Different Transportation and Maintenance Strategies for Offshore Wind Farms

Ambühl, Simon; Sørensen, John Dalsgaard

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Ambühl, S., & Sørensen, J. D. (2017). *Different Transportation and Maintenance Strategies for Offshore Wind Farms*. Department of Civil Engineering, Aalborg University. DCE Technical reports No. 227

DEPARTMENT OF CIVIL ENGINEERING
AALBORG UNIVERSITY

Different Transportation and Maintenance Strategies for Offshore Wind Farms

Simon Ambühl
John Dalsgaard Sørensen

ISSN 1901-726X
DCE Technical Report No. 227

Aalborg University
Department of Civil Engineering
Division of Reliability, Dynamics and Marine Engineering

DCE Technical Report No. 227

Different Transportation and Maintenance Strategies for Offshore Wind Farms

by

Simon Ambühl
John Dalsgaard Sørensen

April 2017

Scientific Publications at the Department of Civil Engineering

Technical Reports are published for timely dissemination of research results and scientific work carried out at the Department of Civil Engineering (DCE) at Aalborg University. This medium allows publication of more detailed explanations and results than typically allowed in scientific journals.

Technical Memoranda are produced to enable the preliminary dissemination of scientific work by the personnel of the DCE where such release is deemed to be appropriate. Documents of this kind may be incomplete or temporary versions of papers—or part of continuing work. This should be kept in mind when references are given to publications of this kind.

Contract Reports are produced to report scientific work carried out under contract. Publications of this kind contain confidential matter and are reserved for the sponsors and the DCE. Therefore, Contract Reports are generally not available for public circulation.

Lecture Notes contain material produced by the lecturers at the DCE for educational purposes. This may be scientific notes, lecture books, example problems or manuals for laboratory work, or computer programs developed at the DCE.

Theses are monograms or collections of papers published to report the scientific work carried out at the DCE to obtain a degree as either PhD or Doctor of Technology. The thesis is publicly available after the defence of the degree.

Latest News is published to enable rapid communication of information about scientific work carried out at the DCE. This includes the status of research projects, developments in the laboratories, information about collaborative work and recent research results.

Published 2017 by
Aalborg University
Department of Civil Engineering
Thomas Manns Vej 23
DK-9220 Aalborg Ø, Denmark

Printed in Aalborg at Aalborg University

ISSN 1901-726X
DCE Technical Report No. 227

Abstract

Inspections as well as transportation of personnel and repair parts are a significant contributor to the levelized cost of energy for offshore wind turbines. There are different operation and maintenance (O&M) strategies for offshore wind turbines. Maintenance can be performed preventively by replacing the component before it breaks down or correctively by replacing it after it failed. A boat or helicopter can be used for transporting personnel and equipment from shore to the wind turbine. This article compares, among others, a risk-based inspection and maintenance approach for an offshore wind turbine farm with other O&M approaches where only boats are used to access the offshore wind turbines or where the downtime of the devices are minimized. This article presents a dynamic approach for total operation and maintenance cost estimations of offshore wind turbine farms including real weather data together with condition modeling of different main components of an offshore wind turbine. In this approach, mechanical failures, electrical failures as well as software failures are considered. Additionally, uncertainties related with costs, structural damage accumulation, failure rates as well as different maintenance strategies are considered. The report contains a case study where the presented approach is applied to a wind turbine farm and a sensitivity study of the different parameters like the operational range of the boat/helicopter, the electricity price, real rate of interest, inspection quality and inspection intervals as well as the efficiency and sensitivity of the condition monitoring system are evaluated focusing on the overall maintenance costs during a lifetime of 20 years and the number of expected repairs/replacements during the lifetime as well as the impact on the cost of energy using different maintenance and transportation strategies.

Acknowledgements

The authors wish to thank the financial support from the Danish Council for Strategic Research (Grant no. 10-093966, REWIND - Knowledge based engineering for improved reliability of critical wind turbine components) which made this work possible.

1 Introduction

The yearly amount of global electricity need is expected to increase from 19,000 TWh in 2012 [1] to 47,000 TWh in 2050 [2] as living standards increase. Furthermore, the trend towards renewable electricity sources is expected to continue in the future in order to reduce pollution. In 2050 it is expected that 60% [2] of the total electricity production will come from renewable electricity sources. A key player in renewable electricity sources is the wind. Wind turbines can be placed onshore as well as offshore. Taking economics and water depths up to 40 meters into account the potential of offshore wind is expected to be in the range of 7000 TWh a year whereas onshore wind has an expected annual potential of 750 TWh [3]. The drawback of electricity from offshore wind turbines is their cost of energy. One reason for these high costs of electricity from offshore is the large operation and maintenance (O&M) expenses, which are typically in the range of 25% [4] of the levelized cost of energy.

The large electricity production costs result from limited accessibility leading to large amount of lost electricity production [5]. There are different O&M models for offshore wind turbine farms available as shown in [6]. These models help to find the optimal maintenance strategy. Common O&M models for offshore wind turbines often model the failure frequency and its occurrence using so-called failure rates as done e.g. in [7], [8], [9] and [10]. Failures of structural components like blades or the main shaft can be modelled by a more advanced approach where crack evolution is directly modeled based on the exposed loads. This approach is e.g. considered in studies performed in [11] and [12] as well as enables to include inspection modeling and the behavior of condition monitoring systems.

There are different maintenance strategies for offshore wind turbines. Maintenance of components can be performed after failure (corrective) or before a breakdown (preventive) occurs. Maintenance actions as well as O&M costs for offshore wind turbines strongly depend on the weather conditions which define the accessibility of the device [13]. Boats and helicopters can be used for crew and their equipment transportation. Helicopters are faster but also more expensive and limited by the wind speed. Boats are slower but also cheaper and mainly limited by the wave height. The optimal maintenance strategy, which minimizes the resulting O&M costs, can be found using a risk-based approach. The theoretical background about risk-based operation and maintenance strategies for offshore wind turbines is given in [13]. Reference [11] applied a risk-based O&M approach for one offshore wind turbine. The next step, as presented in this report, is to apply the risk-based approach for finding the optimal O&M strategy for a wind turbine farm.

By the use of real weather data and failure rate data of the main components of a wind turbine, a methodology for operation and maintenance cost estimations can be developed, as done for a single wind turbine in [11], where weather data as well as failures of different components are directly included and modeled. This article presents a methodology for simulating maintenance operations at offshore wind turbine farms with incorporated weather data and failure formation of the different components. The simulation tool simulates the whole lifetime and enables implementation of specific failure characteristics of mechanical as well as electrical components and software failures. Furthermore, stochastic models for environmental conditions, fatigue modeling, inspection quality, the condition monitoring system and the needed time for repair are implemented. This technical report estimates, based on a case study, the possibility to decrease the O&M expenses of a wind turbine farm by following different maintenance strategies and the use of different vehicles for transportation. Furthermore, a sensitivity study of different parameters used as input for the estimation of the total expected maintenance costs over a lifetime of 20 years is performed.

2 Maintenance Strategies for Offshore Wind Turbine Farms

There are multiple strategies to maintain a system. Figure 1 gives an overview about the different possible maintenance strategies. Corrective maintenance is performed when a component has failed, and preventive maintenance is performed with a certain time interval or based on a certain condition (critical level of directly or indirectly observed damage). Corrective component replacements lead to irregular maintenance actions whereas preventive replacement tries to limit the downtime of the system but which may, on the other hand, increase the number of performed maintenances/repairs. Scheduled maintenance is based on a certain expected lifetime and could include e.g. lubrication, changing filters, check cooling systems or tightening bolts. Conditioned maintenance includes monitoring of damage (e.g. corrosion or wear-out) by the use of a condition monitoring system.

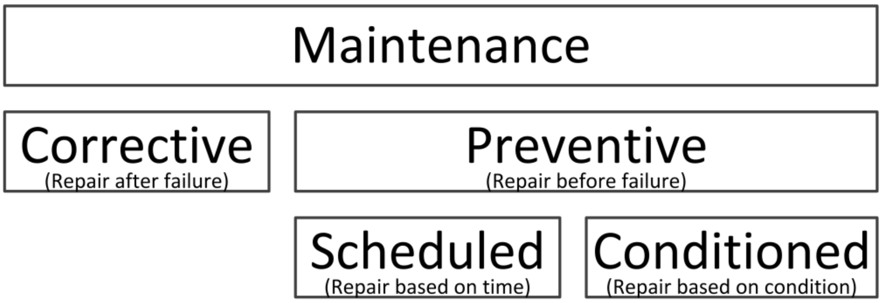

Figure 1 Different maintenance strategies. [14]

A condition monitoring system could be used to detect the health condition of the component as well as to define conditional maintenance and find the events leading up to a fault due to its buffer history capability [15]. When following a preventive maintenance strategy, the wind turbine might still be able to produce electricity between the detection of the damage and the repair, which is not the case when following a corrective maintenance strategy and a failure occurs. The corrective maintenance strategy is the simplest maintenance strategy, but it has large uncertainties in costs as so-called cascade effects may occur where a certain (minor) failure may consequently affect a main component, which is expensive to replace. Furthermore, failure of components should be expected during storm conditions with very limited accessibility and long waiting times where the wind turbine cannot produce electricity.

When a component breaks, costs occur due to replacement or repair of the failed component but also due to the loss of electricity production between the failure occurrence and finishing the repair/replacement of the broken component.

2.1 Transportation Strategies

Additional to the different maintenance strategies there are also different transportation strategies. One can take a boat or a helicopter to access offshore structures. The best transportation strategy is the one leading to lowest overall costs. Based on access possibilities by boat or by helicopter, the following three transportation strategies shown in Figure 2 as a flow chart can be used:

- Only use of boat
- Repair/replacement as soon as possible (ASAP)
- Risk-based approach considering weather forecast

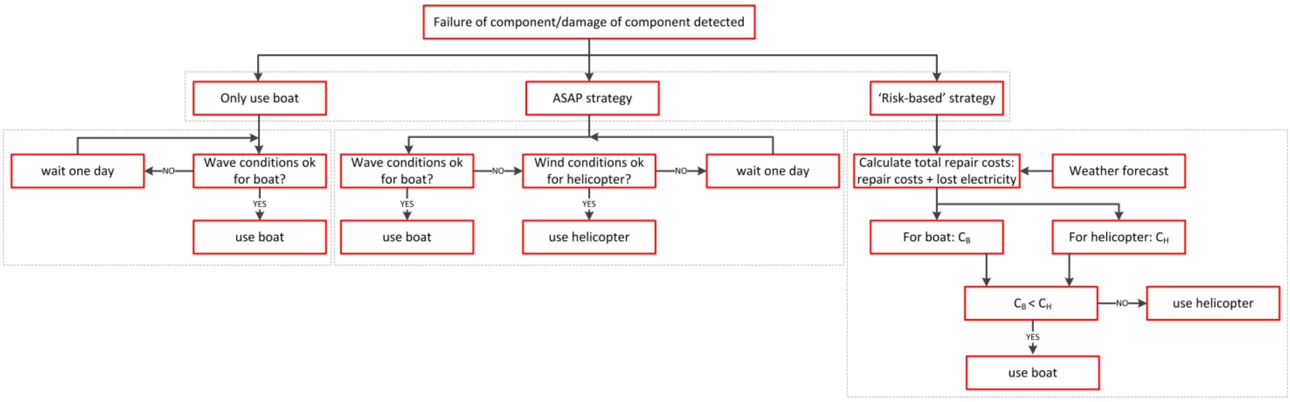

Figure 2 Different transportation strategies when performing maintenance actions offshore.

In some cases only the use of boats is possible as helicopters might not be available or the operator of the wind farm owns the maintenance boats and as such prefers to use the boats. The so-called ASAP strategy targets minimization of the wind turbine downtime. The risk-based approach takes the weather forecast for the expected repair time and the transportation strategy (including effects due to waiting time) in order to find the strategy which minimizes the overall expected costs for the specific replacement.

The operational costs for the boat and the helicopter depend, among others, on the distance from shore, the possible transfer time (transfer speed), the fuel prices as well as the conditions of the contract when the boat or helicopter is chartered from subcontractors. Boats are often chartered on a daily basis whereas the helicopter cost depends on the operational hours (operational hours in flight).

2.2 Optimal Planning of Inspection and Maintenance

Optimal planning of inspections and maintenance actions can be based on applying risk-based methods where experience and information from the past (e.g. from inspections or monitoring results) are taken into account. The theoretical background of using risk-based planning of inspections and maintenance action for offshore wind turbines can be found in [13].

Figure 3 shows a typical decision tree for optimal planning. Risk-based inspection and maintenance planning depends on the initial design decisions, ***z***, of the device. The initial design may include e.g. the design lifetime of the different components as well as their costs. The inspection/monitoring plan depends on the decision parameters, ***e***, which may change during the lifetime of the device due to increased knowledge (Bayesian updating) and decreased cost uncertainties. The future decision parameters depend on the inspection/monitoring results ***S***. Based on the inspection/monitoring results, a maintenance/repair plan, ***d*****(*S*)**, is developed. The decision rule for future repair decisions has to be chosen at the time where the O&M strategy is determined. Together with the realization of uncertain parameters, ***X***, a certain total gain minus costs, **W**, is calculated. Realizations of uncertain parameters include e.g. wind and wave climate as well as model uncertainties.

