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## **On Different Maintenance Strategies for Casted Components of Offshore Wind Turbines**

Ambühl, Simon; Sørensen, John Dalsgaard

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Aalborg University  
Department of Civil Engineering  
Reliability and Risk Analysis Research Group

**DCE Technical Report No. 222**

# **On Different Maintenance Strategies for Casted Components of Offshore Wind Turbines**

by

**Simon Ambühl  
John Dalsgaard Sørensen**

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## Abstract

This report, which is a part of the REWIND project, focuses on maintenance expenses for casted components mounted on offshore wind turbines. The maintenance costs for casted components are extracted from a maintenance operation tool, which simulates maintenance operations at wind turbine farms. This maintenance tool uses Crude Monte Carlo Simulations to estimate the expected maintenance costs. Corrective and preventive maintenance strategies with a constant inspection interval or a condition monitoring system are considered. Furthermore, transportation from shore to the wind turbines by boat and helicopter are considered. A case study assuming a wind turbine farm consisting of ten 6 MW wind turbines placed 30 km off the Danish North Sea coast investigates the cost saving potential for casted wind turbine components (low (LSS) and high speed shaft (HSS) and the hub) when optimizing the maintenance and transportation strategy. The case study shows that the maintenance expenses of casted components correspond to roughly 5% of the overall expected maintenance costs when using a corrective maintenance strategy. This amount can be decreased to roughly 2% when using a condition monitoring system and following a preventive maintenance strategy. The maintenance expenses for the hub dominates the maintenance costs of casted components. The maintenance expenses for LSS and HSS are smaller and much less sensitive to the maintenance strategy or the inspection quality.

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# Chapter 1

## Introduction

This report is part of the REWIND project - WP 6.3: Reliability-based decision tools - which focuses on casted material used in drivetrains for wind turbines. The report itself deals with operation and maintenance studies for casted components of offshore wind turbines.

Maintenance expenses for offshore wind turbines can reach up to 30% [21] of the levelized cost of electricity. A big challenge for wind turbines, in general and especially for offshore wind turbines, is to reduce their levelized costs of energy in order to become more competitive with other electricity sources and be able to produce electricity at a competitive price also in the far future when the financial support is expected to be reduced. In general, financial support for renewable electricity production is given either by pre-defined feed-in tariffs or feed-in premiums where an additional amount is given to the actual sale price of the electricity. The financial support for electricity produced by wind turbines is different among the countries. A further challenge that the offshore wind turbine industry will face in the future is the trend of placing big wind turbine farms farther off the coast at deeper water depths where the wind resources are expected to be better and less regulations due to less dense ship routes, less protection areas, or no visual impacts from shore dominate. But locations farther off the coasts mean larger transportation costs, and due to stronger environmental conditions (higher wind speeds and wave heights), the accessibility is expected to be smaller and leading to longer waiting times where the broken turbine is out of order compared with wind turbine farms placed close to shore. For offshore wind turbines the reduction of maintenance expenses is, among others, necessary to get the electricity production costs down due to the fact that they cover a considerable amount of the total production costs.

A wind turbine consists of casted or forged components like the rotor hub, the main shaft or machine bases and housings, of components made out of composite material (fibreglass) like the blades or the nacelle housing as well as of electrical components mainly consisting of plastic and copper. The focus in this report is on casted components, which are from a failure rate point of view mainly represented by the high speed and low speed main shaft as well as the hub connecting the blades with the drivetrain. Machine housings as well as machine base plates are assumed to have negligible failure rates compared with the actual failure rate of the machine.

The maintenance expenses and their cost saving potential of casted components mounted on wind turbines are estimated in this report based on a case study which uses a reference wind turbine farm. This reference wind turbine farm is assumed to be placed 30 km off the Danish North Sea Coast and consists of ten 6 MW wind turbines. Different maintenance strategies as well as transportation policies are investigated in order to estimate the maintenance cost saving potential of casted components during a lifetime of 20 years. The total expected maintenance costs are estimated based on Crude Monte Carlo Simulations.

The report is organized in different chapters. Chapter 2 presents the theoretical background of different maintenance and transportation strategies. Chapter 3 presents how random machine failures and crack evolution leading to mechanical failure of components can be modeled, and Chapter 4 shows background information about the considered reference wind turbine farm. The results are presented in Chapter 5 including some sensitivity studies on important input parameters. The conclusions are given in Chapter 6.



## Chapter 2

# Different Maintenance Strategies

There are different maintenance strategies for all kind of machines. The following presents a general overview about different maintenance strategies.

Figure 2.1 gives an overview about different strategies to maintain a wind turbine. Maintenance can be performed correctively where repair or replacement is performed after the component broke. On the other hand, a preventive maintenance strategy can be applied where the idea is to replace a certain component before it breaks. Preventive maintenance can be performed based on scheduled inspections or based on condition-based inspections. When following a conditioned preventive maintenance strategy, a condition monitoring system is needed which indicates possible future failure based on directly or indirectly measuring the damage.

The advantage of preventive maintenance is that repairs and replacements can be planned, and the downtime is expected to be lower than when following a corrective maintenance strategy. On the other hand a preventive maintenance strategy leads to a higher number of repairs/replacements over the whole lifetime compared with a corrective maintenance strategy. Furthermore, preventive maintenance strategies may also include some corrective maintenance actions because not all possible failures may be indicated by the condition monitoring system. Additionally, the condition monitoring system may give false alarm where an alarm is given but no future failure is happening.

Offshore wind turbines are exposed to strong weather conditions which limit the accessibility and therefore in-

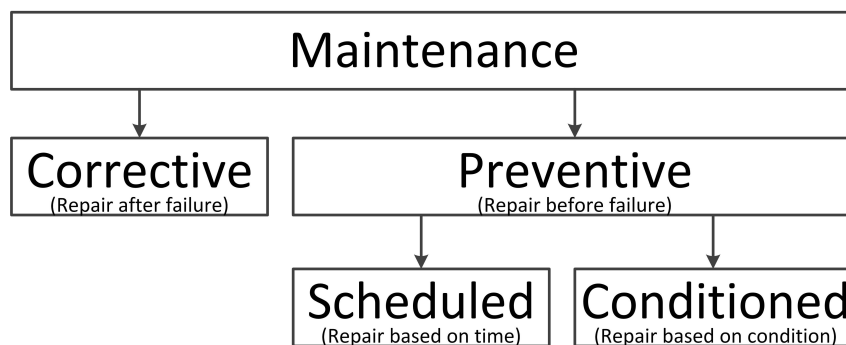


Figure 2.1: Different maintenance strategies.

crease the waiting time while the broken wind turbine is not able to produce electricity and generate an income. Therefore minimizing the overall maintenance costs is an important issue for offshore wind turbines.

Scheduled maintenance contains regular inspections which also may include different inspection intervals between two subsequent inspections. Condition monitoring couples an indicator for a specific failure to a measurable parameter. Measuring oil contamination, vibrations, noise, temperature, accelerations or parameters measured for controlling the wind turbine can be used as indicator for future failures of a certain component. In order to measure the before mentioned parameters indicating future breakdown of the turbine, sensors are needed at specific locations. There are different procedures as to how the measured data can be analyzed in the time domain or frequency domain. Common practice gives an alarm to the operator if a parameter value exceeds a certain threshold which can be a certain absolute value or a certain rate. In a next step a technician crew is sent to the wind turbine in order to perform an inspection and repair the critical component. A detailed study about condition monitoring possibilities for the main shaft of wind turbines is given in [1].

Which maintenance strategies to chose is driven by the motivation to find the lowest total maintenance costs over

the lifetime. When considering a wind turbine farm, it is important to consider the whole wind turbine farm and not optimizing the maintenance strategy for a single wind turbine since many costs can be shared when considering the overall wind turbine farm.

