliability of the wind turbine, efficiency of the transportation and access system (in terms of working hours spent in the wind turbines), and weather conditions. It is therefore much dependent on the logistic strategy.

The access to the wind turbines is performed either by climbing a ladder located on the foundation via Crew Transfer Vessel (CTV), accessing directly the foundation platform via a gangway on accommodation vessel, or by hoisting on the nacelle platform by helicopter. Example of transportation and access systems are depicted in Figure 4-1. Recently, much effort has been put on developing access systems, and launch and recovery systems for daughter craft on accommodation vessel; see e.g. [19]. The safety and efficiency of such systems have a major impact on the overall logistic strategy. A major driver for the transportation strategy is the distance of the wind farm from shore, or more precisely from a suitable harbor for maintenance. For distance beyond 50-60 km, the traveling distance and expected sea sickness after a long time on a vessel requires an offshore maintenance accommodation either via a living platform or an accommodation vessel (generally with a length above 65m).

Figure 4-1: Example of transportation solutions for offshore wind farms. Left: Crew transfer vessel , middle: Helicopter hoisting (http://www.uni-fly.dk), Right access system for CTV (http://www.osbitpower.com)

Two models are proposed in this chapter which focuses mainly on the aspects one through five. The first model is based on an analytical approach, and it considers the effect of queuing due to technician availability. The second model is based on simulation of the maintenance process. The two models are complementary, the analytical model being much faster, which is suitable if many strategy scenarios are investigated. The simulation models is more accurate, and can be used to evaluate the interaction between the different maintenance resources in more details, and to calculate the energy-based availability, and the risk associated with achieved availability. The simulation model was also used to validate the analytical model.

4.2 Analytical model

4.2.1 Introduction

The proposed model presented in Paper IV focuses on the aspects one through five identified in Section 4.1. The model distinguishes between major and minor failures with respect to repair time and required means of transportation. The wind turbine can be accessed by both a CTV and an helicopter for minor failures, while a major failure always requires a CTV. It does not consider the replacement of major components e.g. blades, main bearing, gearbox or generator. These components are continuously monitored, which enables pro-active planning of resources, and their replacement is afflicted with different logistic needs than those taken into account in the present study, e.g. a crane ship.

The model enable the evaluation of possible alternative transportation means (for example the use of a helicopter in cases when the transportation by workboat is impeded by harsh weather), and it considers the effect of the work shift and the queuing of maintenance work in case of a lack of technicians. To the knowledge of the author, no analytical model had been published that considered all these factors.

The objective of the model is to compare different scenario for a maintenance support organization. For each scenario, the optimal number of technicians permanently working on site, and supplementary technicians for performing the service maintenance, is determined, as well as the resulting expected availability and cost of the support organization. The flowchart in Figure 4-2 summarizes the steps in the model for the evaluation of a maintenance support organization.

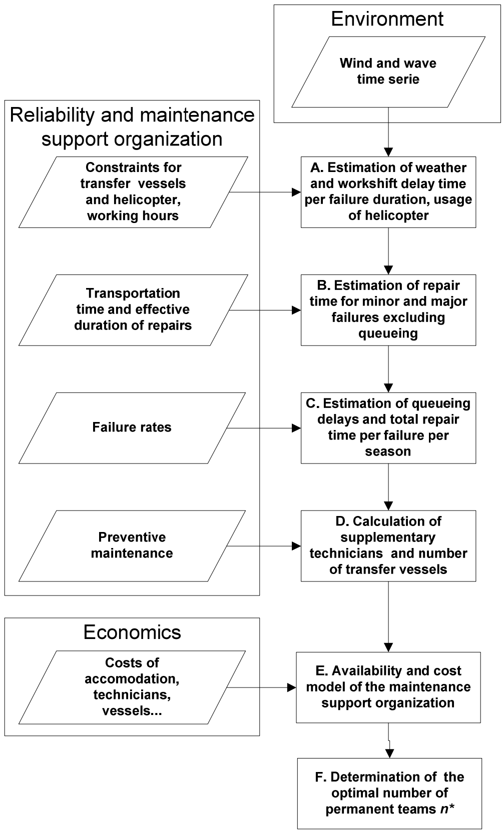

Figure 4-2: Workflow of the different steps of the model.