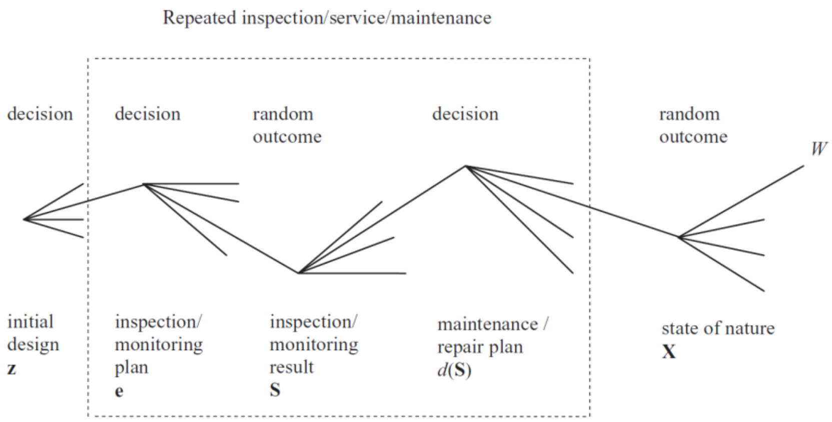

Figure 3: Decision tree for optimal planning of inspections and maintenance. [13]

The application of risk-based decision models for maintenance considerations requires that the condition of the different considered components can be described e.g. with damage models where the uncertain parameters ***X*** are included. When focusing on a wind turbine farm, the maintenance strategy should be optimized by considering the whole farm and not just a single device.

The decision rule for future repair operations as well as the time horizon to be used for risk-based approaches might change over the lifetime of the device. When the remaining expected lifetime of the device is close to zero, maintenance actions might be stopped and a higher risk of failure prior to reaching the end of the lifetime of the wind turbine might be acceptable. Furthermore, the time of the season might drive the decision rule for repairs when following a risk-based approach. During winter the wind turbine might not be accessible for a couple of weeks as the waves and the wind speed are too high. Another factor is the amount of information available – postponing a repair increases the repair costs due to lost electricity production but makes it possible to gain information about the failure itself and more assistance to make the right decision is possible.

The O&M strategy to be favored is the one maximizing the total income from selling electricity minus the total costs due to initial investments, inspections, repair and decommissioning. The value *W*, which should be maximized, is calculated based on:

$$\max_{z,e,d} W = B - C_I(z) - C_{IN}(e,d) - C_{REP}(e,d) - C_F(e,d) - C_D(z) \quad (1)$$

where *B* is the expected income, C_I the initial investment costs, C_{IN} the expected service and inspection costs (e.g. man-hours or special tools), C_{REP} the repair and maintenance costs, C_F the expected failure costs and C_D the costs for decommissioning. The different costs are, among others, driven by the design parameter *z*, the inspection parameter *e* and the decision rule *d*.

When a wind turbine farm is considered Equation (1) should be maximized for the overall wind turbine farm and not for a single wind turbine as some costs can be shared among different wind turbines.

The discounted present values, C_0, are always important in cost considerations:

$$C_0 = \frac{C}{(1+r)^T} \tag{2}$$

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

2.3 Failure costs

It is assumed that electrical and mechanical failures need interaction of technicians on site whereas software problems can be solved offline (e.g. by restarting the control system). The total cost for corrective repair C_{CM} of n broken components within the wind farm can be calculated as:

$$C_{CM} = \mathbf{max}(d_i) \cdot C_T + \sum_{i=1}^{n} d_i \cdot C_{W,i} + C_{E,i} + \sum_{j=1}^{m} \sum_{t=1}^{d_i+d_w} C_{L,j,t} \tag{3}$$

where d_i is the number of days needed to do the corrective repair of broken component i, C_T is the transportation cost to the wind turbine farm per day. The cost $C_{W,I}$ represents the daily working hour costs and $C_{E,I}$ represents the repair/replacement costs for the broken component. The cost of lost electricity production of wind turbine j at the tth day is represented by the variable $C_{L,j,t}$. Corrective replacements also include the waiting time d_w, which accounts for the time while the environmental conditions do not enable access to the broken wind turbine. The parameter m accounts for the number of broken wind turbines within the wind turbine farm. In case several wind turbines are out of order, transportation costs can be shared.

When following preventive maintenance strategies, the resulting costs of one inspection of n wind turbines with m mechanical components to be inspected including h repairs of broken components can be calculated as:

$$C_{PM} = C_T + \sum_{i=1}^{n} \sum_{j=1}^{m} C_{I,i,j} + \sum_{i=1}^{n} \sum_{l=1}^{h} C_{E,i,l} + \sum_{i=1}^{n} C_{L,i} \tag{4}$$

where C_T is the transportation cost of the technician crews from shore to the wind turbines offshore, and $C_{I,i,j}$ is the inspection cost for inspecting component j on wind turbine i, and $C_{L,i}$ indicates the lost electricity production while an inspection and repair is performed. It can be assumed that when following a preventive maintenance strategy with specific inspection intervals, the inspections of all wind turbines can be done within one day as several crews use the same vessel to access different wind turbines and, therefore, the transportation costs can be shared.

When following a preventive maintenance strategy with a condition monitoring system, the variable m indicates the number of components of a certain wind turbine i that gave an alarm and h shows the number of components where a failure is detected and which needs to be repaired. When following a preventive maintenance strategy, corrective replacements might still occur. But the amount of corrective replacements when following a preventive maintenance strategy is expected to be lower than when only performing corrective replacements.

3 Different Failure Types

In a wind turbine different kinds of components can fail and it can be distinguished between the following failure cases:

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

Due to time-dependent deterioration of the component, failure of mechanical components, like the blades, the shaft or gearbox lead to structural failure after a certain amount of time. In order to repair a mechanical failure, access to the device is necessary in order to perform an inspection where structural failure in the near future is possible to be detected as deterioration e.g. based on crack evolution. Electrical failures (e.g. burning of a fuse) are typically not possible to model with a damage model, because they occur randomly and cannot be predicted. But also for repairing electrical failures, access to the device is necessary. On the other hand for software failures a manual restart or improved (updated) software often solves the problem. The following will present the theoretical background of the different failure cases as well as how these failure rates can be modeled.

3.1 Damage Model – Mechanical Failures

Mechanical failures often occur due to time-dependent damage of a structural component. These mechanical failures can be modeled with a damage model enabling estimation of the component condition at a certain time in space. Furthermore, these models enable modeling of the influences from inspections (e.g. reparation of detected crack). The damage model presented here is adapted from [11], [16] and [17]. Other damage accumulation models can be applied equivalently. The damage size can be measured in a relative scale using 0 for no damage and 1 for failure of the component. When the damage size reaches 1, the component needs to be replaced/repaired.

For modeling inspections, the damage needs to be measureable. The general damage accumulation for components is assumed to be described by an initial value problem with the following differential equation:

$$\frac{dD}{dt} = C \cdot F^{m_1} \cdot D^{m_2} \quad (5)$$

where dD/dt is the rate of damage growth, F a measure for the load, and D is the damage size. The parameters C, m_1 and m_2 are model parameters and can be estimated from available component failure rates. This damage accumulation model uses an exponential damage model, which can be used e.g. for fatigue driven damages where the differential equation is based on Paris Law, [18]. The damage accumulation rate dD/dt is given as:

$$\frac{dD}{dt} = \frac{dN}{dt} \cdot C \cdot \Delta K^{m} \quad (6)$$

where C is the damage coefficient, m the damage exponent, and ΔK the change in damage intensity factor which depends, among others, on the current damage D:

$$\Delta K = \beta \cdot \Delta s \cdot \sqrt{\pi D} \tag{7}$$

where β is a geometry factor and Δs the cyclic damage range. For offshore wind turbines, it can be assumed that the damage of the different components is wind and wave load driven. Therefore, the cyclic damage range is assumed to be proportional to the mean significant wave height H_S:

$$\Delta s = H_S \cdot x_S \tag{8}$$

where x_S is the proportionality factor which also models the uncertainty about estimation of Δs. The wind speed (turbulence) could also be the basis for the deterioration model, but this is indirectly taken into account as the significant wave height and the wind speed are correlated. Here, it is assumed that the mean zero-crossing wave period, T_Z, drives the number of cycles:

$$\frac{dN}{dt} = \frac{3600}{T_Z} \tag{9}$$

Modeling the cycle rate dependent on the mean zero-crossing wave period gives the load cycles a stochastic property. When assuming a mean zero-crossing wave period between 5 and 10 seconds, the expected annual number of load cycles is between 6.3e6 and 3.2e6, which is in accordance with the common assumption of 5e6 rotations per year for wind turbine components having on average 9.5 rpm [19].

The damage, D, is calculated and summed up over time with small enough time-steps by (Euler Method):

$$D_{t+\Delta t} = D_t + \frac{dD}{dt} \cdot \Delta t \tag{10}$$

The damage level after repair will depend, among others, on the used repair method. For simplicity, it can be assumed that after a repair the component works independently on its working history before failure occurred and is treated as new.

When inspections are performed, there is the risk that the damage is not detected. The probability that damages of a certain size will be detected depends, among others, on the technique used to detect the damage (see e.g. [20]) as well as on the size of the damage. It is obvious that larger damages are easier to detect and as such have a greater probability of detection. The uncertainty whether damages (cracks) are detected is often modeled using a probability of detection (PoD) curve. One possibility of defining such a curve is by using a one-dimensional exponential threshold model, see e.g. [20]:

$$PoD(D) = P_0 \left(1 - \exp\left(-\frac{D}{\lambda} \right) \right) \tag{11}$$

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

A replacement decision criterion (when detecting damages during inspections) could be that replacement will take place when a detected damage, D_{ins}, is larger than a certain threshold D_{rep}. In case all detected damages are repaired, D_{rep} is set equal to 0. The repair decision is equal to:

$$D_{ins} \geq D_{rep} \tag{12}$$

where D_{ins} is the detected damage, which is equal to the actual damage D if the damage is detected.
The results from an inspection can be used for future inspection planning based on a Bayesian approach, as explained e.g. in [21] for risk-based inspection planning for offshore wind turbines. Also, information from preventive or corrective maintenance as well as monitoring results can be used for inspection planning. Uncertainty about measurements of the crack size (damage) itself can be formulated by a normal distributed [22] variable ε_m. The resulting damage from an inspection (D_{ins}) can be estimated in the following way:

$$D_{ins} = D + \varepsilon_m \tag{13}$$

The measurement uncertainty needs to be estimated based on measurements and depends on the considered inspection technology and the ability of the technician doing the inspection. The smallest detectable crack, λ, can be assumed to be a stochastic variable in order to account for human factors and might also include measurement errors.
A condition monitoring system can be modeled in order to estimate the condition of the different mechanical components. Whenever the damage D of a mechanical component passes a certain alarm threshold D_{alarm}, the condition monitoring system gives an alarm which sends a technician group to the wind turbine to inspect the component causing the alarm. Additionally, in order to represent the fact that not all failures can be indicated by the condition monitoring system, a so called condition monitoring efficiency factor η_{CM} can be considered. This efficiency factor defines the amount of damages crossing D_{alarm} that are detected by the condition monitoring system. According to [23] this efficiency factor needs to be in the range of 60% to 80% in order to be cost-effective.
When implementing a preventive maintenance strategy with regular inspection intervals, the time between two inspections, ΔT, can be fixed over the whole lifetime or might be adapted during the lifetime as knowledge is gained by the previously performed inspections.

3.2 Failure Rates - Electrical/Software Failures

Possible electrical or software failures cannot (or seldom) be detected by inspections as these failures occur suddenly without any indication. Failure rates can be estimated based on a database containing the points in time of failure as well as their causes. For (offshore) wind turbines, the following databases can be taken as a starting point for estimating the failure rates of components installed in wind turbines. As a starting point, the following failure databases from wind turbine projects can be taken: [24], [25], [26], and [27]. But also failure rates from the petrochemical industry (see e.g. [28]) or generic reliability databases (see e.g. [29] and [30]) can be used to estimate failure rates of different electrical components installed in wind turbines.
The failure rate behavior over the lifetime is based on the bathtub curve, shown in Figure 4. The bathtub curve shows the change in failure rates during the lifetime of a component. The failure rate behavior can be divided into three phases and be modeled e.g. with a Weibull distribution using different distribution parameters for the three phases. In phase I, the failure rate decreases due to the presence of early life failures like quality problems (manufacture failure) or wrong dimensioning (dimension failure). Once the

component is burnt-in, phase II will only have operation failures like handling failures, maintenance failures, physical random failures and failure due to disturbances. In phase II, the failure rate is assumed to be constant over time and can be calculated as:

$$\lambda_{PhaseII} = \frac{1}{MTBF} = \frac{\left(\frac{\text{Total number of failures}}{\text{Component population}}\right)}{\text{Operating period (years)}} \quad (14)$$

where $MTBF$ is the so-called Mean Time Between Failures that indicates the mean time between two subsequent failures. After a certain time, the failure rate increases due to wearing problems and moves to phase III.

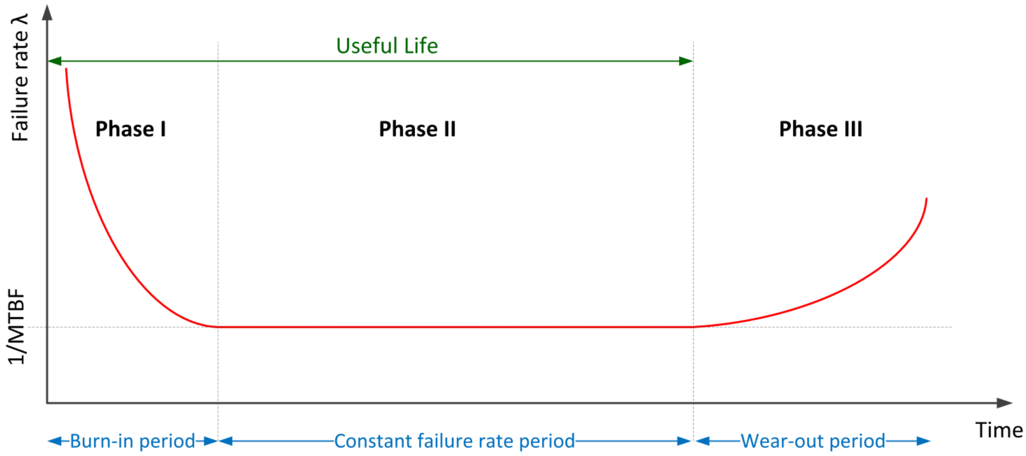

Figure 4: Bathtub curve of a component showing the failure rate over time. MTBF: Mean time between failure.