## 2.1 Transportation Strategies

Offshore wind turbines can be accessed by boat and by helicopter. The boat is assumed to be limited by the wave characteristics (mainly wave height) and the helicopter's operational range is mainly bounded to the wind speed. There are many factors, which drive the cost of the different means of transport. The cost for transportation depends, among others, on means of transportation specific costs like:

- Transportation speed/time,
- Fuel consumption and prize, or
- Renting contract condition (e.g. rented on daily or hourly-basis).

But also location specific facts drive the costs, like:

- Distance to shore, or
- Environmental condition

drive the transportation costs. In order to decide how transportation should be performed, different strategies can be used. The following strategies are considered in this report:

- Only use of boat (helicopter not available/boat owned by operator).
- Repair as soon as possible (called ASAP) to minimize downtime.
- Risk-based strategy where the means of transportation leading to the lowest overall costs is chosen.

Figure 2.2 shows a flow chart of the decision procedure for the different considered transportation strategies. The ASAP strategy prioritizes the use of the boat because many offshore wind turbine operators own their own boats and transportation costs by boat are expected to be cheaper than by helicopter. But if the boat cannot be used, a helicopter will be rented for accessing the broken wind turbine.

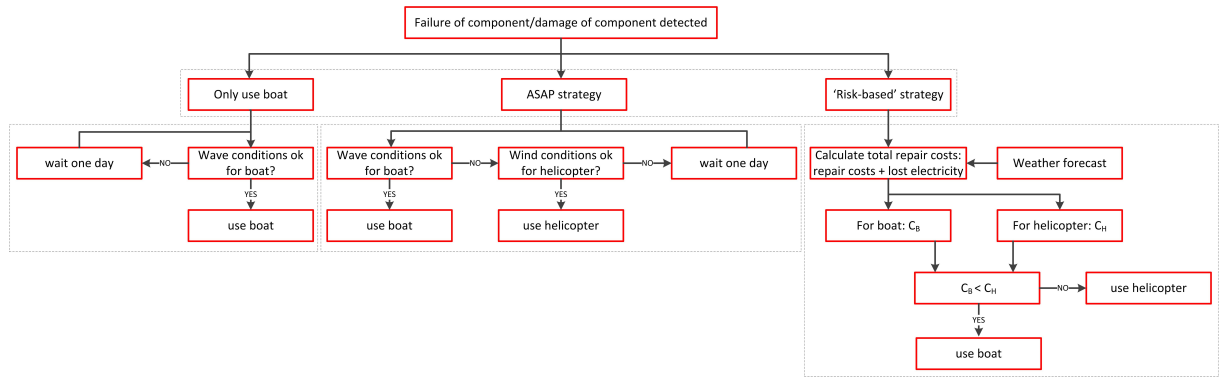


Figure 2.2: Considered different transportation strategies when performing maintenance actions offshore. 'only use boat': no helicopter available; 'ASAP': As soon as possible; 'Risk-based': Minimization of overall repair costs.

## 2.2 Optimal Maintenance and Inspection Planning

Optimal planning of maintenance and inspection actions aims to decrease and minimize the overall maintenance expenses during the whole lifetime of the wind turbine farm. The minimal maintenance expenses can be found by using risk-based methods. Risk can be given as the product of the probability of occurrence and the resulting consequences to the surroundings. This means the risk is a measure for the degree of impact. The framework about risk-based planning of inspections and maintenance actions for offshore wind turbines is explained in [22].

Decision-making for risk-based maintenance planning is based on so-called decision trees which show all different multiple outcomes of the different decisions. Figure 2.3 shows a typical decision tree for optimal planning that corresponds to a pre-posterior decision problem where the state at one point in time is affected by the previous

decisions. Before starting with optimal planning of maintenance and inspection actions, the initial conditions  $\mathbf{z}$  of the wind turbines and the wind turbine farm (e.g. expected lifetime, geometry, dimensions or costs) need to be defined. Based on the defined inspection and monitoring parameters represented in  $\mathbf{e}$  defining the inspection/monitoring plan, a random outcome,  $\mathbf{S}$ , from performed inspections/monitoring occurs and drives the decisions for the repair plan  $d(\mathbf{S})$ . The decision rule  $d(\mathbf{S})$  is applied to future inspection/maintenance information unknown at the time when the inspection/monitoring plan is determined. The realizations of uncertain parameters  $\mathbf{X}$  such as model uncertainties, environmental conditions or degradation parameters lead to different outcomes during the lifetime. The optimal strategy for a fixed initial design,  $\mathbf{z}$ , can be found as the one with maximum difference between the income from selling electricity and the total costs due to installations, inspections, repair and decommissioning. The value,  $W$ , which should be maximized can be calculated as:

$$\max_{\mathbf{z}, \mathbf{e}, \mathbf{d}} W = B - C_I(\mathbf{z}) - C_{IN}(\mathbf{e}, \mathbf{d}) - C_{REP}(\mathbf{e}, \mathbf{d}) - C_F(\mathbf{e}, \mathbf{d}) - C_D(\mathbf{z}) \quad (2.1)$$

where  $B$  is the expected income from selling electricity,  $C_I$  the initial investment costs,  $C_{IN}$  the expected service and inspection costs,  $C_{REP}$  the repair and maintenance costs,  $C_F$  the expected failure costs and  $C_D$  the decommissioning costs. The different costs are driven by the design parameters  $\mathbf{z}$ , the inspection parameters  $\mathbf{e}$  and the chosen decision rules for repair  $\mathbf{d}$ .

Risk-based maintenance planning is also used in other industry branches like petroleum refining and chemical

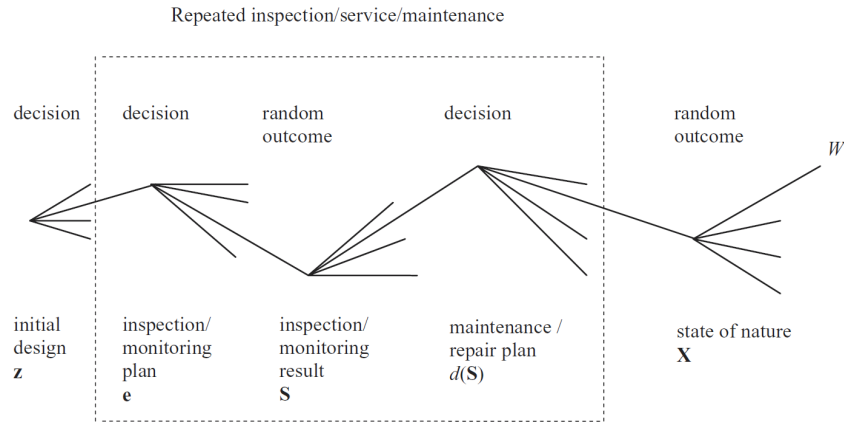


Figure 2.3: Decision tree for optimal planning of operation and maintenance actions. [22]

engineering, shipbuilding, gas and electric power, steel-making and railway industry. Risk-based approaches for wind turbines are only based on cost considerations as humans are not in danger when collapse and partial failure occurs because the machine is unmanned during operation. Furthermore, compared with other industry branches where risk-based approaches are applied, the environmental pollution in case of failure is small for (offshore) wind turbines.

When using risk-based maintenance planning for offshore wind turbines, probabilities of deterioration amplification, probabilities of monitoring results, probabilities of inspection results, probabilities of repair and probabilities of costs as well as probabilities to access the broken device need to be known. This means all decisions are based on a stochastic model. How risk-based methods can be applied for offshore wind turbines is presented in [13].

When considering costs, the discounted present values,  $C_0$  is considered here and can be calculated as:

$$C_0 = \frac{C}{(1 + r)^T} \quad (2.2)$$

where  $C$  is the real cost,  $T$  the time in years when the cost occurs and  $r$  the annual rate of interest.

Maintenance planning is related to many input parameters which need to be known in advance. These parameters are often not exactly known and not always the same over time as e.g. the inspection quality is dependent on the technicians and their experience and will be different for different inspection intervals. Therefore, uncertainties related to these parameters need to be taken into account when estimating the resulting maintenance costs.