4.2.2 Main results

The proposed model has been demonstrated by means of a case study of a fictitious offshore wind farm consisting of 100 wind turbines located 60 km from a harbor. Each turbine has a rated capacity of 5MW. Wind and wave data are based on real data from the 160MW Horns Rev offshore wind farm located 15 km off the coast of Esbjerg in Denmark. The reader is referred to Paper IV for a description of the assumptions.

The study compares several maintenance support organizations with respect to different locations of the maintenance accommodation (onshore or offshore accommodation platform), work shift arrangements (12/7 or 24/7) and transportation means, for the purpose of identifying the most cost-effective solution.

Two different types of CTVs are investigated, CTV1 and CTV2, as well as the use of helicopter. The main difference between the vessels is that the CTV2 is equipped with an access system, in the form of a gangway or stabilizing platform to enable access to the wind turbine at higher significant wave height.

The main results obtained from the analysis of the maintenance support organizations investigated are presented in

Table 4-1. It can be observed that the organization scenario 10, which consists of an offshore accommodation with 24/7 work shifts and the use of CTV2, offers the most cost-efficient solution closely followed by the options 12, 2 and 4. All options include the use of CTV2, clearly more cost-beneficial than using CTV1. The economic benefit of scenario 10 is in the range of 0.6 M€-5.2 M€ per year as compared to alternative support organizations, which corresponds to 4-30% of the logistic costs.

The cost-benefit of using the helicopter differs with the type of CTV as well as the work shift arrangement. The yearly availability increase is in the range of 0.2%-0.7% for an organization with 24/7 work shifts and type CTV2 vessels as well as for an organization with 12/7 work shifts and CTV1, respectively. The use of the helicopter is cost-beneficial in all cases except for the case of an offshore accommodations with 24/7 work shifts and CTV2.

It can also be observed that an offshore accommodation is cost beneficial only in the case of the 24/7 work shift. This can be attributable to the relatively low increase in the availability and work efficiency due to the location of the accommodation alone. The benefit would increase with a longer distance from the shore and harsher weather conditions. It can be noted that the availability increases by almost 1% for each logistic solution for 24/7 instead of 12/7 work shifts.

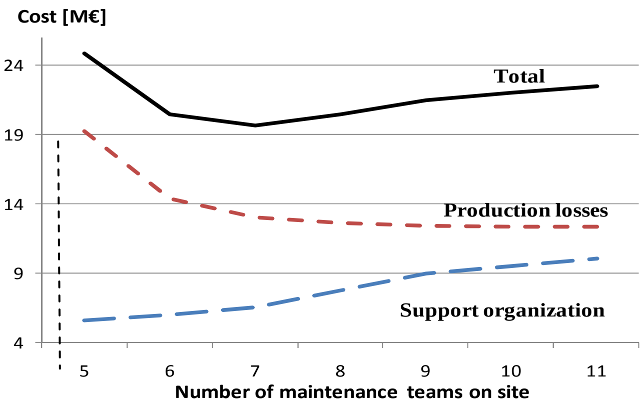

Figure 4-3: Cost based on the organization Scenario 1 in

Table 4-1 as a function of the number of maintenance teams. The optimal number of teams is $n^{*} = 7$.

Table 4-1: Summary of results of analyzing maintenance support organization scenarios in Paper IV $n_{PM}^{spr}(n^*)$ denotes the number of supplementary technicians during the summer, b^{win}/b^{spr} the number of CTV per season, U_h^{yr} the usage rate of the helicopter, $A(n^*)$ the availability and $C_{org}^{tot}(n^*)$ and $C_{losses}^{tot}(n^*)$ the cost of the maintenance support organization and production losses.