Ideally, the lifetime of the considered component ends at the transition point between phases II and III. When building up failure rate databases, one assumes that the failure occurs in phase II. The high failure rate phases I and III can be prevented by checking the component (quality control) and operating them under realistic conditions (pre-aging) before selling it to the customer (phase I) or by preventive replacement (preventive maintenance in phase III) as well as condition monitoring which leads to conditional maintenance actions in phase III.
Failure rates also exist for mechanical components and can be used to calibrate the damage model described in Section 3.1.

4 Considered Wind Turbine Farm – Case Study

This study considers a wind turbine farm consisting of 10 6 MW offshore wind turbines, which has been considered already in other studies, see [16], [31]. Figure 5 shows a sketch about the arrangement of the wind turbines and transformer station within the wind turbine farm. The wind turbine farm is assumed to be placed 30 km off the Danish coast. The expected lifetime of this wind turbine park is assumed to be 20 years. Furthermore, the basis for the helicopter being in the harbor is that the distance for the helicopter and the vessel to reach the wind park is the same.

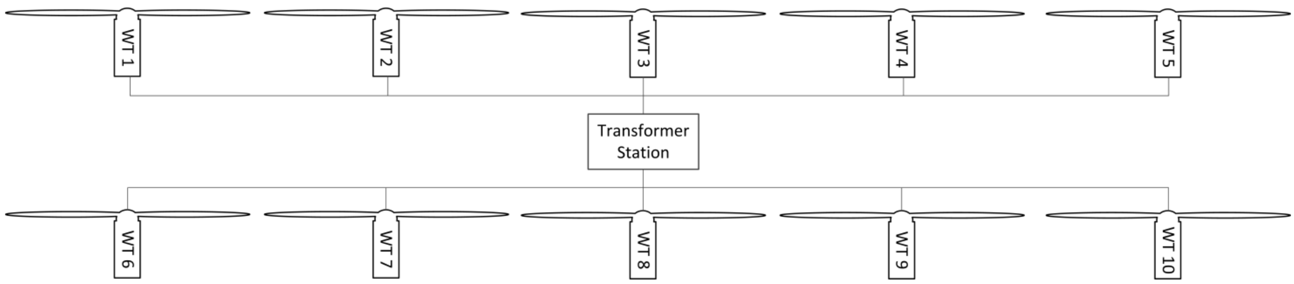

Figure 5: Wind turbine farm layout (not drawn to scale). WT: Wind Turbine.

Failures of large structural parts like the tower or the foundation, which need a large transportation vessel and jack-up or crane vessel and possibly lead to total collapse of the wind turbine are not considered here. The focus in this example is on failure of system components like e.g. the generator due to minor/medium structural damages or electrical shortcuts.

The electricity feed-in tariff for this example is chosen as 0.08 €/KWh, which is a typical value for fixed feed-in tariffs for European offshore wind turbine parks [32] and is kept constant over the whole lifetime of the wind turbine farm. The following three different maintenance strategies are considered in this case study:

- Only corrective maintenance actions.
- Preventive (and corrective) maintenance actions with fixed regular inspection interval.
- Preventive (and corrective) maintenance actions based on indications from a condition monitoring system.

The purpose of this report is to show the maintenance cost saving potential of different O&M technologies which can be applied to offshore wind turbines based on a generic example. For each condition, 500 lifetimes are simulated, and the following figures show the expected values. Figure 6 shows a flow chart for preventive maintenance illustrating how the methodology is implemented and simulations are performed.

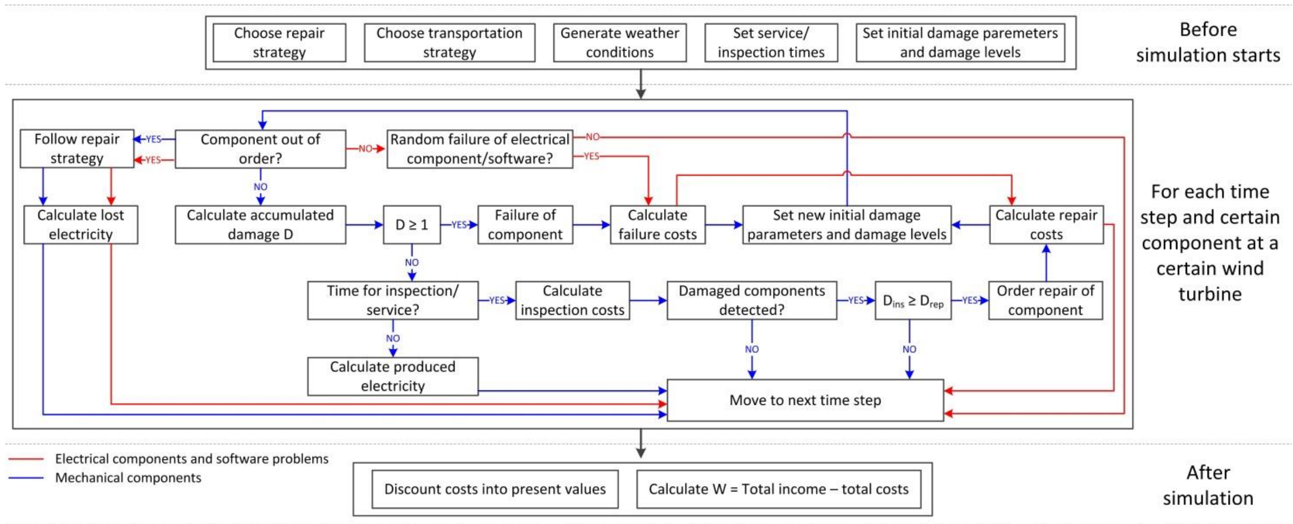

Figure 6: Flow chart for O&M simulation following a preventive (with scheduled inspection intervals) maintenance strategy.

4.1 Wind Turbine Specifications

The considered turbine in this study is a 6 MW wind turbine, which is partly based on the Senvion 6 MW wind turbine. The power curve is shown in Figure 7, and the key parameters are given in Table 1. The reference wind turbine has an internal lift with a capacity of 2 tons.

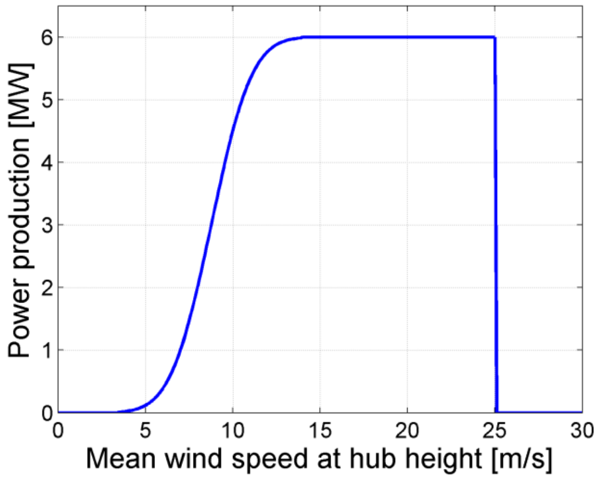

Figure 7 Power curve of considered 6 MW reference offshore wind turbine. [16]

Table 1: Properties of the 6 MW reference offshore wind turbine considered in [16] and [31].

Nominal Power	6 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Rotor Diameter	126 m
Cut-in, rated, cut-out wind speed	4 m/s, 14 m/s, 25 m/s
Hub Height	90 m
Power control	Electrical pitch
Gear system (gear ratio)	Three stage planetary gearbox (97)

The reference wind turbine is simplified with the number of components considered for the maintenance strategy analysis. Figure 8 shows the considered components of the maintenance study of the 6 MW reference wind turbine. The impact of wakes from other wind turbines within the wind turbine farm is not considered in this study. Therefore, each wind turbine has the same power curve as shown in Figure 7 and operates under free flow conditions.

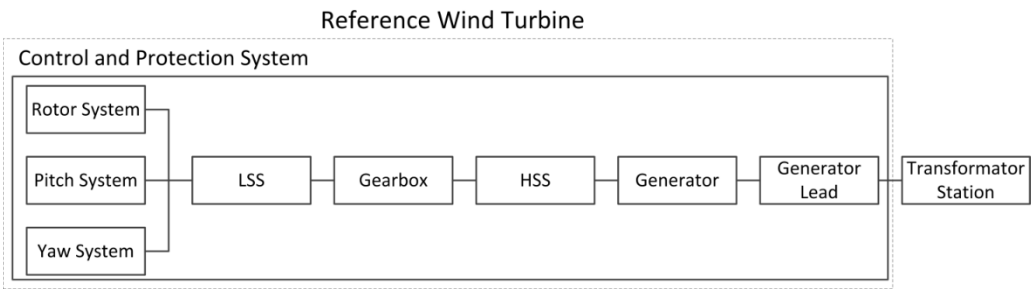

Figure 8: Considered components of the 6 MW reference wind turbine for maintenance study. HSS: High Speed Shaft; LSS: Low Speed Shaft. [16]

4.2 Considered Failure Rates

Recent studies on failure rates of offshore wind turbines (see e.g. [33], [34], [35]) show that the annual failure rate is in the range of 9 failures per year and turbine. Due to the fact that the wind turbine considered in this study is simplified and not all different components are considered, the estimated failure rates are adapted in order to reach 9 failures per year and turbine (see Table 2). Table 2 shows the estimated mean failure rates for the different considered components of the 6 MW offshore wind turbine. These failure rates of the different components are, where necessary, divided into mechanical and electrical/software failure rates. Mechanical components like the rotor system (blades and hub), shafts (low and high speed shafts) or the gearbox, which do not contain a control system in itself are assumed to only have mechanical failures whereas other components of the wind turbine used to generate (generator lead) and transfer electricity (transformer station) are assumed to have electrical failure modes. The control and protection system, which includes the condition monitoring system and common sensors, is assumed to have electrical failures (e.g. blowing of a fuse of the condition monitoring system or failure of control sensors) as well as software failures (e.g. software breakdown of control system). The dominating failure mode for the yaw system is fatigue failure as according to [36] the most critical parts are the yaw gear, the caliper and the sliding pads. Therefore, only mechanical failures are considered for this component. The generator has rotating mechanical subcomponents, which are exposed to fatigue failures as well as a control system and electrical parts leading to sudden failures of the software and the electrical subcomponents. Therefore, this component is assumed to contain mechanical as well as electrical and software failures. There is no detailed failure rate database available distinguishing between electrical and software failures of the generator as well as the control and protection system. Therefore, for these two components it is assumed that 50% of the failures are due to failure in the electrical supply system and the rest due to software problems. Failure of the transformer station leads to breakdown of electricity production of the whole wind turbine farm.

Table 2: Estimated failure rates for the different considered wind turbine.

Description	**Mean annual failure rates (λ)**		**Failure type**	**Source**
	original	**adapted**		
Rotor system (Mainly blades)	0.456	0.830	mechanical	[34]
Blade adjustment (pitch system and bearing rings)	0.978	1.781	mechanical	[33], [24]
Gearbox	0.587	1.069	mechanical	[24], [34]
Generator	0.325	0.592	mechanical	[33], [24]
	0.600	1.092	electrical/software	[33], [24]
Generator lead	0.465	0.847	electrical	[33], [24]
HSS	0.046	0.084	mechanical	[24]
LSS	0.037	0.067	mechanical	[24]
Yaw system	0.507	0.923	mechanical	[24]
Control and protection system turbine	0.862	1.569	electrical/software	[33], [24]
Transformer station	0.080	0.147	electrical	[33], [34]
Total annual failure rate	**4.942**	**9.000**		

4.2.1 Considered Damage Model

In order to implement the time-dependent condition of the component with respect to fatigue failures from the failure rates shown in Table 2, these failure rates need to be transferred into a model representing cracks which can be inspected and detected. Table 3 provides the resulting values of the damage coefficient *C* and the proportionality factor x_S (see Section 3.1) together with other parameters used for the considered damage model. The failure rate for mechanical failures is used to calibrate the mean values of parameters *C* and x_S using a corrective maintenance strategy for the different considered wind turbine components.

All considered components have an initial damage, D_0, which is assumed to be exponentially distributed for all components. The exponential distribution representing D_0 has a mean value equal to 0.02 and a coefficient of variation (COV) equal to 0.02 [11].

Table 3: Values for damage parameters of the different considered wind turbine components caused by mechanical failures. The damage coefficient C and proportionality factor x_S are assumed to follow a Lognormal distribution as considered in [11]. Damage exponent m and geometry factor β are constant (deterministic values). COV: Coefficient of variation.

Component of Wind Turbine	Damage exponent m	Geometry factor β	Damage Coefficient C		Proportionality factor x_S	
			Mean	COV	Mean	COV
Rotor system	2	1	11.63e-10	0.2	9.2	0.1
Blade adjustment			23.82e-10		10.0	
Gearbox			16.54e-10		8.6	
Generator			21.58e-10		6.0	
HSS			10.68e-10		3.0	
LSS			10.52e-10		2.7	
Yaw system			15.71e-10		8.2	

4.2.2 Considered Failure Types

Table 4 gives a summary of the three considered failure types and their consequences in case a mechanical/electrical component fails or software problems occur. Failures of mechanical and electrical components necessitate access to the device as replacement/repair on site is necessary whereas software problems can be solved by restarting as well as online access to the control system of the wind turbine.