## Chapter 3

# Failure Modeling

The following three different kinds of components exist in a wind turbine:

- mechanical/structural components
- electrical components
- software (control)

The above mentioned components can fail in different ways. This needs to be accounted for when doing maintenance cost estimations. Mechanical components like blades, gearboxes or shafts fail due to cyclic loading (fatigue) and are based on time-dependent deterioration processes. The condition of a mechanical component can be investigated by doing inspections as deterioration is shown by e.g. corrosion or evolution of cracks. Electrical failures are not based on deterioration processes, but occur as random failures. When a wind turbine fails due to software problems, a manual restart or update of the operating software often solves the problem. Failures of mechanical as well as electrical components make access to the device necessary whereas software failures can often be solved by online access to the wind turbine.

### 3.1 Mechanical Failure

Mechanical failures are often based on time-dependent damage accumulation. Damage accumulation uses models which estimate the condition of the component at a certain time in space. Additionally, these models enable modeling the influences of inspection. The model considered in this article is based on the model shown in [12]. The damage size is presented as a number between 0 and 1. When the damage size reaches 1, failure of the considered component occurs and needs to be repaired/replaced.

The general damage accumulation for components is assumed to be described by an initial value problem with the following equation:

$$\frac{dD}{dt} = C \cdot F^{m_1} \cdot D^{m_2} \quad (3.1)$$

where  $dD/dt$  represents the damage growth,  $F$  a load measure and  $D$  is the damage size. The parameters  $C$ ,  $m_1$  and  $m_2$  are model parameters, which can be estimated from available failure rates. The above presented damage accumulation model uses an exponential damage model, which can be used for fatigue driven damages based on Paris Law [15] where the damage accumulation rate  $dD/dt$  is given as:

$$\frac{dD}{dt} = \frac{dN}{dt} \cdot C \cdot \Delta K^m \quad (3.2)$$

where  $C$  is the damage coefficient,  $m$  the damage exponent and  $\Delta K$  the damage intensity factor, which, among others, depends on the actual damage  $D$ :

$$\Delta K = \beta \cdot \Delta s \cdot \sqrt{\pi D} \quad (3.3)$$

where  $\beta$  is the geometry factor and  $\Delta s$  the cyclic damage range. The damage coefficient  $C$  and the damage exponent  $m$  can be calibrated from available failure rates of the corresponding components.

For offshore applications, it can be assumed that the damage of the different components is wind and wave load driven. The cyclic damage  $\Delta s$  can, therefore, be assumed to be proportional to the significant wave height  $H_S$  (see. e.g [12]):

$$\Delta s = H_S \cdot x_S \quad (3.4)$$

where  $x_s$  represents the proportionality factor which models the uncertainty about estimation of  $\Delta s$ . Also, the wind speed, which is correlated with the significant wave height could be used to model  $\Delta s$  through the turbulence. The mean zero-crossing wave period,  $T_Z$ , is assumed to drive the number of cycles  $N$ :

$$\frac{dN}{dt} = \frac{3600}{T_Z} \quad (3.5)$$

The damage  $D$  is calculated and summed up over the successive time steps:

$$D_{t+\Delta t} = D_t + \frac{dD}{dt} \cdot \Delta t \quad (3.6)$$

A replacement decision criterion when detecting damages during inspections will take place when a detected damage  $D_{det}$  is larger than a certain threshold  $D_{rep}$ . This means the repair decision criterion is equal to:

$$D_{det} > D_{rep} \quad (3.7)$$

where  $D_{det}$  is the detected damage, which is equal to the actual damage  $D$  if the damage is detected. Inspections can be modeled using so-called probability of detection curves ( $PoDs$ ), which account for the inspection technique and the probability that a certain damage is not detected during inspection. One possibility of defining such a probability of detection curve is by using a one-dimensional exponential threshold model, see e.g. [23]:

$$PoD(D) = P_0 \left[ 1 - \exp \left( -\frac{D}{\lambda} \right) \right] \quad (3.8)$$

where  $P_0$  is the maximum probability of detection,  $D$  the actual damage and  $\lambda$  the expected value of smallest detectable damage.

Inspections can either be performed based on regular inspection intervals or based on alarms from a condition monitoring system. When implementing a preventive maintenance strategy with regular inspection intervals, the time between two inspections,  $\Delta T$  can be fixed or changing over the lifetime of the wind turbine. When using a condition monitoring system, the condition monitoring system gives an alarm when a possible future failure is indicated. This alarm sends a technician group to the device for inspection. Alarm occurs whenever a damage  $D$  is crossing a certain threshold  $D_{alarm}$ . Additionally, in order to present the fact that not all failures can be detected by the condition monitoring system, a condition monitoring efficiency factor,  $\eta_{CM}$ , can be implemented. This efficiency factor defines the percent of mechanical failures which can be detected by the condition monitoring system.

## 3.2 Electrical/Software Failure

Electrical and software failures cannot be detected by inspections before they fail as these components suddenly fail without indication. Electrical and software failures can be characterized by so-called failure rates  $\lambda$ , which model the expected (mean) failure rate for a given time horizon (often one year). The annual failure rate from a data set of failure reports can be estimated based on:

$$\lambda = \frac{n_{fail}/N}{T} \quad (3.9)$$

where  $n_{fail}$  is the number of failures,  $N$  is the component population and  $T$  indicates the operational period (in years). Failure rates for components used in offshore wind turbines can be estimated from databases developed from wind turbine projects, like [7, 20, 24, 26]. But also failure rates from the petrochemical industry (see e.g. [14]) or generic reliability databases (see e.g. [8, 11]) can be used to get an idea about failure rates of the installed electrical components and software/control systems in an offshore wind turbine.

## Chapter 4

### Case Study

The impact of different maintenance and transportation strategies on the maintenance costs for casted components mounted on wind turbines are investigated by looking at a case study. The reference wind turbine is a 6 MW wind turbine, which is similar to the 6 MW Senvion turbine. The power curve of the considered reference wind turbine is given in Figure 4.1. The wind turbine farm considered in the case study consists of ten 6 MW wind turbines, which are placed 30 km off the Danish North Sea coast.

In this case study the wind turbine is not considered down to each single screw or bolt, only the main components

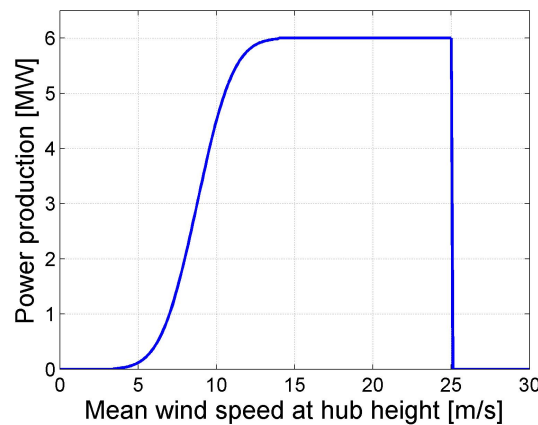


Figure 4.1: Power curve of 6 MW reference offshore wind turbine.

are considered. Figure 4.2 gives an overview about the different components which are considered in the case study. Failures of the components shown in Figure 4.2 can have different severity levels. Minor failures can be repaired by simply repairing the electrical or mechanical component or even exchanging a sub-component like single screws, fixations or bearings. Major failures, like collapse of the tower or breaking of a blade, lead to partial or complete collapse of the wind turbine structure as well as may lead to secondary damages. To repair major failures jack-up vessels with a big crane are needed. In this case study only minor failures are considered.

The expected lifetime of the wind turbines is 20 years. It is assumed that all turbines are operating under free flow conditions. Wake impacts are not considered here as the wind direction and the layout of the wind turbine park is not specified in this example. Furthermore, the weather forecast, where needed in order to plan maintenance actions, is assumed to be perfect. The expected total maintenance costs for the whole wind turbine farm during the lifetime of 20 years are estimated based on Crude Monte Carlo simulations. The electricity feed-in tariff is chosen to be 0.08 €/KWh, which according to [6] is a common value for fixed feed-in tariffs for offshore wind turbine farms. The following three different maintenance strategies are considered in this study:

- Only corrective maintenance actions.
- Preventive (and corrective) maintenance actions with a fixed inspection interval of 0.5 years.
- Preventive (and corrective) maintenance actions based on alarms from a condition monitoring system.