Scenario description					**Results**							
Org.	Location	Workshift	CTV	Heli.	n^*	$n_{PM}^{spr}(n^*)$	b^{win}/b^{spr}	U_h^{yr}	$A(n^*)$	$C_{org}^{tot}(n^*)$	$C_{losses}^{tot}(n^*)$	**Total cost**
1	onshore	12/7	CTV1	No	7	0	2 - 2	n.a.	95.7%	6.6	12.9	19.5
2	onshore	12/7	CTV2	No	6	0	2 - 2	n.a.	96.8%	6.9	9.6	16.5
3	onshore	12/7	CTV1	Yes	6	0	2 - 2	25%	96.3%	7.3	11.2	18.5
4	onshore	12/7	CTV2	Yes	4	5	1 - 2	14%	96.6%	6.6	10.0	16.7
5	offshore	12/7	CTV1	No	6	0	2 - 2	n.a.	96.0%	9.0	11.9	21.0
6	offshore	12/7	CTV2	No	4	4	1 - 2	n.a.	96.8%	8.5	9.7	18.2
7	offshore	12/7	CTV1	Yes	6	0	2 - 2	25%	96.7%	10.3	9.7	19.9
8	offshore	12/7	CTV2	Yes	4	4	1 - 2	14%	97.2%	9.8	8.2	18.0
9	offshore	24/7	CTV1	No	4	0	1 - 2	n.a.	97.0%	10.9	9.2	20.0
10	offshore	24/7	CTV2	No	3	0	1 - 1	n.a.	97.9%	9.6	6.2	15.8
11	offshore	24/7	CTV1	Yes	3	0	1 - 1	12%	97.5%	10.2	7.5	17.7
12	offshore	24/7	CTV2	Yes	3	0	1 - 1	7%	98.1%	10.8	5.6	16.4

4.3 Simulation model

4.3.1 Introduction

The analytical model was further developed into a simulation model in order to improve the availability results. The simulation model has several benefits compared to an analytical model, for example, it enables to evaluate the interaction between the different maintenance resources, to calculate the energy-based availability, and to evaluate the risk of the availability results over a given period. The reader is referred to the Paper V for a description of the model and the logic of the simulation process.

4.3.2 Main results

The same case study as in Paper IV has been performed in Paper V the base scenarios where selected according to the optimized solution.

Table 4-2 summarizes the main results. A general conclusion is that, as expected, the availability increases when the support organization is enhanced by higher accessibility and lower transportation time. However the availability depends also much on the effective working hours, and number of technicians as it can be observed by comparing the results for the Scenario 1 and 5, and the Scenarios 2 (or 3) and 4 respectively.
It can also be observed that the energy-based availability is generally slightly lower than the time-based availability except if the accessibility is low, i.e. if only the CTV1 is used as in the case for the scenarios 1, 5 and 9 for which the difference between the energy-based and time-based availability is in the range of 0.4-0.9%.

The helicopter increases the energy-based availability by 1.3%-1.9% if the CTV1 is used, while the benefit is much lower if the CTV2 is used. It should be noted that the benefit of the increased working hours due to transportation with the helicopter has not been modeled. This would slightly increase the availability and improve the working efficiency of the technicians. Similarly to the conclusion for the helicopter, the CTV2 leads to an improvement of the energy-based availability by 1.3%-1.9% in all the scenarios for which the helicopter is not used.

The benefit of placing the maintenance accommodation offshore seems limited from an availability point of view, which can be due to the lower number of technicians resulting from the economic optimization in Paper IV. However there is an indication that the energy-based availability can be increased by 0.7%-1.1% if the maintenance work can be performed during the night.

There is an intrinsic uncertainty associated with the randomness in failure occurrence, as well as in the variability in the annual weather. This uncertainty can be evaluated by the standard deviation of the annual availability which is noted $\sigma_{P_y^{WF}}$ in

Table 4-2. It can be observed that the uncertainty decreases when the accessibility is enhanced.

4.3.3 Comparison with the analytical model

The availability results from the proposed simulation model are compared with the results from the analytical model in Paper IV in the last three columns in Table 4-2. Since the analytical model excludes the major component failures, the unavailability due to the failure of the major component is excluded in the adjusted time-based availability A_y^{WF*}.

It can be observed that the availability calculated by the simulation model is higher in all scenarios considered, and that the difference is in the range 0.3-0.5% except for the scenarios with CTV1 and helicopter for which the difference is 0.7-0.9%. A possible explanation is that the Markov queuing model used in the analytical model considers only an average repair time per failure without differentiation between minor and major repair. This suggests that the analytical model may be improved by differentiating the type of failures in the state model.

Table 4-1: Summary of results of analyzing maintenance support organization scenarios in Paper IV $n_{PM}^{spr}(n^*)$ denotes the number of supplementary technicians during the summer, b^{win}/b^{spr} the number of CTV per season, U_h^{yr} the usage rate of the helicopter, $A(n^*)$ the availability and $C_{org}^{tot}(n^*)$ and $C_{losses}^{tot}(n^*)$ the cost of the maintenance support organization and production losses.