It is assumed here that there is no interaction between different failure modes. Also, no secondary damages, which are damages induced by other damages, are considered in this example. Furthermore, this study does not consider the complete structural collapse of the main structural parts like the foundation or tower, which will need complete replacement of the turbine and make the use of a heavy jack-up vessel necessary.

Table 4 Summary of the three considered failure types and their consequences.

Failure type	Considered model	What happens when failure occurred
Mechanical components	Damage model (see Section 3.1)	Replacement on site, access necessary
Electrical components	Failure rate (see Section 3.2)	Replacement on site, access necessary
Control system (software)	Failure rate (see Section 3.2)	Restarting (software update), no access necessary

4.3 Parameters for Inspection and Maintenance Modeling

Table 5 shows the variables used for the PoD curve defining the probability of detection dependent on the crack size and parameters needed for modeling different preventive maintenance strategies. In this example it is assumed that the PoD curve is the same for all components having mechanical failures. The smallest detectable damage λ is modeled as a stochastic variable reflecting human uncertainties as well as measurement uncertainties. Due to the fact that the same crew and the same inspection method as well as equipment are used for inspecting the whole device and all components are inspected at the same day, the uncertainty about λ is assumed to be constant during a certain inspection. The COV value for the λ value is assumed to be 0.1. In this example the decision rule, which is represented by D_{rep}, as well as the statistical values of the PoD curve are assumed to be constant over the whole lifetime. The parameters D_{alarm} and η_{CM} representing the sensitivity and efficiency of the condition monitoring system, respectively, are needed as input parameters when simulating a condition-based condition maintenance strategy. When following a preventive maintenance strategy with regular inspection intervals, default annual inspection intervals are considered.

Table 5 Values used for the PoD curve of the components having mechanical failure as well as input parameters for preventive (regular inspection intervals and condition-based) maintenances. COV: Coefficient of variation. Adapted from [16].

Symbol	Meaning	Mean	COV	Distribution
P_0	Maximum probability of detection	1	-	Deterministic
λ	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
η_{CM}	Detection efficiency of condition monitoring system	0.7	-	Deterministic
ΔT	Time interval between two inspections	1 year	-	Deterministic

It needs to be mentioned that the investment and operational costs of the condition monitoring system is not considered in this case study and is assumed to be negligible compared with the initial other investment costs.

4.4 Costs and Time for Repair, Inspection and Transportation

Table 6 shows the expected repair costs C_E for different considered components. The values shown in Table 6 are based on studies collecting and summarizing real data. Reference [34] estimated the expected repair costs from a study from roughly 350 offshore wind turbines throughout Europe. Expected costs for the low speed shaft part (main shaft and main shaft bearing) as well as the high speed shaft are not explicitly available and are summarized in one category in reference [34] as these failure rates are much smaller than the other listed failure rates in the study. The considered repair costs for a 6 MW wind turbine are adjusted based on scaling law presented in [37] assuming that the considered capacity per offshore wind turbine considered in [34] is 3 MW.

The number of working days on the site is assumed to be Lognormal distributed in order to prevent negative values.

Table 7 shows the mean value and the coefficient of variation (=0.5, taken from [11]) for the different mechanical and electrical failures of the wind turbines. The number of days needed on the device in order to fix the failure is estimated from [34] and [36]. In this study only integer values for the days on the site needed for the repair are considered and a minimum of one day is needed to fix a certain failure on the wind turbine.

Table 6 Expected repair (material) costs C_E for different considered components. Data is adapted from [34] and [16].

Description	**Expected repair costs C_E (€)**	
	Baseline from [34]	**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

Table 7 Repair durations (in days) on the device for different mechanical and electrical failures - Data is taken from [11], [16], [34], [36].

Description	**Number of days *d* needed on the site for the 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	

Software failures can be solved by online access (e.g. by restarting the control software). Experience shows that software problems can be solved relatively quickly compared with physical break-down of the system where access to the device is necessary. The only costs the operator of the wind turbine farm has when a software failure occurs are labor costs. It is assumed due to lack of knowledge that repairing a software problem (including manual restart and observation, problem analysis wind turbine manufacturer and operator) takes one working day and, in each case, two specialists are working on it.

Table 8 shows the assumed costs for the inspection of a wind turbine, the transportation costs by boat/helicopter, and the labor costs per day for a technician crew as well as the considered interest rate. The labor costs C_W on the device are according to [33] in the range of 3600 € per day resulting from the assumption that a technician costs 150 € an hour (including insurance and offshore premium), and the technician crew consists of 2 people each working for 12 hours a day. The transportation cost by boat reflects the daily transportation cost for a crew transporting vessel (CTV). The expected renting costs for such a boat is in the range of 5000 € a day [38], [35] for maintenance actions of offshore wind turbines 30 km off the coast. The ratio between transportation by helicopter and by boat is chosen according to [39] where the transportation cost by helicopter are roughly 2 times larger than by boat when the offshore wind farm is placed 30 km off the coast. When an electrical or mechanical failure on an offshore wind turbine occurs, the replacement or repair starts the day after (at 6 o'clock) the damage occurred. The rest of the day is used to order the repair parts, brief the technicians, and prepare the helicopter/boat for the transport. The inspection costs for one component are assumed to be 1000 € including equipment costs and labor costs for two technicians. An interest rate of 5%, as considered e.g. in other studies presented in [35] or [11], is also considered in current study.

Table 8 Inspection and transportation costs as well as considered interest rate. Data is taken from [16] and [31].

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

When performing inspection it is assumed that this is done by boat as these operations can be planned and take place during the summer months when the weather is moderate. Consequently, there might be seasonal differences in hiring costs, which are not considered in this example, due to large demands during summer months for performing inspections and preventive maintenance actions. In this study it is assumed that all components are inspected during an inspection.

Waiting times due to bad weather conditions are represented by the lost electricity production. Waiting costs of the transportation vehicles is not considered in this example as the boat and the helicopter are paid based on the days on sea. Furthermore, this example assumes that the boat as well as the helicopter is always available. In this example the hiring and inspection costs are assumed to be constant over the whole lifetime.

It needs to be mentioned that additional investment costs like installation costs for a landing platform when accessing the device by helicopter or costs for installing a condition monitoring system as well as operational costs for running a condition monitoring system may be necessary for different transportation and maintenance strategies. These additional costs are not considered in this study.

4.5 Operational Range Boat and Helicopter

Boats and helicopters are used in this example to transport crew and material from the shore to the device. Accessing the device by boats is limited by significant wave heights whereas when accessing the device via helicopter, the wind speed can limit safe lowering of crew and material. There are different types of boats with different wave height operational limits, see e.g. [40]. For the minor/medium repair, where no additional crane boat is needed, a so-called CTV can be used. These boats are highly maneuverable, fast, and enable a comfortable transport of personnel to the offshore devices. Furthermore, these boats are developed to operate in strong weather conditions. The following limitations are used here:

Boat:	Maximum significant wave height:	1.5 m	[11], [35], [41], [42]
Helicopter:	Maximum wind speed:	20 m/s	[11]

The access limitation does not only depend on whether boat or helicopter is used but also on the weight of the considered spare parts to be transported or the need for a crane vessel. Also, other parameters not considered here may affect the use of boats (e.g. strong current velocities) and helicopters (e.g. fog) for transportation. Furthermore, the above mentioned limitations for boat and helicopter operations are not strict limitations but depend on the skills of the pilots as well as the boat operators.

4.6 Environmental Conditions

Weather data is available for the period 1979–2009 with 1-hour values of significant wave height (H_S), mean zero-crossing wave period (T_Z), and wind speed (V). The weather data is recorded 30 km off the Danish North Sea Coast near Hanstholm. In order to get an idea about the wave characteristics at the considered location, Table 9 shows the scatter diagram representing the probability of occurrence of a certain wave state given by H_S and T_Z. The wave characteristics are of importance for defining weather windows where the boat can be used as well as the calculation of the accumulated damage (see Section 3.1). Figure 9 shows the histogram of the measured mean wind speed between 1979 and 2009. During 94% of the time, the turbine is able to produce electricity whereas for the rest of the time the wind speed is either below 4 m/s or above 25 m/s. At the considered location during 28% of the time, the wind turbine is able to produce electricity at rated power of 6 MW.

In order to make the weather a pseudo-random variable, the available weather data is bootstrapped based on yearly steps. Bootstrapping enables resampling of a dataset by different combinations of weather conditions over the lifetime. The weather forecast, which is needed for the risk-based transportation strategy, is assumed to be perfect in this example.

Table 9 Probability of occurrence of different wave states given by the significant wave height and the mean wave period (Scatter diagram) at the considered location taking the whole period (1979-2009) into account. H_S: significant wave height; T_Z: mean 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	0.00
0.75	0.01	0.07	0.16	0.11	0.05	0.01
1.25	0.00	0.00	0.06	0.11	0.05	0.01
1.75	0.00	0.00	0.00	0.06	0.05	0.01
2.25	0.00	0.00	0.00	0.01	0.04	0.02
2.75	0.00	0.00	0.00	0.01	0.02	0.02

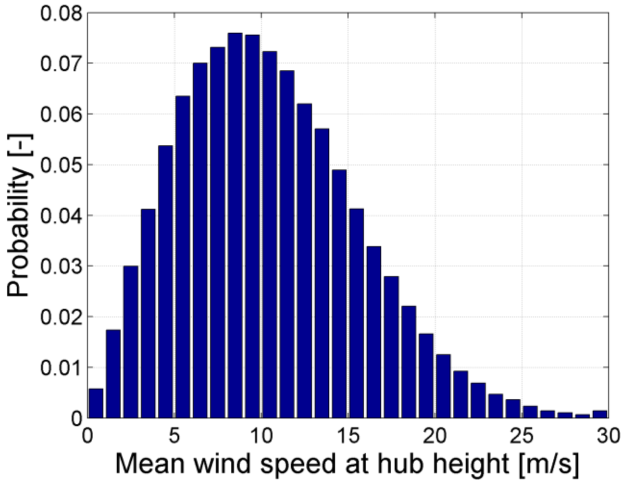

Figure 9 Histogram of mean wind speeds at hub height taking all measurements from 1979 to 2009 into account.

5 Results and Discussion

This section presents the expected total maintenance expenses as well as the number of needed repairs/replacements of the considered reference wind turbine farm including a sensitivity analysis of different input parameters for different transportation and maintenance strategies.

Corrective and preventive maintenance strategies with either regular inspection intervals or a condition monitoring system are considered here. Transportation strategies include the case where access is only performed by boat (called 'only boat') or where the target is to minimize the downtime of the different wind turbines and repair or replacement of the broken component should be done as soon as possible (called 'ASAP') as well as the transportation strategy where the overall costs are minimized (called 'risk-based'). Figure 10 shows the expected total maintenance costs for the considered wind turbine farm during a lifetime of 20 years for different transportation and maintenance strategies as explained in Section 2. The highest total expected maintenance expenses are reached when only using the boat for a given maintenance strategy due to high loss of electricity production. This means that the availability of a helicopter – as considered in the 'ASAP' and 'risk-based' strategy – makes it possible to decrease the total expected maintenance expenses. The lowest expected maintenance expenses following a certain maintenance strategy can be reached when installing a condition monitoring system giving an indication of the condition of the different components.

Furthermore, one can see that the difference between the 'ASAP' and the 'risk-based' maintenance strategy is small (range of 2.5% - 5%) for a given maintenance strategy. The 'ASAP' gives, as expected, a slightly lower loss of electricity but, on the other side, it is necessary with larger costs for the repair/replacement of the device compared with the 'risk-based' maintenance strategy. The 'risk-based' transportation strategy leads for a given maintenance strategy to the lowest maintenance expenses.

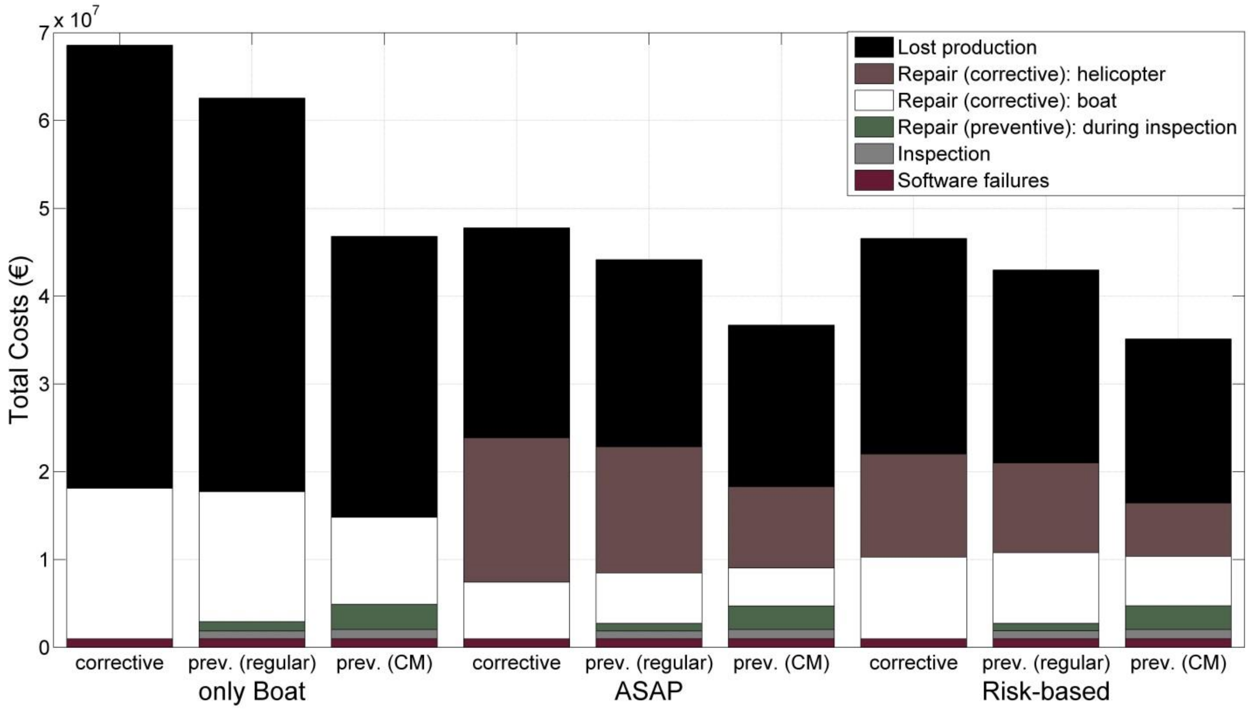

Figure 10: Influence of maintenance and transportation strategy on total maintenance costs during one lifetime. 'only Boat': only boat used to access the wind turbines; 'ASAP': replacement/repair as soon as possible considering helicopter and boat for transportation; 'Risk-based': Minimization of overall costs considering boat and helicopter for transportation. CM: Condition monitoring; regular: regular inspection interval of 1 year.