Real weather data measured in one-hour steps between 1979 and 2009 at the considered location are used and re-sampled based on bootstrapping. The wind speed, the significant wave height as well as the mean zero-crossing

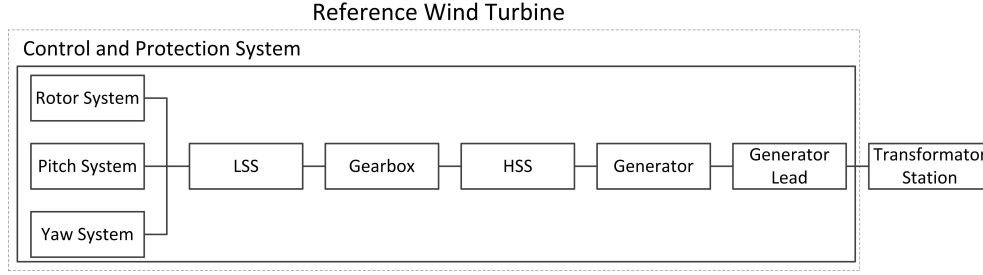


Figure 4.2: Considered main components of the 6 MW reference wind turbine. LSS: low speed shaft (main shaft); HSS: high speed shaft.

wave period are considered here. Table 4.1 shows the wave characteristics at the considered location and Figure 4.3 the corresponding wind speed distribution.

Table 4.1: Considered scatter diagram including probability of occurrence of different wave states at the considered location taking the whole period (1979-2009) into consideration.  $H_S$ : Significant wave height;  $T_Z$ : Mean zero-crossing wave period.

$H_S$ (m)	$T_Z$ (s)					
	2.5	3.5	4.5	5.5	6.5	7.5
0.25	0.01	0.04	0.04	0.02	0.01	0
0.75	0.01	0.07	0.16	0.11	0.05	0.01
1.25	0	0	0.06	0.11	0.05	0.01
1.75	0	0	0	0.06	0.05	0.01
2.25	0	0	0	0.01	0.04	0.02
2.75	0	0	0	0.01	0.02	0.02

## 4.1 Failure Data

Mechanical failures can be detected by inspections, which aim to repair components before they fail. These failures are modeled in this study based on a damage model as presented in Section 3.1. The mechanical damage model parameters mean value of  $C$  and  $x_S$  are calibrated by considering commonly used failure rates for these mechanical components published e.g. in [3, 9, 26]. Table 4.2 shows the considered damage values for different mechanical components. The stochastic parameters  $C$  and  $x_S$  are assumed to be Lognormal distributed [12]. The damage exponent  $m$  and the geometry factor  $\beta$  are treated as deterministic values and the same numbers are considered for all mechanical components. More detailed damage models as well as component-specific damage exponents for the different mechanical components can be found in [2, 18, 19] for casted components (main shaft). All mechanical components have an initial damage,  $D_0$ , which is assumed to be exponentially distributed with mean value equal to 0.02 and a coefficient of variation of 0.02, as considered in the study performed by [12].

Failure of electrical components as well as software failures occur randomly and are modeled based on failure

Table 4.2: Considered damage parameters for different mechanical components of a wind turbine. Dam.: Damage; exp.: exponent; Geom.: Geometry; HSS: high speed shaft; LSS: low speed shaft; COV: coefficient of variation.

Component	Dam. exp. $m$	Geom. factor $\beta$	Dam. Coefficient $C$		Proportionality factor $x_S$	
			Mean	COV	Mean	COV
Rotor system	2	1	1.16E-09	0.2	9.2	0.1
Blade adjustment			2.38E-09		10	
Gearbox			1.65E-09		8.6	
Generator			2.16E-09		6	
HSS			1.07E-09		3	
LSS			1.05E-09		2.7	
Yaw system			1.57E-09		8.2	

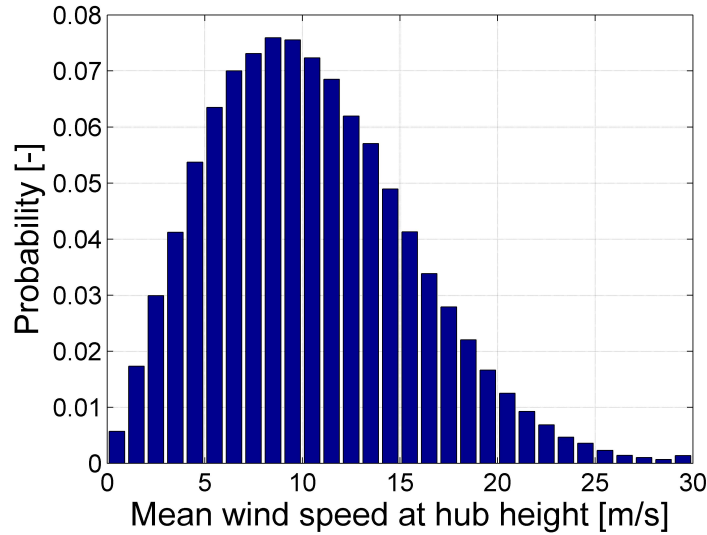


Figure 4.3: Wind speed histogram of mean wind speed at hub height considering all measurements from 1979 to 2009.

rates, as explained in Section 3.2. Table 4.3 shows the considered failure rates for software problems and failure of electrical components mounted at the reference offshore wind turbine. It is assumed that the generator as well as the control and protection system can have electrical failures as well as software problems. But there is no data available specifying the ratio of electrical failures and software problems. Therefore, for these components the resulting overall failure rates shown in Table 4.3 are equally divided into software and electrical failure rates. Recent studies [3, 4, 16] on failure rates of offshore wind turbines show that an offshore wind turbine has roughly 9 incidents per year. Due to the fact that the considered simplified wind turbine model as shown in Figure 4.2 does not cover all components, the estimated failure rates from the original sources are adapted such that the sum of all mean annual failure rates including the mechanical failure rates to calibrate the damage model parameters reach 9 failures per year.

Failure of mechanical/electrical components as well as software failures are modeled differently and have different

Table 4.3: Considered failure rates for failures of electrical components and software.

Description	Mean annual failure rates $\lambda$		Failure type	Source
	original	adapted		
Generator	0.600	1.092	electrical/software	[9, 26]
Generator lead	0.465	0.847	electrical	[9, 26]
Control and protection system turbine	0.862	1.569	electrical/software	[9, 26]
Transformer station	0.08	0.147	electrical	[9, 3]

consequences. If an electrical or mechanical component fails, a technician crew needs to access the wind turbine in order to fix the problem. When a software failure occurs, it is assumed that the technicians can access the software online and by updating or restarting the controller the problem can be solved.

#### 4.1.1 Parameters for Inspection and Maintenance Modeling

Inspections are performed for mechanical components in order to identify future failures by detecting cracks. The probability of detection when doing inspections are modeled using so-called *PoD* curves (see Equation 3.8). It is assumed in this study that the *PoD* curve is the same for all mechanical components during the inspection as the same crew is inspecting the different mechanical components as well as the same inspection method is used for all mechanical components. The smallest detectable damage,  $\lambda$ , is modeled as stochastic variable representing human errors and measurement uncertainties. The smallest detectable damage is assumed to be Normal distributed with a COV equal to 0.1 [12]. The decision rule for repair given a detection of a crack, which is represented by  $D_{rep}$ , as well as parameters of the *PoD* curve are assumed to stay constant over the whole lifetime of the wind turbine.

A condition monitoring system is modeled by  $\eta_{CM}$  and  $D_{alarm}$  representing the efficiency and sensitivity of the condition monitoring system. According to [10] this efficiency factor needs to be in the range between 60% and 80% in order to be cost-effective.

The regular inspection interval ( $\Delta T$ ) is equal to half an year over the whole lifetime of the wind turbine farm.