Scenario description					**Results**							
Org.	Location	Workshift	CTV	Heli.	n^*	$n_{PM}^{spr}(n^*)$	b^{win}/b^{spr}	U_h^{yr}	$A(n^*)$	$C_{org}^{tot}(n^*)$	$C_{losses}^{tot}(n^*)$	**Total cost**
1	onshore	12/7	CTV1	No	7	0	2 - 2	n.a.	95.7%	6.6	12.9	19.5
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3	onshore	12/7	CTV1	Yes	6	0	2 - 2	25%	96.3%	7.3	11.2	18.5
4	onshore	12/7	CTV2	Yes	4	5	1 - 2	14%	96.6%	6.6	10.0	16.7
5	offshore	12/7	CTV1	No	6	0	2 - 2	n.a.	96.0%	9.0	11.9	21.0
6	offshore	12/7	CTV2	No	4	4	1 - 2	n.a.	96.8%	8.5	9.7	18.2
7	offshore	12/7	CTV1	Yes	6	0	2 - 2	25%	96.7%	10.3	9.7	19.9
8	offshore	12/7	CTV2	Yes	4	4	1 - 2	14%	97.2%	9.8	8.2	18.0
9	offshore	24/7	CTV1	No	4	0	1 - 2	n.a.	97.0%	10.9	9.2	20.0
10	offshore	24/7	CTV2	No	3	0	1 - 1	n.a.	97.9%	9.6	6.2	15.8
11	offshore	24/7	CTV1	Yes	3	0	1 - 1	12%	97.5%	10.2	7.5	17.7
12	offshore	24/7	CTV2	Yes	3	0	1 - 1	7%	98.1%	10.8	5.6	16.4

5 Optimization of maintenance planning

5.1 Introduction

Maintenance planning is the prioritization and planning of maintenance tasks with respect to available maintenance crew, spare part and maintenance equipment. Maintenance planning applies to all maintenance activities, and much saving can be achieved by its optimization. The main cost savings are related to the production losses and logistic costs including fuel, and mobilization costs.

Generally, scheduled service maintenance is performed during a fixed period of time and with little consideration for the power production. When maintenance is performed, the WT is stopped, which results in costs for production losses. If these maintenance activities were instead performed at low wind production, it would result in cost savings. Moreover, WTs are subject to failure, and each failure provides an occasion to perform part of the scheduled service maintenance. By doing so, it would avoid the need to access the WT later on, and may reduce transportation and work costs as well.

Wind power forecasting tools are important for the maintenance planning. Forecasting models have been developed to predict wind power production up till 7 days using ensemble input from numerical weather prediction as available from the European Centre for Medium Range Weather Forecasts in Europe, see more details in [20]. Chaos theory was used in [21] to show that the limit of weather predictability is around two weeks. Longer horizons are of interest for the purpose of maintenance planning. An option is to use seasonal forecasts based on wind power historical data for the horizon above the 7 days.

The objective of the models presented in paper VI and VII is to develop an approach for optimizing the planning of service maintenance activities by taking advantage of opportunities at failure and low production forecasts to reduce costs for transportation and production losses. The models are even more relevant with the increased level of redundancy and increased efficiency of the condition monitoring systems for offshore wind turbines. These changes will result in more scheduled maintenance activities that could be planned similarly as the service maintenance activities.

The model in Paper VI assumes a deterministic production forecast (also known as point forecasting) and neglected the wind and wave constraints. The model is further improved in Paper VII by considering ensemble wind production forecasting instead of point forecasting. Moreover, constraints on the accessibility to the wind turbines were added, as well as transportation decision on using the helicopter in case of bad weather.

The model proposed in Paper VII is a rolling horizon stochastic optimization model which considers the production forecast and corrective maintenance activities in order to determine a set of preventive and corrective maintenance tasks that are advised to be performed during the present day and maintenance planning forecasts for the following days.

5.2 Main results

The example consists of five 3MW wind turbines with four Preventive Maintenance (PM) tasks to be performed on each turbine. In total this corresponds to two days of work, e.g. the major service maintenance during the summer in an offshore wind farm. The tasks 1 and 3 take 4 hours per turbine and the tasks 2 and 4 take 3 hours. A scenario of 60 days is used, which means that 60 maintenance planning optimizations are performed using the model. It is assumed that the PM tasks 1 and 2 have to be performed within the first 20 days and the PM tasks 3 and 4 should be performed during the first 50 days:

$$N_{Tshort} = 7, N_{Tlong} = 4$$

$$\tau_{10} = \tau_{30} = 4 \text{ h}, \tau_{20} = \tau_{40} = 3 \text{ h}$$

The failure scenario was generated randomly assuming a failure rate of 5 failures per turbine per year. The failure scenario is depicted in Figure 5-1. The repair time was assumed to be 4 hours for each failure.