Figure 11 shows the number of performed repairs at the reference wind turbine farm during a lifetime of 20 years. It shows that the number of repairs is not dependent on the transportation strategy, but on the maintenance strategy (preventive or corrective). The lowest number of repairs is reached, as expected, when following a corrective maintenance strategy. When following a corrective maintenance strategy, roughly 1500 repairs are needed during the expected lifetime of 20 years. When following a preventive maintenance strategy with inspections every year, the number of repairs increases to 1600 and with a condition monitoring system, the number of performed replacements and repairs is in the range of 1700.

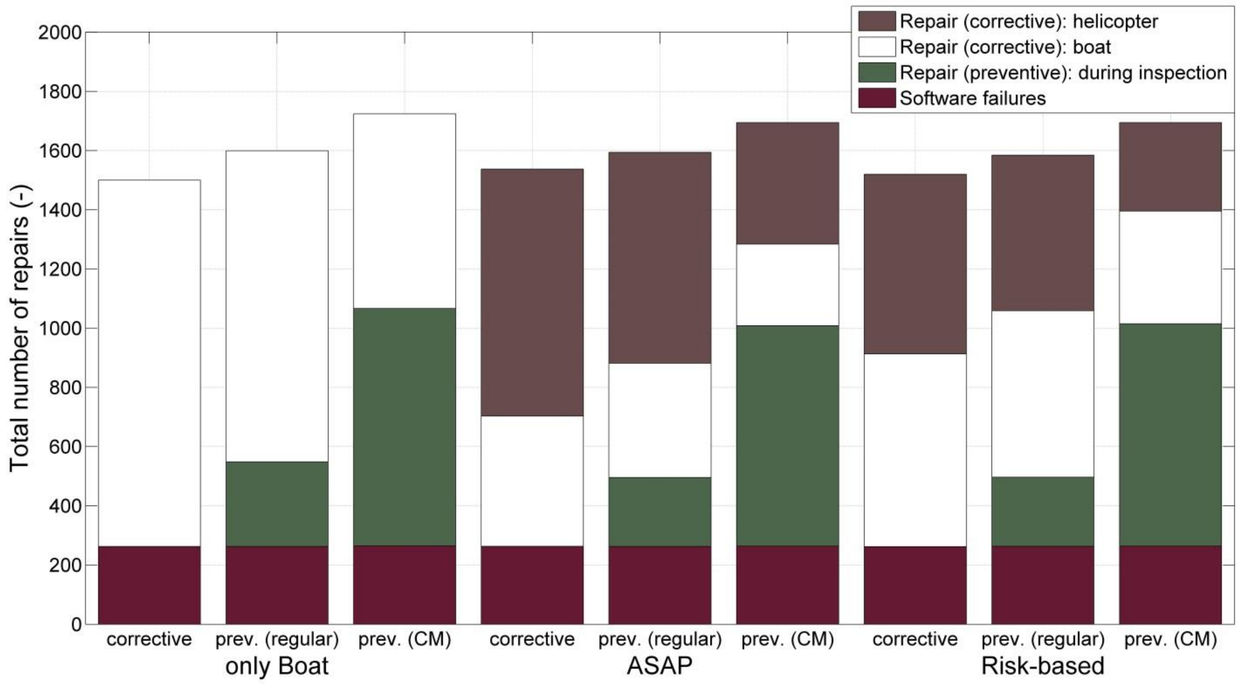

Figure 11: Average total number of repairs for different transportation and maintenance strategies during one lifetime. 'only boat': only Boat used to access the wind turbines; 'ASAP': replacement/repair as soon as possible considering helicopter and boat for transportation; 'Risk-based': Minimization of overall costs considering boat and helicopter for transportation. CM: Condition monitoring; regular: regular inspection interval of 1 year.

Table 10 provides further information about the expected availability of the wind turbine farm dependent on the transportation and maintenance strategy. Availability is considered based on the down and uptime (time-based) as well as the lost and produced power (power-based). Lowest availabilities are in the range of 80% and reached when following a corrective maintenance strategy where only the boat is used for assessing the wind turbines. Larger availabilities in the range of 90% - 93% can be reached when following the ASAP as well as the risk-based transportation strategy. The expected O&M expenses per KWh in this study are in the range between 32.1% (corrective maintenance, only boat) and 14.3% (preventive maintenance, condition monitoring, risk-based), which corresponds to 0.026 € and 0.011 € per produced KWh of electricity. Table 10 also shows the COV of the overall maintenance costs considering the simulation results. High COV (only boat) values of the resulting overall maintenance costs mean high risk due to uncertain costs. The COV is the standard deviation of the different simulations for a given maintenance and transport strategy divided by its mean value. The higher the COV value, the larger the risk as high variations between the different lifetime simulation result in uncertain cost estimations. In this study, the largest COV values with a value around 8% - 9% are reached when only using the boat to access the wind turbines. The smallest COV of 5% is reached when following a preventive maintenance strategy using the ASAP or risk-based transportation strategy to access the wind turbines.

Overall it can be seen that a corrective maintenance strategy leads to a lower number of repairs, but higher expected maintenance expenses compared with preventive maintenance strategies. The smallest maintenance expenses are reached when using a condition monitoring (CM) system to detect future structural failures and the risk-based transportation strategy.

Table 10 Expected values for availability (time-based and power-based) total O&M expenses (in €/KWh and as % of the electricity price) as well as the COV values for the total maintenance costs presented in Figure 10. Corr.: corrective; Prev.: Preventive; CM: Condition Monitoring; COV: Coefficient of variation.

Transport strategy	**Only Boat**			**ASAP**			**Risk-based**		
Maintenance strategy	**Corr.**	**Prev. regular**	**Prev. CM**	**Corr.**	**Prev. regular**	**Prev. CM**	**Corr.**	**Prev. regular**	**Prev. CM**
Availability (time-based)	0.842	0.860	0.887	0.924	0.931	0.926	0.918	0.926	0.924
Availability (power-based)	0.807	0.828	0.879	0.909	0.919	0.930	0.906	0.916	0.929
O&M expenses/KWh (€/KWh)	0.026	0.023	0.016	0.016	0.015	0.012	0.015	0.014	0.011
O&M expenses/KWh (%)	32.1	28.5	20.1	19.9	18.2	14.9	19.4	17.7	14.3
COV total maintenance expenses (-)	0.083	0.088	0.082	0.056	0.058	0.050	0.055	0.058	0.050

The resulting maintenance costs as well as the number of repaired components are dependent on the inspection intervals as well as the efficiency and sensitivity of the condition monitoring system when following a preventive maintenance strategy, the quality of the performed inspections, the operational conditions for the boat and helicopter, the impact of the electricity price and the value of the real rate of interest. Therefore, different sensitivity analyses are performed in the following.

5.1 Preventive Maintenance – Regular Inspection Intervals

Figure 12 shows the total expected costs when following a preventive maintenance strategy with fixed inspections intervals for different intervals between two inspections. The figure shows that the optimal inspection interval is 0.15 years when only using the boat for accessing the wind turbines whereas when using the boat and the helicopter the optimal inspection interval is in the range between 0.15 and 0.25 years for this reference wind turbine farm. Short inspection intervals between two inspections lead to large overall inspection expenses, and large inspection intervals lead to a larger amount of corrective failures which need to be repaired followed by an increased amount of lost electricity.

Table 11 shows the relative impact on maintenance expenses per produced KWh of electricity. By reducing the inspection interval form 1 year to 0.25 year, the maintenance expenses can be reduced by 17% - 25% per produced unit of electricity. The optimal inspection interval is, among others, dependent on the failure rates of the mechanical components as these failure rates define the benefit of doing preventive replacements at a certain point in time.

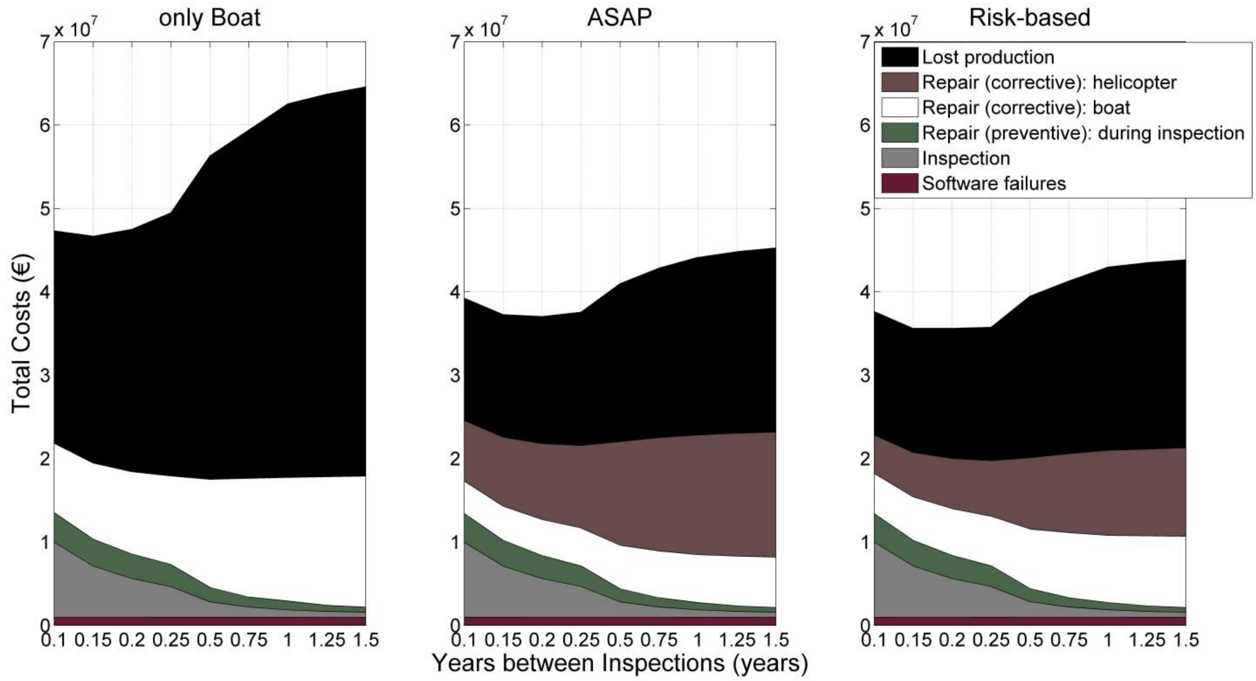

Figure 12 Influence of inspection interval on the total expected costs during one lifetime for different transportation strategies. 'only Boat': only boat used to access the wind turbines; 'ASAP': replacement/repair as soon as possible considering helicopter and boat for transportation; 'Risk-based': Minimization of overall costs considering boat and helicopter for transportation.

Table 11 Relative impact on maintenance expenses per produced KWh of electricity (Normalized by using the risk-based transportation strategy and an inspection interval of 1 year) dependent on the interval between two inspections. (D_{REP}=0.3).

Transportation strategy	**Inspection interval between two Inspections (years)**				
	0.15	**0.25**	**0.5**	**1**	**1.5**
Only boat	1.110	1.198	1.410	1.507	1.608
ASAP	0.841	0.855	0.943	1.026	1.041
Risk-based	0.806	0.814	0.910	1.000	1.024

5.2 Preventive Maintenance – Condition Monitoring System

When using a condition monitoring system, mechanical failures can be detected before they will occur. But the benefit using a condition monitoring system depends on the sensitivity meaning how early future failures can be detected but also on the efficiency of the condition monitoring system indicating the probability that an existing damage is detected by the condition monitoring system. The following sections will investigate these two aforementioned factors.

5.2.1 Influence of Alarm Threshold of Condition Monitoring System

The influence of the total expected maintenance costs for the reference wind turbine farm dependent on the alarm threshold, D_{alarm}, of the condition monitoring system is given in Figure 13. Figure 14 shows the number of total repairs and replacements during one lifetime.

Figure 13 indicates that the lowest expected total maintenance costs are reached when having an alarm threshold of 0.6 as the total number of replacements is minimal with an alarm threshold of 0.6 (see Figure 14). For smaller and larger alarm thresholds, the total maintenance costs increase as the number of corrective repairs (high alarm thresholds) and the number of preventive repairs (low alarm thresholds) slightly increase compared with an alarm threshold of 0.6.