Table 4.4: Considered  $PoD$  values for inspection of mechanical components as well as parameters for preventive maintenance actions. COV: coefficient of variation.

Symbol	Meaning	Mean	COV	Distribution
$P_0$	Maximum probability of detection	1	-	Deterministic
$\lambda$	Expected smallest detectable damage	0.4	0.1	Normal
$D_{rep}$	Minimal damage for reparation/replacement	0.3	-	Deterministic
$D_{alarm}$	Damage threshold for alarm of condition monitoring system	0.8	-	Deterministic
$\eta_{CM}$	Detection efficiency of condition monitoring system	0.7	-	Deterministic
$\Delta T$	Time interval between two inspections	0.5 years	-	Deterministic

### 4.1.2 Considered Costs

The total repair costs for a corrective repair of electrical and mechanical components consist of the transportation cost, the costs for working hours on the site as well as the cost for the material (new component or repaired component) and the downtime of the wind turbine leading to lost production including the waiting time due to bad weather conditions. When several components fail, the transportation costs can be shared. When performing inspections, the overall inspection costs consist of the transportation costs, the actual downtime (lost electricity production) as well as the repair costs when a crack is detected. It is assumed in this example that inspections and any repairs due to detected cracks can be performed within one working day.

Table 4.5 shows the expected material costs for the different mechanical and electrical components for repairing a failure. The material costs for a failure at the considered 6 MW reference wind turbine are taken from a study performed in [3], which collected cost data from 350 offshore wind turbines throughout Europe. The costs are among others dependent on the installed capacity of the wind turbine. Due to the fact that the average capacity of wind turbines considered in [3] are smaller than 6 MW, the scaling laws presented in [5] are used to estimate the corresponding material costs for the considered reference wind turbine.

Table 4.6 shows the number of days for repair/replacement, which are needed on the device for different failures.

Table 4.5: Expected material and repair costs for different electrical and mechanical components.

Description	Expected repair costs (€)	
	Baseline from [3]	Adapted for 6 MW machine
Rotor system	1500	4250
Blade adjustment	1900	4770
Gearbox	2500	5000
Generator	3500	7000
Generator lead/ cables	3600	9860
HSS part	2400	6530
LSS part	2400	6530
Yaw system	3000	8380
Control and protection system turbine	2200	4400
Transformer station	2300	14520

In this study only full days for repair are considered as equipment (e.g. boat and technicians) are often hired on a daily basis. Repairs are able to be started the following day after failure occurrence at 6:00 am if the weather allows it.

Software failure can be solved by online access, and experience shows that they can be solved relatively quickly compared with failures of electrical or mechanical components. The only costs which result from software repairs are the labor costs needed to analyze the problem and restart the machine. It is assumed that a wind turbine with

Table 4.6: Stochastic model  $X_{REP}$  representing the repair durations (in days) on the device for different mechanical and electrical failures. Data is adapted from [3, 12, 16]. HSS: High speed shaft; LSS: Low speed shaft.

Description	Days needed on site for repair	
	Mean	COV
Rotor system	4	0.5
Blade adjustment	2	
Gearbox	3	
Generator	3	
Generator lead	2	
HSS part	3	
LSS part	3	
Yaw system	3	
Control and protection system turbine	2	
Transformer station	3	

a software failure can resume service after one working day when two specialists were working on fixing the software problem.

Table 4.7 shows the costs related with inspections and transportation as well the considered interest rate. The labor costs per day for a crew of two technicians is, according to [9], in the range of 3600€ (12 hours working day and 150€ per hour). The daily hiring fares for a boat (crew transportation vessel) is in the range of 5000€ [4, 17] for maintenance actions 30 km off the shore. According to [25] the transportation costs by helicopter for a wind turbine farm 30 km off the shore are roughly twice as expensive as transportation by boat. An interest rate of 5% is considered in this study as also considered in other studies performed by [4, 12].

When the weather conditions are too poor to fly or sail out to the broken wind turbines, the cost of waiting

Table 4.7: Inspection and transportation costs as well as considered interest rate.

Description	Costs (€) and rate (%)
Labor costs per day	3600€
Inspection (material) costs per component	1000€
Transportation cost by boat	5000€
Transportation cost by helicopter	10000€
Interest rate $r$	5%

is represented by lost electricity production. Waiting fees for the boat and the helicopter due to bad weather conditions are not considered in this study. Furthermore, it is assumed that the boat as well as the helicopter are always available and the hiring costs are constant over the whole lifetime. When sailing out for inspections, the boat is always used as these actions can be planned and waiting is not a big issue because the wind turbines can go on producing electricity.

### 4.1.3 Operational Range of Boat/Helicopter

Transportation from shore to the offshore wind turbines is either done by boat or by helicopter. Access by boat is mainly limited by the wave height (given a limitation of the significant wave height) and the maneuverability of the helicopter as well as safe lowering of personnel and material is limited by the wind speed. The common limitations (boat: [4, 12]; helicopter: [12]) for boat and helicopter operations are the following:

Boat:	maximum significant height	1.5 m
Helicopter:	maximum mean wind speed	20 m/s

It needs to be kept in mind that accessibility is not only limited by the significant wave height and the wind speed, respectively. Also other factors like humidity and temperature leading to limited visibility due to fog or wind directions as well as wave periods may limit the access.





## Chapter 5

## Results

Figure 5.1 shows the expected (mean) maintenance costs for a lifetime of 20 years of the whole reference wind turbine farm for different transportation and maintenance strategies. Largest maintenance costs are expected when only using boats for accessing the wind turbines. Lowest expected maintenance costs are reached when using a condition monitoring system and a risk-based approach to chose the cheapest means of transportation. The difference between the two preventive maintenance strategies for a given transportation strategy is small. The dominating cost factor when considering maintenance costs are the costs due to lost electricity production. Costs due to software failures, inspection costs and preventive repair costs are of minor size compared with corrective repair costs and lost electricity production.

Figure 5.2 shows the total number of performed repairs during the whole lifetime of 20 years dependent on the

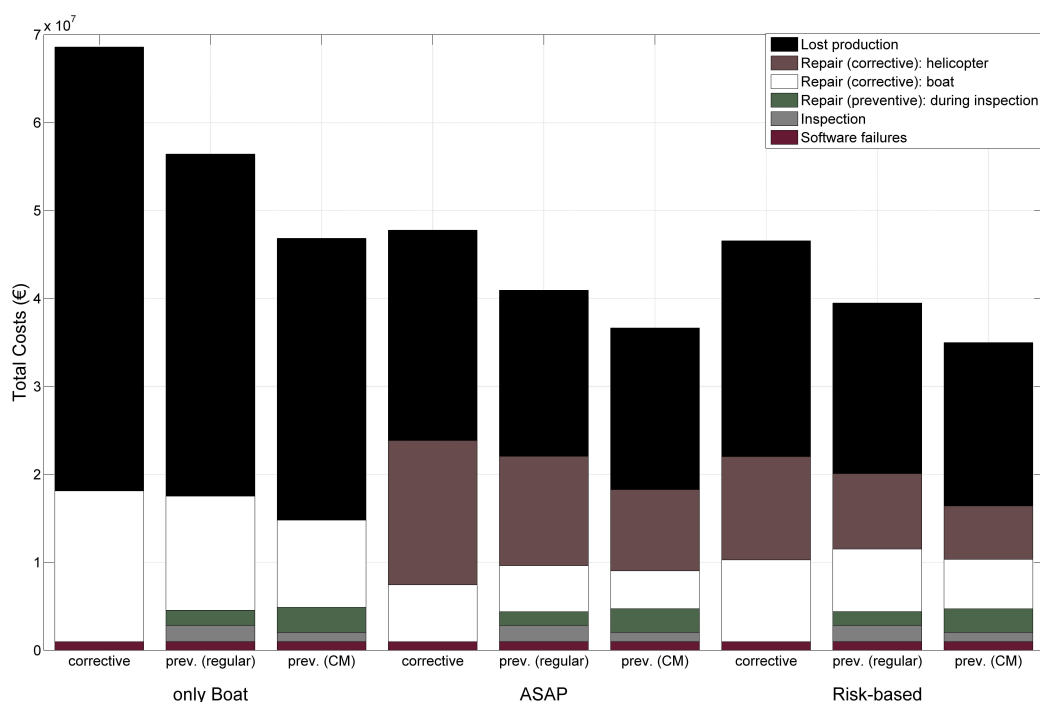


Figure 5.1: Impact on expected maintenance costs for the reference wind turbine farm for different maintenance and transportation strategies. CM: condition monitoring; regular: regular inspections every 0.5 year.

maintenance and transportation strategy. The number of repairs is not dependent on the transportation strategy, but the maintenance strategy. As expected, the number of total repairs is increasing when following a preventive maintenance strategy compared with a corrective maintenance strategy. It needs to be kept in mind that a preventive maintenance strategy also includes corrective repairs because not all future failures can be detected by inspection and the condition monitoring system.