The wind data were based on a summer period at Lillgrund offshore wind farm. 7-days forecasting scenarios were considered for the example case. The wind forecast for each scenario was generated randomly assuming a normal distribution of the forecasting error with increasing variance. The production forecasts were based on the wind scenarios using a power curve. An example of the power production scenarios is shown in Figure 5-1. The power losses for CM activities, denoted P_{ts}^{CM}, were calculated using the production scenarios and repair times τ_i^{CM}.

A selected scenario and solution is presented in Figure 5-1 and Figure 5-2. The maintenance manager performs an optimization of the maintenance planning every day based on the present Corrective Maintenance (CM) tasks to be performed and available power forecasts. The result is a set of PM and CM tasks that are advised to be performed during the present day and maintenance planning forecasts for the following days. Figure 5-2 shows the daily advised schedule. The advised tasks are assumed to be performed during the day.

One can notice that PM is only performed at low power production and if CM is required. For example, in day 7 (highlighted by the left dashed line) a failure occurs in wind turbine 1 and the solution indicates to perform the preventive maintenance task 2 in the wind turbine 2 at the same time. This is due to the fact that the tasks 1 and 2 had already been performed in the wind turbine 1, and the maintenance tasks 3 and 4 are not urgent. In day 14 (highlighted by the right dashed line), no failure occurs but the wind power production is quite low. The solution advises to perform the maintenance activities 2 and 4 in wind turbine 3.

The average total maintenance cost for performing the PM tasks was 15,172 €. It is assumed that the transportation costs should not be paid if corrective maintenance is performed at the same time. This cost can be compared with the case where all preventive maintenance tasks are performed without taking into consideration wind forecasts, e.g. during the first days of the scenario, two days per turbine. The maintenance cost without optimization is 22,342 €. It means that 7,170 € or 32% of the costs of the transportation and production losses could have been saved using the proposed approach.

This example demonstrates that it is possible to save costs by taking advantage of low power forecasts and CM opportunities to perform the PM tasks. The implementation of the methodology requires that the maintenance schedule is flexible. The maintenance technicians need to be prepared to perform some service maintenance activities after a failure has been corrected (i.e. material and consumables for the service should be in the wind turbine or on the boat), if the time allows it.

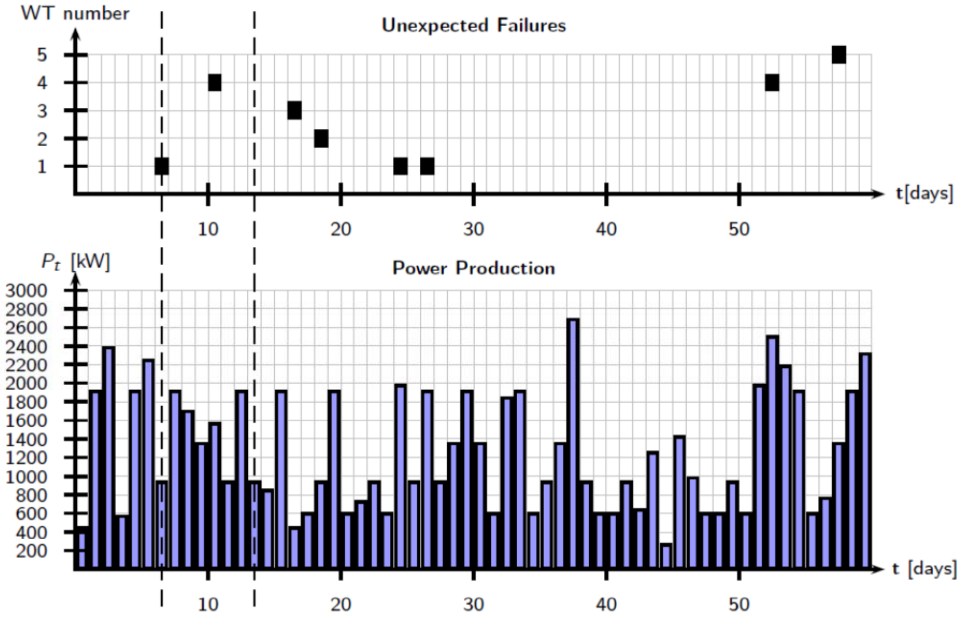

Figure 5-1: Production and failure scenario.