Table 12 shows impact on relative maintenance expenses per produced KWh of electricity dependent on the alarm threshold (D_{alarm}) of the condition monitoring system. It can be seen that the reduction potential of the maintenance expenses per produced unit of electricity by choosing the optimal alarm threshold is of minor importance compared with the differences in expenses due to different transportation strategies.

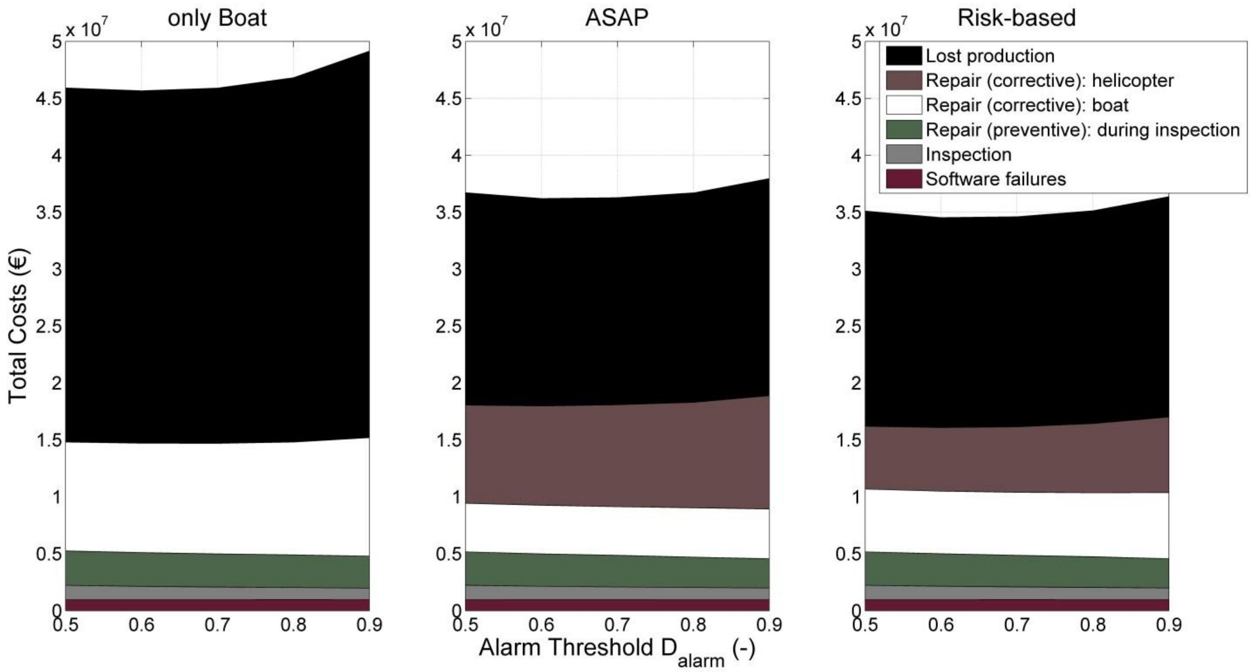

Figure 13 Influence of alarm threshold D_{alarm} of the condition monitoring efficiency on the total expected costs during one lifetime for different transportation strategies. 'only Boat': only boat used to access the wind turbines; 'ASAP': replacement/repair as soon as possible considering helicopter and boat for transportation; 'Risk-based': Minimization of overall costs considering boat and helicopter for transportation. The detection efficiency (η_{CM}) is set to 0.7 and the damage level for repair for detected damages (D_{REP}) is set to 0.3 for all simulations.

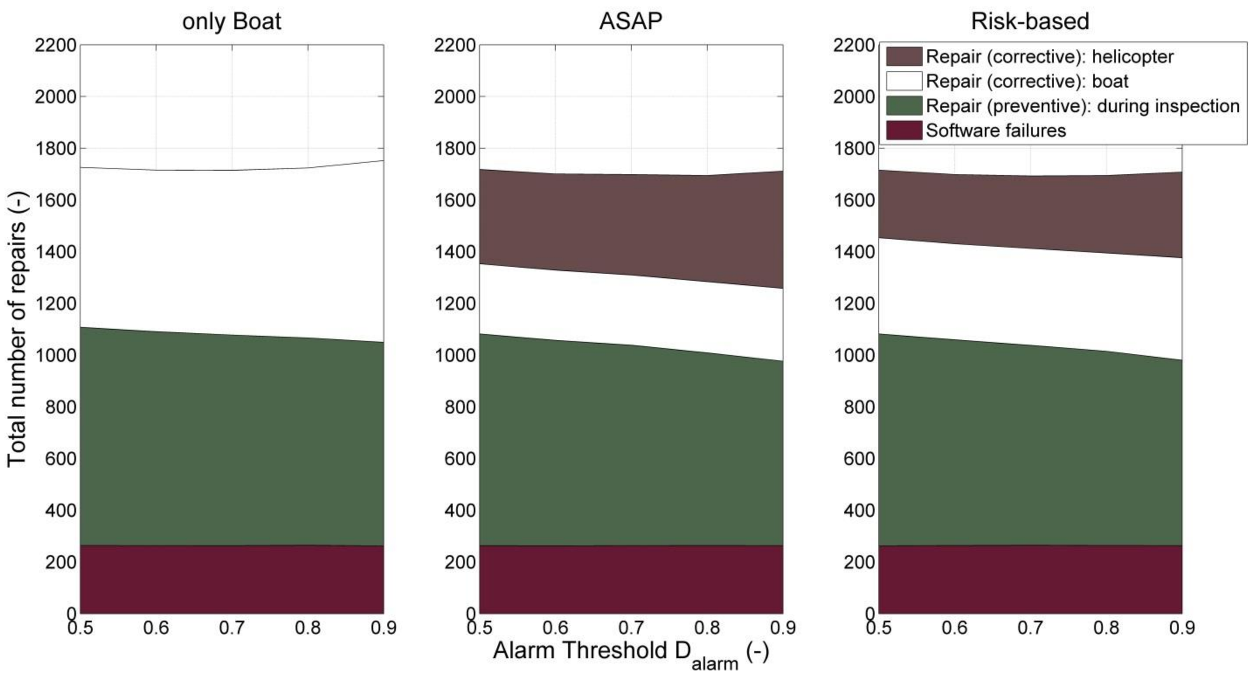

Figure 14 Influence of alarm threshold D_{alarm} of the condition monitoring efficiency on the expected number of total repairs/replacements during one lifetime for different transportation strategies. 'only Boat': only boat used to access the wind turbines; 'ASAP': replacement/repair as soon as possible considering helicopter and boat for transportation; 'Risk-based': Minimization of overall costs considering boat and helicopter for transportation. The detection efficiency (η_{CM}) is set to 0.7 and the damage level for repair for detected damages (D_{REP}) is set to 0.3 for all simulations.

Table 12 Relative impact on maintenance expenses per produced KWh of electricity (Normalized by using the risk-based transportation strategy and an alarm threshold of 70%) dependent on the condition monitoring alarm threshold D_{alarm}. (η_{CM}=0.7;D_{REP}=0.3).

Transportation strategy	**Alarm Threshold Condition Monitoring System (D_{alarm})**		
	0.5	**0.7**	**0.9**
Only boat	1.401	1.397	1.427
ASAP	1.061	1.044	1.062
Risk-based	1.016	1.000	1.015

5.2.2 Influence of Failure Detection Efficiency of Condition Monitoring System

The influence of the detection efficiency, η_{CM}, of the condition monitoring system on the total expected maintenance cost during one year is shown in Figure 15 for different transportation strategies. In general, a high detection efficiency of the condition monitoring system is desired as the total expected maintenance costs can be decreased. Figure 16 shows the expected total number of repairs and replacements during one lifetime of the reference wind turbine farm. When the condition monitoring system is improved from a detection efficiency of 70% to 100%, the total maintenance expenses could be decreased by roughly 7% - 10%. A high detection efficiency of future mechanical failures leads to slightly more repairs/replacements as more repairs are performed preventively instead of correctively as done when the condition monitoring has low detection efficiency. The number of total repairs increases by roughly 2% when having a perfect condition monitoring system (η_{CM}=100%) instead of η_{CM}=70%.

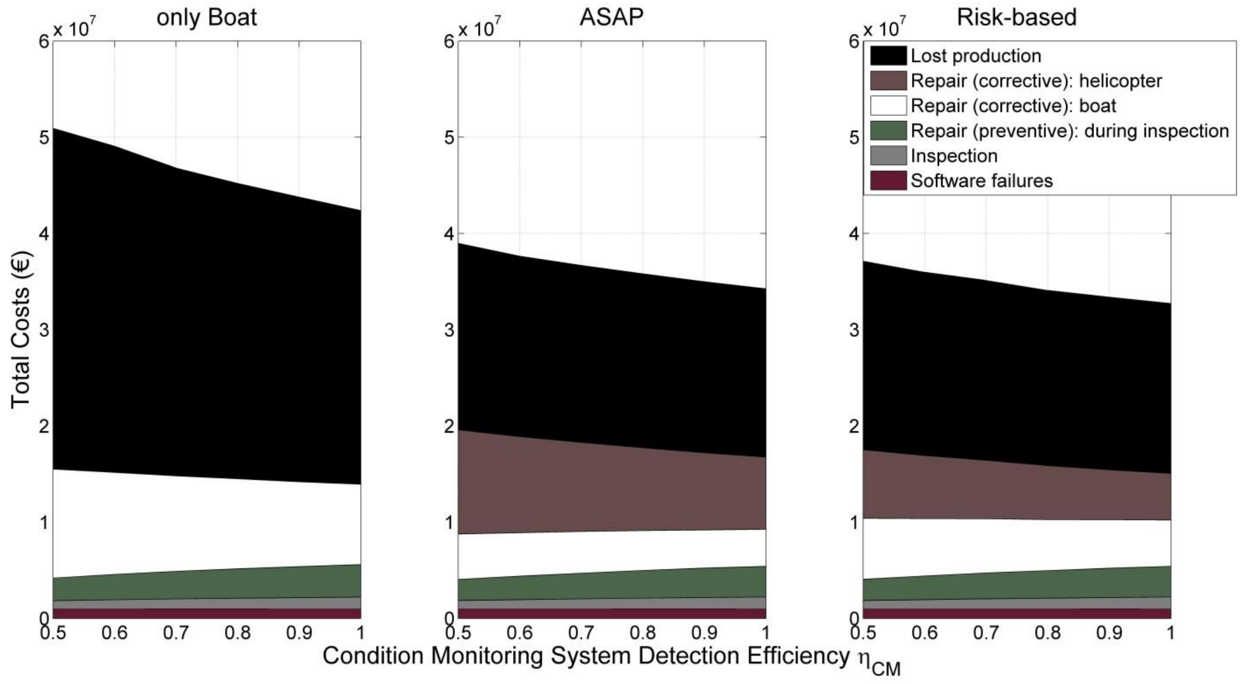

Figure 15 Influence of detection efficiency η_{CM} of the condition monitoring efficiency on the total expected costs during one lifetime for different transportation strategies. 'only Boat': only boat used to access the wind turbines; 'ASAP': replacement/repair as soon as possible considering helicopter and boat for transportation; 'Risk-based': Minimization of overall costs considering boat and helicopter for transportation. The alarm threshold (D_{alarm}) is set to 0.8 and the damage level for repair for detected damages (D_{REP}) is set to 0.3 for all simulations.

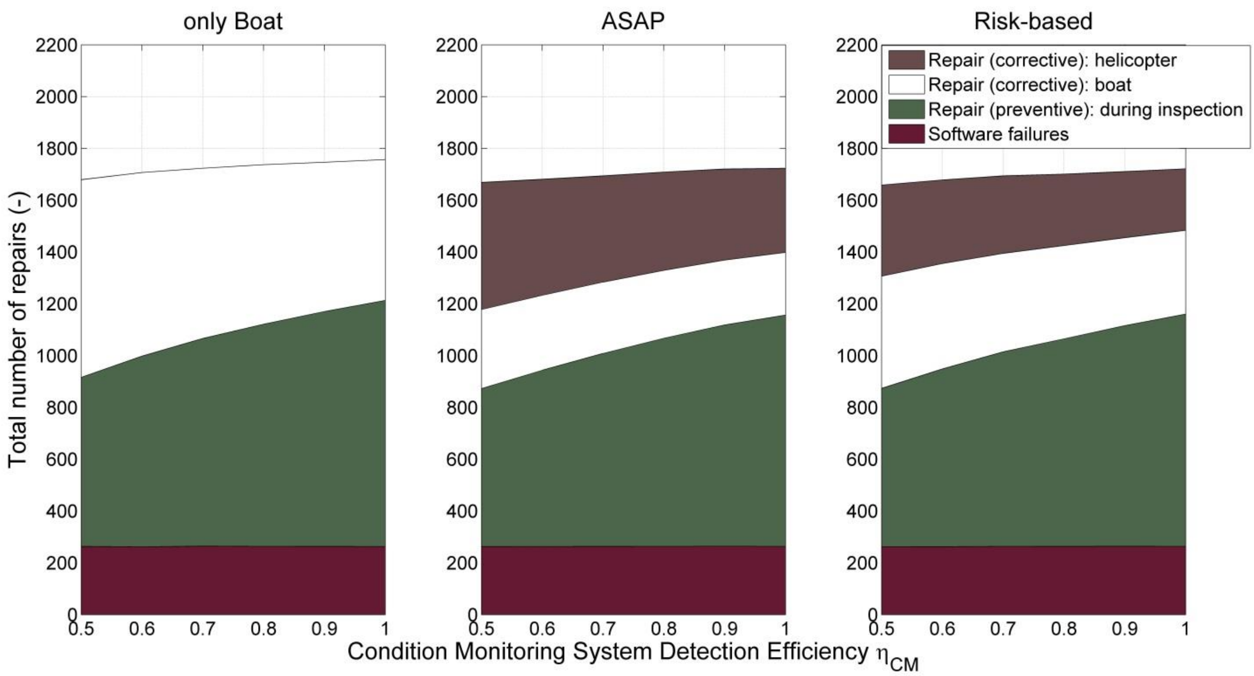

Figure 16 Influence of detection efficiency η_{CM} of the condition monitoring efficiency on the expected number of total repairs/replacements during one lifetime for different transportation strategies. 'only Boat': only boat used to access the wind turbines; 'ASAP': replacement/repair as soon as possible considering helicopter and boat for transportation; 'Risk-based': Minimization of overall costs considering boat and helicopter for transportation. The alarm threshold (D_{alarm}) is set to 0.8 and the damage level for repair for detected damages (D_{REP}) is set to 0.3 for all simulations.