Table 5.1 shows a more detailed overview about some important key parameters important for the economics of the

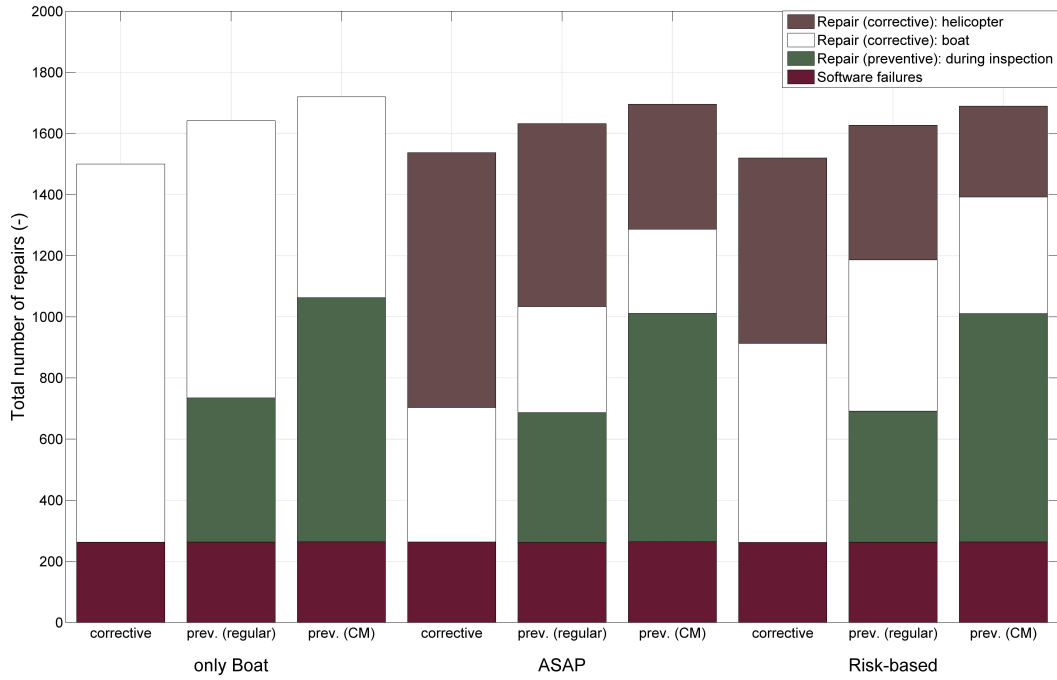


Figure 5.2: Impact on expected maintenance costs for the reference wind turbine farm for different maintenance and transportation strategies. CM: condition monitoring; regular: regular inspections every 0.5 year.

wind turbine farm. The expected mean availability of the wind turbines is dependent on the transportation strategy as well as maintenance strategy. Highest availabilities in the range of 90% to 93% are reached when following the ASAP transportation strategy. Lowest availabilities are present when only doing corrective repair and using the boat to access the wind turbines. The relative operation and maintenance expenses are in the range between 32.1% and 14.2%. The coefficient of variation (COV) of the total maintenance costs shown in Figure 5.1 are between 0.08 and 0.09 when only using the boat and between 0.045 and 0.063 for the case when the boat as well as the helicopter can be used to access the wind turbine (risk-based and ASAP approach).

Table 5.1: Expected values for availability, O&M expenses per produced KWh and coefficient of variation (COV) of total maintenance costs. corr.: corrective; prev.: preventive; reg.: regular; CM: condition monitoring.

	only boat			ASAP			Risk-based		
	corr.	prev. (reg.)	prev. (CM)	corr.	prev. (reg.)	prev. (CM)	corr.	prev. (reg.)	prev. (CM)
Availability (time-based) (-)	0.842	0.878	0.887	0.924	0.937	0.926	0.918	0.933	0.924
Availability (power-based) (-)	0.807	0.852	0.878	0.909	0.928	0.930	0.906	0.926	0.929
O&M expenses/KWh (€/KWh)	0.026	0.020	0.016	0.016	0.013	0.012	0.016	0.013	0.011
O&M expenses/KWh (%)	0.321	0.250	0.202	0.200	0.167	0.149	0.194	0.161	0.142
COV total maintenance costs(-)	0.087	0.083	0.080	0.057	0.055	0.047	0.063	0.057	0.051

## 5.1 Consideration of all Different Components

Figure 5.3 shows the total expected maintenance expenses for the different components installed at the reference wind turbine dependent on different maintenance and transportation strategies. The largest maintenance expenses are reached for the blade adjustment system and the generator. The maintenance expenses for the rotor system (blades and hub) as well as gearbox are high for a corrective maintenance strategy. For preventive maintenance actions, the expenses for the control system becomes dominating as well.

Table 5.2 shows the coefficient of variation (COV) of the expected maintenance costs shown in Figure 5.3 for the

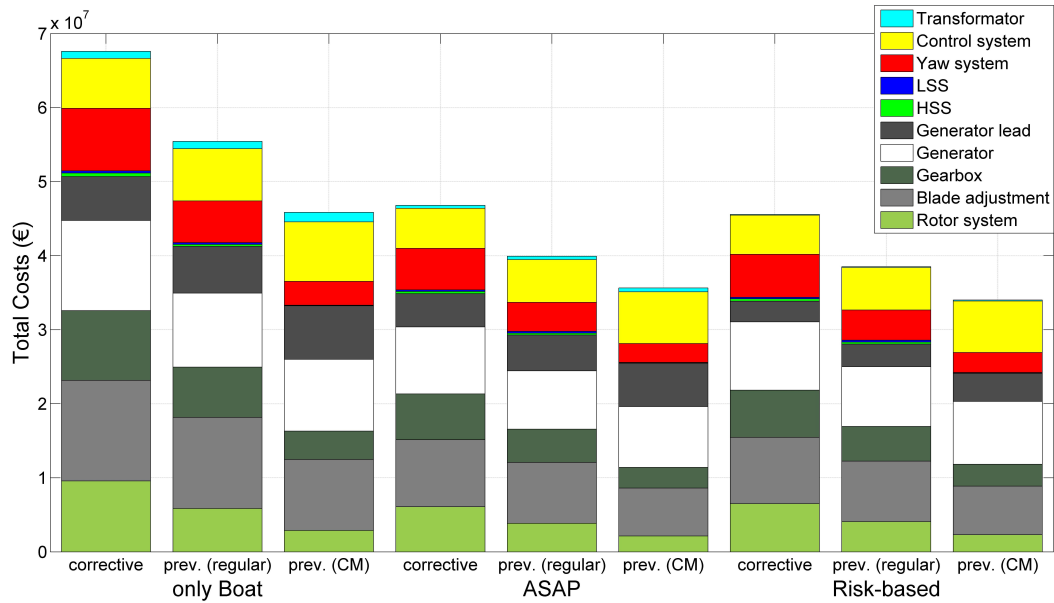


Figure 5.3: Impact of total expected maintenance expenses for the components installed at the reference wind turbine farm for different maintenance and transportation strategies. CM: condition monitoring; regular: regular inspections every year.

different components. Table 5.2 illustrates that components with small failure rates like LSS, HSS and transformer have, in general, large COV values. Furthermore, if only the boat is used to access the wind turbine, the COV values for maintenance costs are larger compared with transportation strategies where the boat and the helicopter can be used for transportation. There cannot be drawn a clear tendency of the COV value dependent on the maintenance strategy. The corrective maintenance strategy leads to the largest cost uncertainties (large COV values) for the HSS and LSS components as well as the transformer, whereas the preventive maintenance strategies have high COV values of maintenance costs for the rotor system, the blade adjustment, the gearbox, the yaw system and the transformer. For some components like the generator, the generator lead, the transformer and the control system, the maintenance cost COV is more or less constant for the different maintenance strategies. But as seen above (see Table 5.1) the largest uncertainty is bounded to a corrective maintenance strategy when considering all components together.