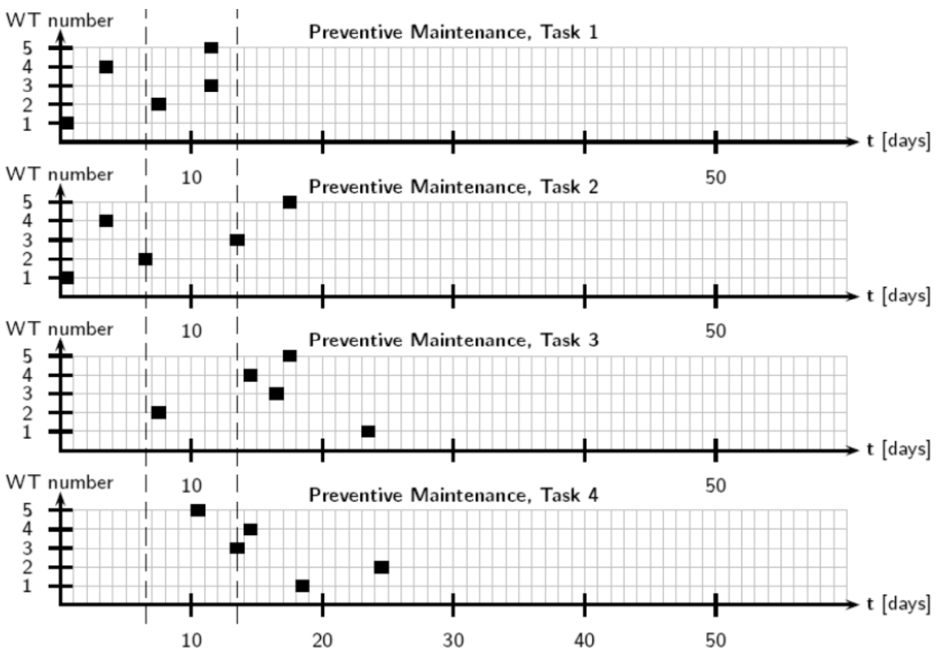

Figure 5-2: Results from the planning optimization

6 Closure

6.1 Conclusions

This project resulted in several models to optimize the maintenance of offshore wind farms in different inter-connected areas. The main results are recommendations for maintenance strategies, maintenance support organization and a demonstration of the benefit of opportunistic maintenance for maintenance planning

Maintenance strategies

Two models are introduced to optimize the maintenance strategies for the drive train and for blades. The main idea of both models was to evaluate the benefit of condition based maintenance strategies based on inspection or continuous condition monitoring. The models are stochastic life cycle cost models dependent on reliability and maintenance processes. The results indicate that condition monitoring of the drive train results in an economic benefit of 26% of the total cost of maintenance and production losses over the lifetime and that it decreases the risk of high maintenance costs.

The cost-benefit of inspection based on condition based maintenance techniques, or continuous monitoring of blades is much dependent on the reliability assumptions. The results indicate that online condition monitoring is the optimal solution in case of high failure rate, or short deterioration time.

Maintenance support organization

Two complementary models have been proposed to optimize the maintenance support organization for offshore wind farm, considering several factors affecting the maintenance performance: the location of the maintenance accommodation and distance to the wind farm, the number and type of crew transfer vessels, the use of a helicopter and the work shift organization. The models enable to determine the optimal support organization for a given wind farm according to the reliability of the wind turbine, weather conditions, distance from shore and logistic costs. An analytical model enables fast computation of the optimization, which can be further investigated by a simulation model in order to calculate energy-based availability and the risk associated with the solution. The results from a case study for a wind farm of 100 wind turbine with 5MW rated capacity indicate that an economic benefit in the range of 0.6 M€-5.2 M€ per year can be achieved by selecting the optimal maintenance support solution, as compared to other possible solutions.

Maintenance planning

A model for the optimization of maintenance planning is proposed to determine the optimal time for performing the scheduled maintenance activities, with consideration for the cost for transportation and production losses. The model is based on a rolling moving horizon taking into account the knowledge on short term weather forecasts and long term weather statistics, together with opportunities at corrective maintenance. The case studies indicate that an economic benefit of up to 1.4 kEur per wind turbine per year could be achieved compared to a classic time based approach.