Table 13 gives the normalized maintenance expenses per produced unit of electricity dependent on the transportation strategy and the condition monitoring system detection efficiency (η_{CM}). It can be seen that larger detection efficiencies of the condition monitoring decreases the maintenance expenses per KWh of produced electricity. The impact of the detection efficiency (η_{CM}) of the condition monitoring system (see Table 13) has larger impact on the expected maintenance expenses per produced unit of electricity than the alarm threshold (D_{alarm}) of the condition monitoring system (see Table 12).

Table 13 Relative impact on maintenance expenses per produced KWh of electricity (Normalized by using the risk-based transportation strategy and a CM efficiency of 70%) dependent on the condition monitoring system detection efficiency (η_{CM}).(D_{alarm}=0.8;D_{REP}=0.3).

Transportation strategy	Condition Monitoring System Detection Efficiency (η_{CM})		
	0.5	**0.7**	**1**
Only boat	1.550	1.333	1.207
ASAP	1.110	1.045	0.976
Risk-based	1.057	1.000	0.932

5.3 Inspection Quality

The inspection quality is investigated in this case by looking at the influence of the damage threshold for repair (D_{REP}) once damage is detected as well as the accuracy of the inspection by looking at the minimal detectable damage (λ).

5.3.1 Influence of Damage Threshold for Repair (D_{REP}) During Inspections

The damage threshold for repair (D_{REP}) defines the threshold for repair/replacement given a detection of a damage D (see Section 3.1 for more details about damage factor D). The damage threshold for repair is used whenever inspections take place following a preventive maintenance strategy.

Figure 17 shows the total expected maintenance costs for a preventive maintenance strategy with annual inspections. The costs are minimal having a repair threshold equal to 0 and are increasing the larger the damage threshold for repair is defined. Figure 18 shows the expected number of repairs of the whole wind turbine farm for different transportation strategies having inspections once an year dependent on D_{REP}. Large D_{REP} lead to lower number of preventive repairs but more costly corrective repairs compared with no threshold (D_{REP}=0).

Table 14 gives the relative maintenance expenses per produced unit of electricity for different transportation strategies and D_{REP} values. A D_{REP} value of 0 enables decrease of the cost by 3% - 5% compared when having a D_{REP} value of 0.3 for a given transportation strategy. It can be concluded that it is beneficial for this wind turbine farm to replace and repair damages whenever they are detected independent on the severity and level of damage.

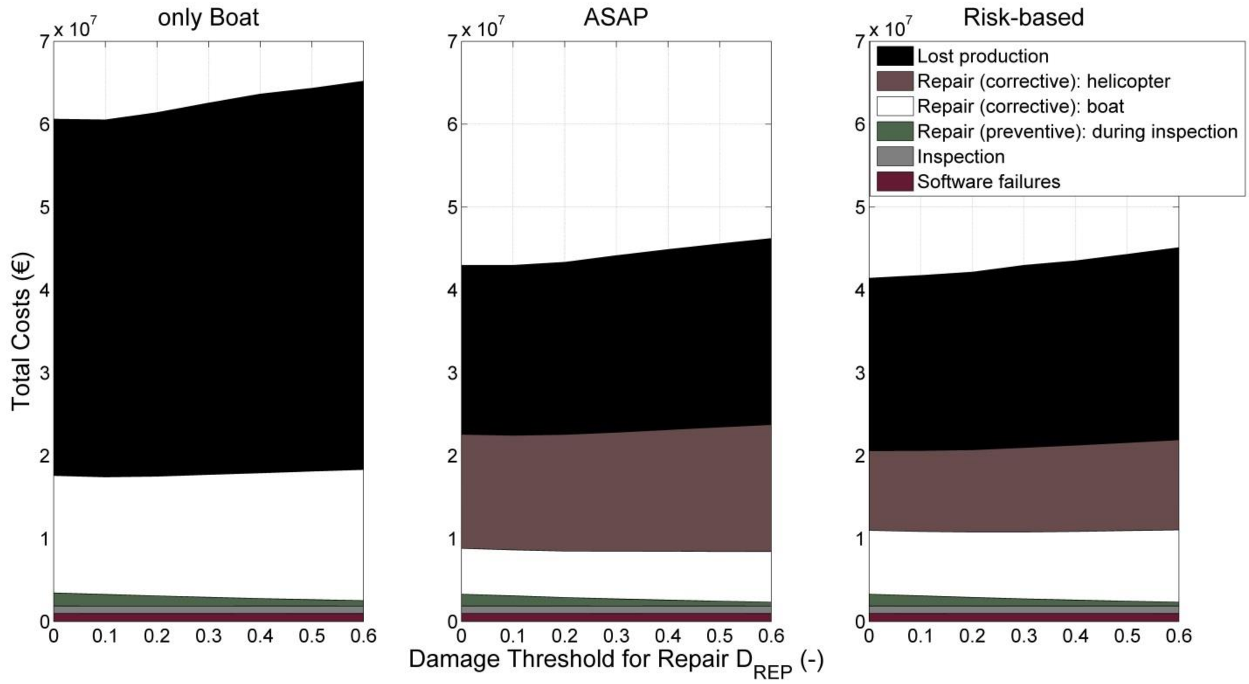

Figure 17 Influence of damage threshold for repair D_{REP} during inspections on the total expected costs during one lifetime for different transportation strategies following a preventive maintenance strategy with annual inspections. 'only Boat': only boat used to access the wind turbines; 'ASAP': replacement/repair as soon as possible considering helicopter and boat for transportation; 'Risk-based': Minimization of overall costs considering boat and helicopter for transportation.

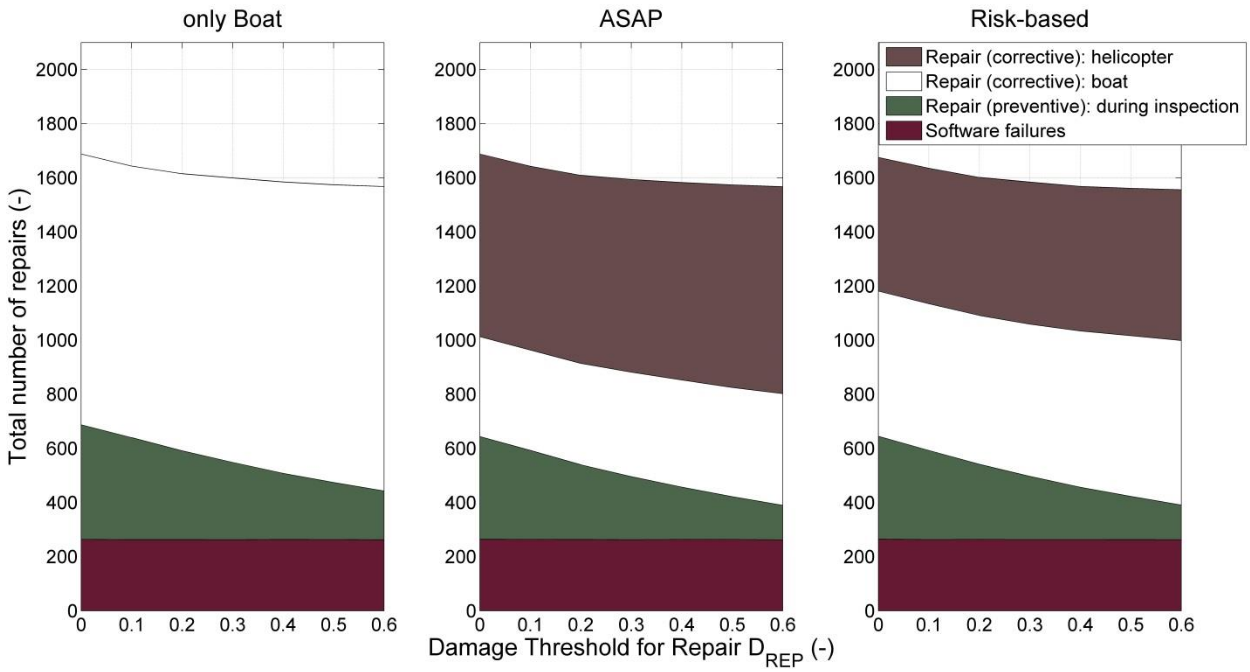

Figure 18 Influence of damage threshold for repair D_{REP} during inspections on the total number of repairs during one lifetime for different transportation strategies following a preventive maintenance strategy with annual inspections. 'only Boat': only boat used to access the wind turbines; 'ASAP': replacement/repair as soon as possible considering helicopter and boat for transportation; 'Risk-based': Minimization of overall costs considering boat and helicopter for transportation.

Table 14 Relative impact on maintenance expenses per produced KWh of electricity (Normalized by using the risk-based transportation strategy and a damage threshold for repair of 0.3) dependent on the damage threshold of repair D_{REP} following a preventive maintenance strategy with regular inspection intervals of 1 year.

Transportation strategy	Damage Threshold for Repair (D_{REP})		
	0.0	**0.3**	**0.6**
Only boat	1.410	1.455	1.517
ASAP	1.000	1.027	1.075
Risk-based	0.964	1.000	1.050

Figure 19 and Figure 20 show the expected total maintenance costs and the total number of expected repairs, respectively, during one lifetime when using a condition monitoring system (condition-based preventive maintenance). The influence on the total maintenance costs (see Figure 19) as well as the total number of repairs (see Figure 20) looks slightly different when using a condition monitoring system compared with the previously shown Figures (see Figure 17 and Figure 18) with a preventive maintenance strategy with constant inspection intervals. The lowest total expected maintenance costs are reached when using a low damage threshold for repair (D_{REP}) of 0.1 independent on the transportation strategy. When repairing all detected damages independent on its size (choosing D_{REP}=0), the preventive repair costs increase due to many preventive replacements during inspections (see Figure 20) compared with the optimal case. When moving to D_{REP} values larger than 0.1, the amount of lost electricity is increasing due to longer down times because of more corrective replacements need to be performed. Figure 20 shows that the larger the damage threshold for the repair chosen, the lower the expected total number of repairs.

Table 15 presents the relative impact on maintenance expenses per produced KWh of electricity following a preventive maintenance strategy using a condition monitoring system. A D_{REP} value of 0.6 instead of 0.3 increases the cost by 10% - 12%.

In general, one can say that the sensitivity of the damage threshold for repair on the maintenance expenses is larger when using a condition monitoring system compared with regular and fixed inspection intervals.

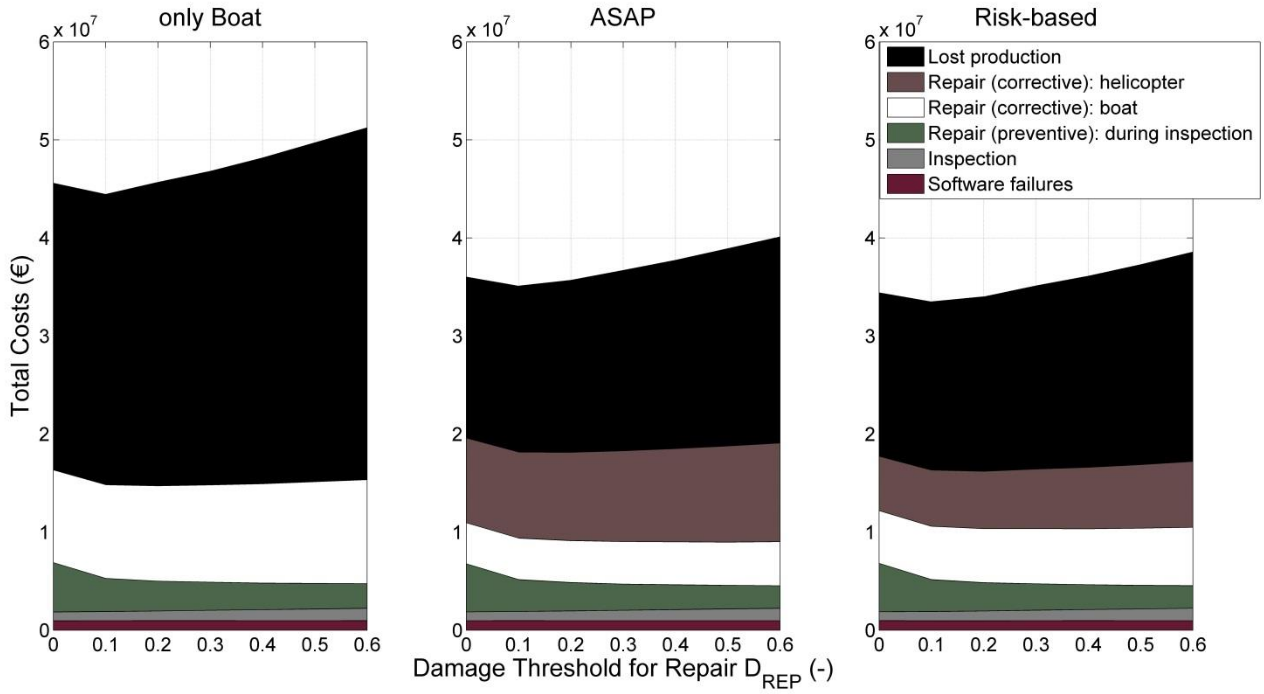

Figure 19 Influence of damage threshold for repair D_{REP} during inspections on the total expected costs during one lifetime for different transportation strategies following a preventive maintenance strategy with a condition monitoring system (D_{alarm}=0.8; η_{CM} =0.7). 'only Boat': only boat used to access the wind turbines; 'ASAP': replacement/repair as soon as possible considering helicopter and boat for transportation; 'Risk-based': Minimization of overall costs considering boat and helicopter for transportation.