The following section will focus more on maintenance expenses related with casted components.

Table 5.2: Coefficient of variation (COV) values of maintenance expenses of the different wind turbine components dependent on the transportation and maintenance strategy. corr.: corrective; prev.: preventive; reg.: regular; CM: condition monitoring.

Component	only boat			ASAP			Risk-based		
	corr.	prev. (reg.)	prev. (CM)	corr.	prev. (reg.)	prev. (CM)	corr.	prev. (reg.)	prev. (CM)
<b>Rotor system</b>	0.128	0.190	0.246	0.091	0.145	0.197	0.096	0.150	0.191
<b>Blade adjustment</b>	0.098	0.112	0.134	0.068	0.080	0.092	0.069	0.087	0.106
<b>Gearbox</b>	0.125	0.159	0.205	0.080	0.123	0.147	0.085	0.118	0.147
<b>Generator</b>	0.102	0.105	0.103	0.071	0.080	0.075	0.072	0.081	0.080
<b>Generator lead</b>	0.118	0.122	0.108	0.090	0.082	0.094	0.116	0.110	0.104
<b>HSS</b>	0.400	0.044	0.171	0.269	0.033	0.170	0.282	0.040	0.161
<b>LSS</b>	0.504	0.057	0.211	0.358	0.031	0.211	0.361	0.033	0.213
<b>Yaw system</b>	0.120	0.170	0.192	0.085	0.122	0.134	0.085	0.121	0.140
<b>Control system</b>	0.105	0.104	0.098	0.076	0.074	0.075	0.076	0.076	0.081
<b>Transformer</b>	0.533	0.526	0.538	0.475	0.490	0.436	0.450	0.369	0.388

## 5.2 Casted Components

Casted components in this case study are the hub (without blades) as well as the main shafts (low and high speed shaft). Other casted elements like machine frames and housings are not considered here since failure rates are missing, and it is expected that these failure rates are negligible with the actual failure rate of the machine itself. The failure rate summed up over the considered casted components lead to 0.38 failures per year and is small compared with the overall failure rate of 7.5 per wind turbine and per year (see Figure 5.2).

According to [3], 28% of the failure rates of blades and hubs occur at the casted hub. Figure 5.4 shows the total expected maintenance expenses over a lifetime of 20 years for casted components mounted at the reference wind farm. The largest maintenance expenses for casted components occur when considering corrective maintenance with only use of boats to access the device. The largest maintenance expenses occur due to failure in the hub. For casted components, the lowest maintenance expenses are reached when doing regular inspections (here twice a year), whereas the condition monitoring system leads to slightly larger maintenance expenses.

Table 5.3 shows the relative expenses of casted components related with the total expected maintenance costs for

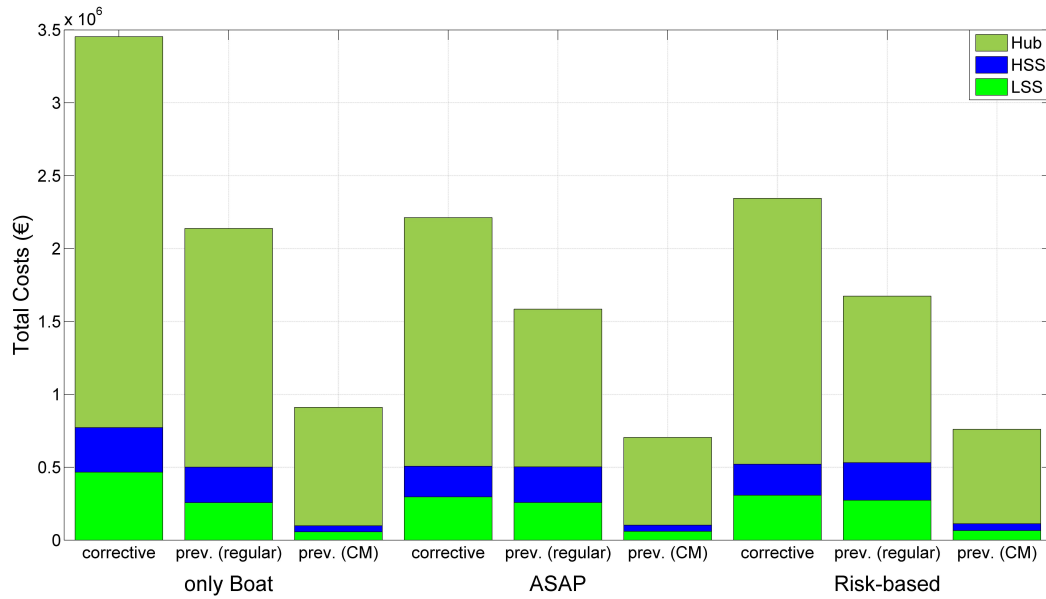


Figure 5.4: Impact of total expected maintenance expenses for casted components installed at the reference wind turbine farm for different maintenance and transportation strategies. CM: condition monitoring; regular: regular inspections every year.

different transportation and maintenance approaches. The maintenance costs related with casted components is, in general, small compared with the total expected maintenance costs during a lifetime of 20 years. Therefore, the potential of optimizing the maintenance expenses is limited (with respect to the absolute amount of money). The expenses can be reduced from roughly 5% when following a corrective maintenance strategy to roughly 2% when using a preventive maintenance strategy with a condition monitoring system. The costs of a condition monitoring system are not considered here. When using a condition monitoring system, the costs of the monitoring system as well as its operating costs need to be compared with the Value of Information (VoI) gained using the installed condition monitoring system. Furthermore, the gained VoI shows how much one can invest in a condition monitoring system.

Table 5.3: Ratio of the maintenance expenses related to casted components to the total expected maintenance costs for a given transportation and maintenance strategy. corr.: corrective; prev.: preventive; reg.: regular; CM: condition monitoring

only boat			ASAP			Risk-based		
corr.	prev. (reg.)	prev. (CM)	corr.	prev. (reg.)	prev. (CM)	corr.	prev. (reg.)	prev. (CM)
0.051	0.039	0.020	0.047	0.040	0.020	0.051	0.043	0.022

### 5.3 Sensitivity on Inspection Quality

The inspection quality is reflected by the size of the minimal detectable damage size  $\lambda$  which can be detected and is considered in the definition of the  $PoD$  curve (see Equation 3.8). By default this value is set equal to 0.4. This section will investigate the impact of this value on the expected maintenance expenses for casted components. The costs for performing an inspection are kept constant when adapting the inspection quality. But it is expected that the inspection costs for smaller  $\lambda$  values increase. These increased inspection costs should be compared with the gained VoI enabling to decrease the overall maintenance costs. Better inspection quality only makes sense when the overall maintenance costs can be decreased.

Figure 5.5 shows the expected total maintenance costs for the different considered components dependent on the expected minimal detectable damage size  $\lambda$ . A risk-based maintenance approach is considered where either inspections every 0.5 years or based on the alarm of a condition monitoring system are performed. It can be seen that when decreasing the inspection quality by increasing the  $\lambda$  value, the expected maintenance costs are increasing for the mechanical components like the rotor system, the yaw system or the blade adjustment. The total maintenance costs for electrical components and software are not affected by the inspection quality as these parts cannot be inspected.