6.2 Future work

Maintenance support organization

It was identified that the analytical model presented in this thesis could be further improved by differentiating between the minor and major repairs in the queuing model. This improvement could be implemented and the results compared with the simulation model.

Several simulation models have been proposed in order to optimize the maintenance support organization for offshore wind farms. Each model has a different level of detail, limitations and constraints. It would be beneficial to compare the different models to validate them by comparison with reliability and maintenance time-series data from an existing wind farm.

Maintenance planning optimization for major components

The replacement of large components at offshore wind farms requires crane ships that have limited availability and high costs. It could be advantageous to prioritize, group and optimize the planning of these activities based on reliability and weather statistics in order to reduce the production losses due to unavailable crane ship, long weather downtime or mobilization costs. A related topic is the optimization of the supply strategy for the crane ship, where alternative such as supply via the spot market, periodic contracting or purchase could be compared.

Reliability analysis

The prerequisite for maintenance strategy optimization models is to have component lifetime models. Lifetime models were unfortunately not available during this thesis work mainly due to a lack of structured and systematic reliability data collection and therefore reliability assumptions had to be made. Reliability and maintenance data collection has now received much focus, and standardized data collection systems will enable to develop lifetime models. It is important that not only failures but also inspection results are recorded in order to be able to develop deterioration models.

Since the technology is evolving rapidly and the lifetime is dependent on many environmental factors, physic based reliability model would be most beneficial to estimate the reliability of new technology or concepts, and to develop prognosis models.

High voltage power system

The focus of this thesis has been on wind turbines at offshore sites. The high voltage export system connecting the wind farm to the electrical grid onshore is, however, critical for the transmission of the power. Due to the higher distance from shore, complex HVDC grid solutions and long underwater cables are likely to be introduced. The reliability, maintenance and risks related to the high voltage export system will be critical. Synergies with the maintenance support organization for the wind farm could also be identified in order to reduce the total maintenance costs.

Publications from the project

Papers related to maintenance strategies

I. F. Besnard, J. Nilsson and L. Bertling, “On the Economic Benefits of using Condition Monitoring Systems for Maintenance Management of Wind Power Systems”, *In proc. of IEEE conference PMAPS 2010*, Singapore, 14-17 June 2010.

II. F. Besnard and L. Bertling, “An Approach for Condition-Based Maintenance Optimization Applied to Wind Turbine Blades”, IEEE Transaction on Sustainable Energy, 1(2):77-83, 2010

III. Besnard F., Fischer, K and Bertling L., “Reliability-Centred Asset Maintenance – A step towards enhanced reliability, availability, and profitability of wind power plants”, *In proc. of the conference IEEE PES Innovative Smart Grid Technologies*, Gothenburg, Sweden, 10-13 October 2010.

Papers related to maintenance support organization

IV. F. Besnard, K. Fischer and L. Bertling, “A model for optimization of maintenance support organization for offshore wind farms”, Accepted for publication in IEEE Transactions on Sustainable Energy, 2013.

V. F. Besnard and L. Bertling, “A Simulation Model for Reliability Evaluation of Maintenance Support Organizations for Offshore Wind Farms”, submitted to IEEE Transactions on Sustainable Energy, October 2012.

Papers related to optimization of maintenance planning

VI. F. Besnard, M. Patriksson, A.-B. Stromberg, A. Wojciechowski and L. Bertling, “An Optimization Framework for Opportunistic Maintenance of Offshore Wind Power System”, *In Proc. of IEEE PowerTech 2009 conference*, Bucharest, Romania, 28 June - 2 July 2009.

VII. F. Besnard, M. Patriksson, A.-B. Stromberg, A. Wojciechowski, K. Fischer and L. Bertling, “A Stochastic Model for Opportunistic Service Maintenance Planning of Offshore Wind Farms”, *In Proc. of IEEE Powertech conference*, Trondheim, Norway, 19-23 June 2011.

Other related publications

VIII. F. Fischer, F. Besnard and L. Bertling, “Reliability-Centred Maintenance for Wind Turbines Based on Statistical Analysis and Practical Experience”, *IEEE Transaction on Energy Conversion*, 27(1): 184-195, 2012.

IX. K. Fischer, F. Besnard, L. Bertling, ”A Limited-Scope Reliability-Centred Maintenance Analysis of Wind Turbines“, *In Proc. of the European Wind Energy Conference EWEA 2011*, Brussels, Belgium, 14-17 March 2011.

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