Figure 5.6 shows the total maintenance expenses for casted components mounted at the wind turbines of the

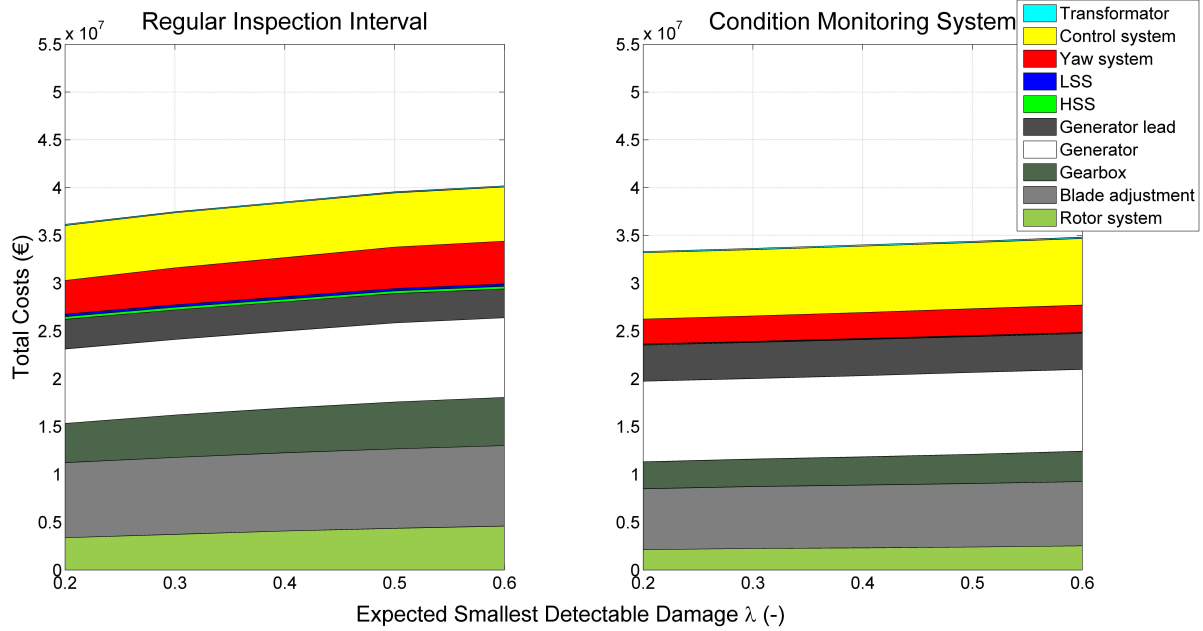


Figure 5.5: Impact on expected maintenance costs for the different wind turbine components dependent on the inspection quality during the whole lifetime of 20 years. A risk-based maintenance strategy is considered here and the regular inspection interval is set equal to 0.5 years.

reference wind turbine farm. The maintenance costs for the two different shafts (HSS and LSS) are independent on the inspection quality whereas the maintenance costs for the hub is increasing when decreasing the inspections quality.

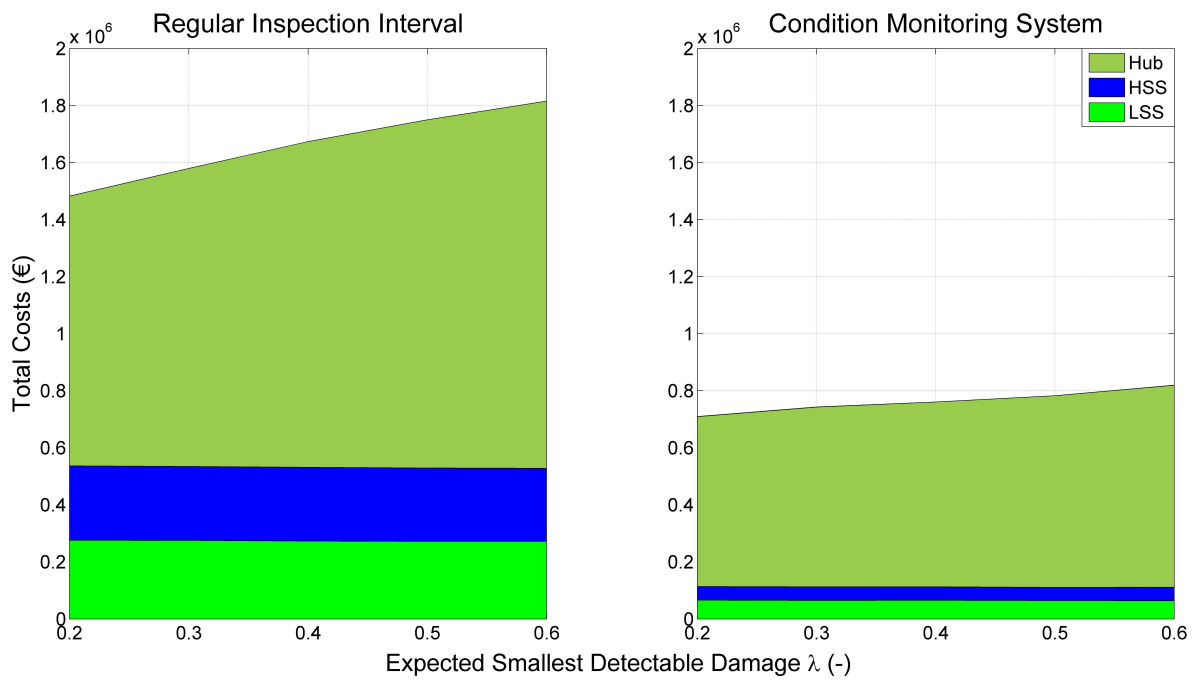


Figure 5.6: Impact on expected maintenance costs for the casted wind turbine components dependent on the inspection quality during the whole lifetime of 20 years. A risk-based maintenance strategy is considered here and the regular inspection interval is set equal to 0.5 years. HSS. High speed shaft; LSS: low speed shaft.

## Chapter 6

# Conclusions

This report focuses on maintenance cost estimations for casted components installed in offshore wind turbines. The high speed shaft (HSS) and the low speed shaft (LSS) as well as the hub are considered as casted components in this report. There are further casted components in a wind turbine like the machine base plates or machine housings. However, no specific failure rates are available for these sub-components and, therefore, they are assumed negligible when comparing to the actual failure rate of the components installed at a wind turbine.

The impact of corrective and preventive maintenance strategies as well as transportation by boat and by helicopter are investigated. The maintenance costs are estimated from Crude Monte Carlo simulations using a reference wind turbine farm consisting of ten 6 MW wind turbines placed 30 km off the Danish North Sea coast. Furthermore, this tool considers failure of mechanical and electrical components as well as software failures.

Dominating components with respect to maintenance costs are the pitch system, the generator, the gearbox and the generator lead. The overall failure costs of casted components cover a small amount of the total expected maintenance costs. The overall maintenance expenses for casted components are in the range of 5% for a corrective maintenance strategy and can be reduced to roughly 2% when following a preventive maintenance strategy with a condition monitoring system. The maintenance costs for the hub dominates the overall maintenance costs for casted components. The maintenance costs for HSS and LSS are small because of their small failure rate. The maintenance costs for LSS and HSS are bound to large uncertainties where their coefficient of variation can reach values up to 0.5 due to their small failure rates.

A sensitivity study on the inspection quality showed that the total expected maintenance expenses for HSS and LSS remain independent on the inspection quality whereas the expected maintenance expenses for the casted hub are expected to raise when the inspection quality drops.

It can be concluded from the case study in this report that there is a high saving potential from the relative perspective like e.g. more than 50% saving potential between corrective and preventive maintenance strategies for casted components when finding the optimal maintenance and transportation strategy. But the overall maintenance expenses for casted elements in a wind turbine are small compared with the overall maintenance expenses (less than 5%).





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# On Different Maintenance Strategies for Casted Components of Offshore Wind Turbines

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