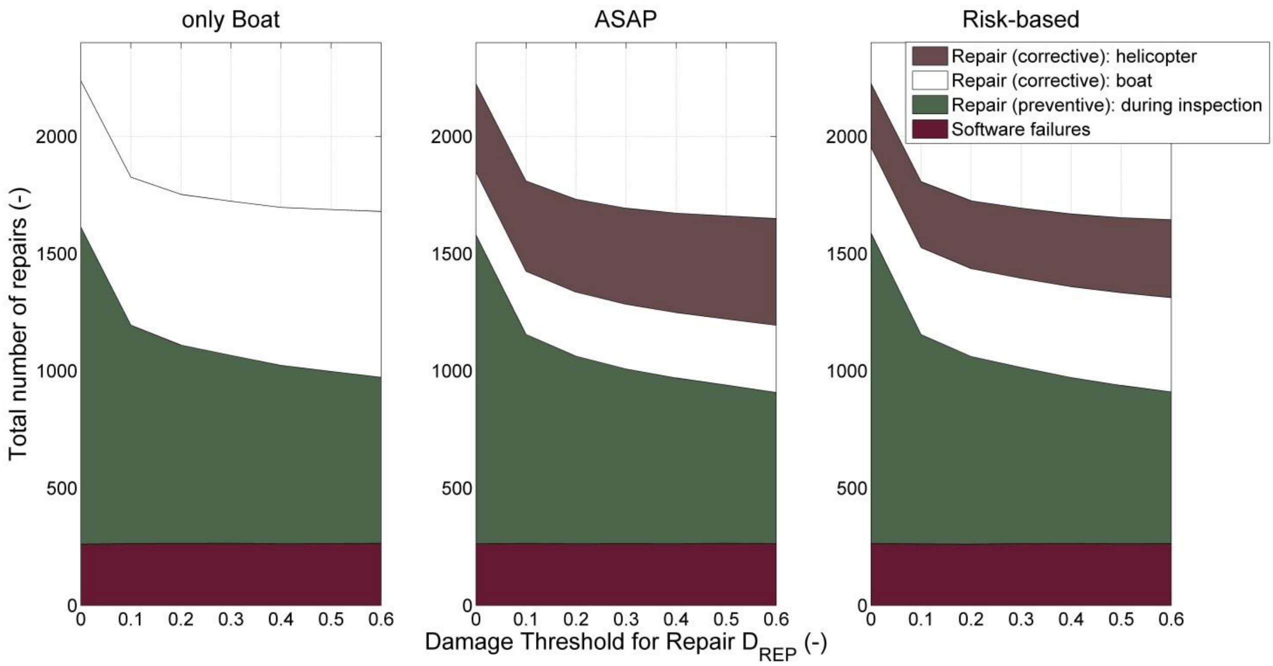

Figure 20 Influence of damage threshold for repair D_{REP} during inspections on the total number of repairs during one lifetime for different transportation strategies following a preventive maintenance strategy with a condition monitoring system (D_{alarm}=0.8; η_{CM} =0.7). 'only Boat': only boat used to access the wind turbines; 'ASAP': replacement/repair as soon as possible considering helicopter and boat for transportation; 'Risk-based': Minimization of overall costs considering boat and helicopter for transportation.

Table 15 Relative impact on maintenance expenses per produced KWh of electricity (Normalized by using the risk-based transportation strategy and a damage threshold for repair of 0.3) dependent on the damage threshold of repair D_{REP} following a preventive maintenance strategy using a condition monitoring system. (D_{alarm}=0.8; η_{CM} =0.7).

Transportation strategy	Damage Threshold for Repair (D_{REP})		
	0.0	**0.3**	**0.6**
Only boat	1.356	1.407	1.571
ASAP	1.018	1.046	1.155
Risk-based	0.973	1.000	1.113

5.3.2 Influence of Minimal Detectable Damage (λ) During Inspections

The minimal detectable damage influences the total maintenance costs as replacements and repairs will be differently distributed between corrective and preventive repairs when following a preventive maintenance strategy. Figure 21 and Figure 22 show the total maintenance expenses during one lifetime for the considered wind turbine farm considering different minimal detectable damage values when performing annual inspections (Figure 21) and using a condition monitoring system (Figure 22), respectively. Both maintenance strategies show that increased minimal detectable damages slightly increase the expected total maintenance expenses. The main reason for increased maintenance costs when increasing the minimal detectable damage is due to increased lost electricity resulting from increase in corrective replacements and decrease in preventive replacements.

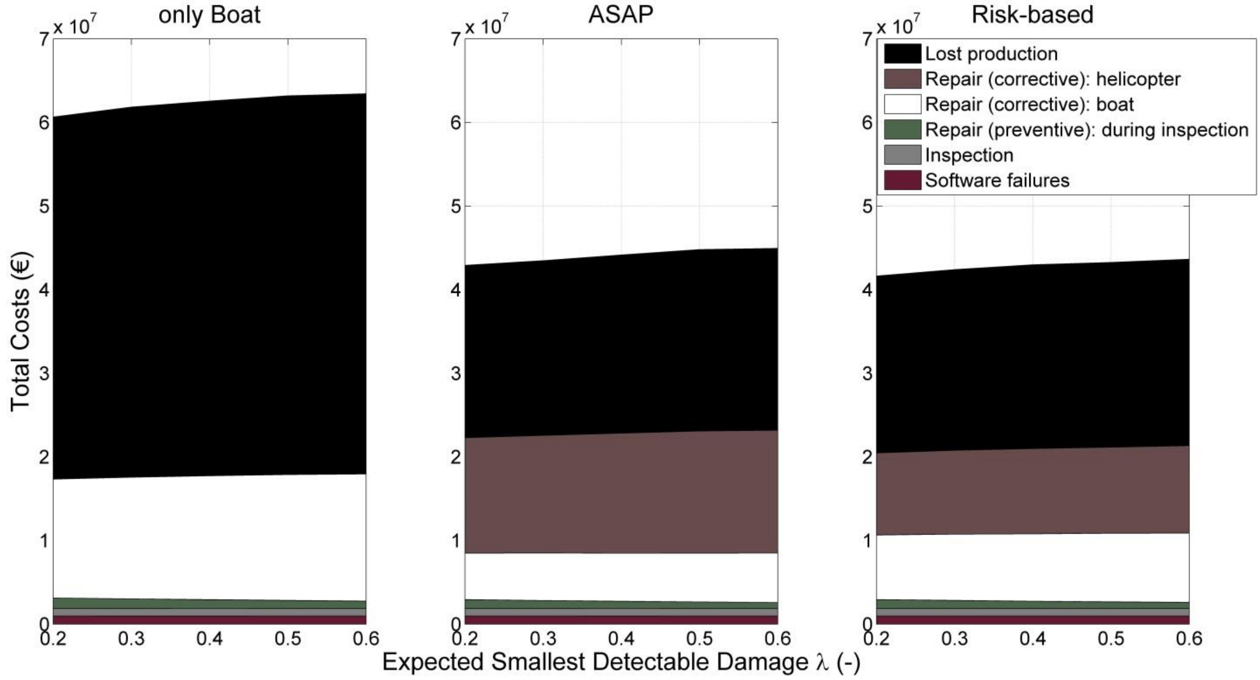

Figure 21 Influence of minimal detectable damage λ during inspections on the total expected costs during one lifetime for different transportation strategies following a preventive maintenance strategy with a regular inspection interval of one year (D_{REP}=0.3). 'only Boat': only boat used to access the wind turbines; 'ASAP': replacement/repair as soon as possible considering helicopter and boat for transportation; 'Risk-based': Minimization of overall costs considering boat and helicopter for transportation.

Table 16 and Table 17 show the relative impact on maintenance expenses per produced unit of electricity for different maintenance strategies (Table 16: regular annual inspection intervals; Table 17: inspections based on a condition monitoring system) and different minimal detectable damages. The results show that the maintenance expenses per produced unit of electricity can be reduced by 5% - 9% (annual inspections) or 4% - 8% (condition monitoring system) when reducing the minimal detectable damage from 0.6 to 0.2.

Table 16 Relative impact on maintenance expenses per produced KWh of electricity (Normalized by using the risk-based transportation strategy and a minimal detectable damage of 0.3) dependent on the minimal detectable damage λ following a preventive maintenance strategy annual inspection intervals. (D_{REP}=0.3).

Transportation strategy	Minimal detectable damage (λ)		
	0.2	**0.4**	**0.6**
Only boat	1.548	1.608	1.636
ASAP	0.994	1.026	1.046
Risk-based	0.965	1.000	1.018

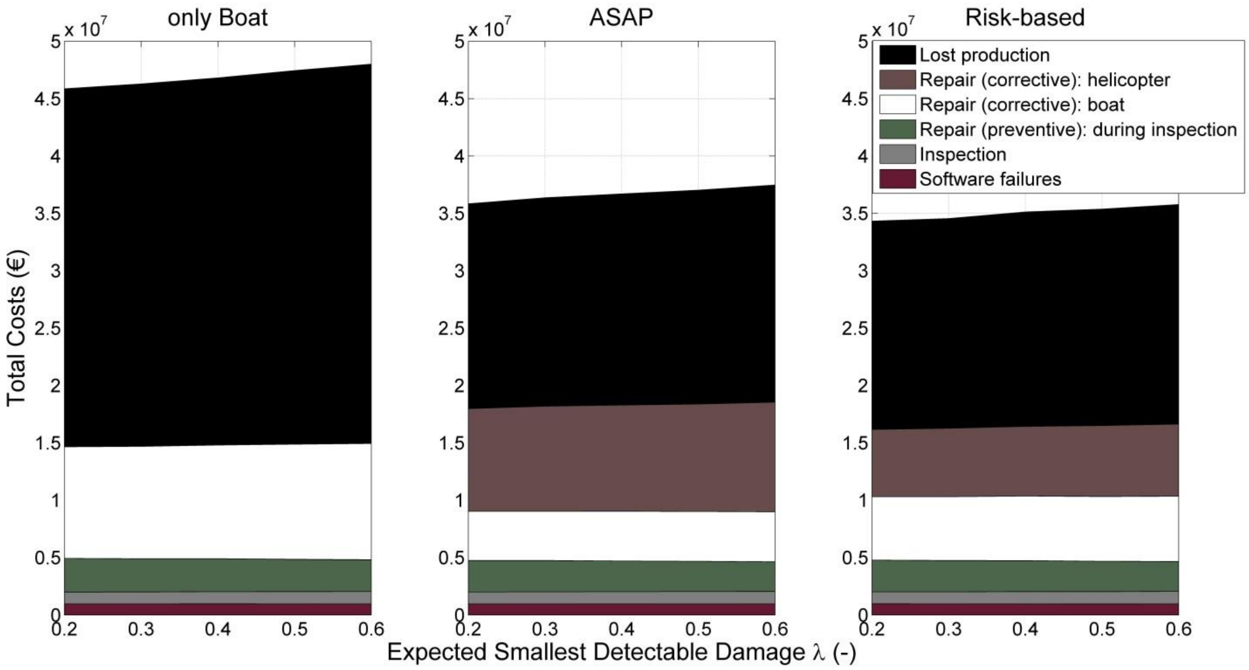

Figure 22 Influence of minimal detectable damage λ during inspections on the total expected costs during one lifetime for different transportation strategies following a preventive maintenance strategy with a condition monitoring system (D_{alarm}=0.8; η_{CM} =0.7). 'only Boat': only boat used to access the wind turbines; 'ASAP': replacement/repair as soon as possible considering helicopter and boat for transportation; 'Risk-based': Minimization of overall costs considering boat and helicopter for transportation.

Table 17 Relative impact on maintenance expenses per produced KWh of electricity (Normalized by using the risk-based transportation strategy and a minimal detectable damage of 0.3) dependent on the minimal detectable damage λ following a preventive maintenance strategy using a condition monitoring system. (D_{alarm}=0.8; η_{CM} =0.7).

Transportation strategy	Minimal detectable damage (λ)		
	0.2	**0.4**	**0.6**
Only boat	1.377	1.407	1.453
ASAP	1.020	1.046	1.068
Risk-based	0.976	1.000	1.020

5.4 Influence on Operational Range Ship and Helicopter

The sensitivity of the operational range of the boat and the helicopter is investigated by adding and subtracting 20% of the initial chosen maximum operational mean wind speed of 20 m/s and significant wave height of 1.5 meters. No additional costs due to larger operational ranges of the helicopter and the boat are considered in this case study.

Figure 23 shows the expected total maintenance costs for the considered wind farm for different maintenance strategies using the risk-based approach dependent on the maximum significant wave height the boat can be used to access the wind turbines. It can be seen from this figure that the larger the range of the significant wave height for operating the boat, the lower the expected total maintenance expenses. The reason for decreasing maintenance expenses is, on the one hand, due to shorter waiting times leading to lower amount of lost electricity and, on the other hand, some repairs can be performed by boat instead of using the more expensive helicopter for accessing the wind turbines. The total number of repairs is not affected by the operational range of the boat.

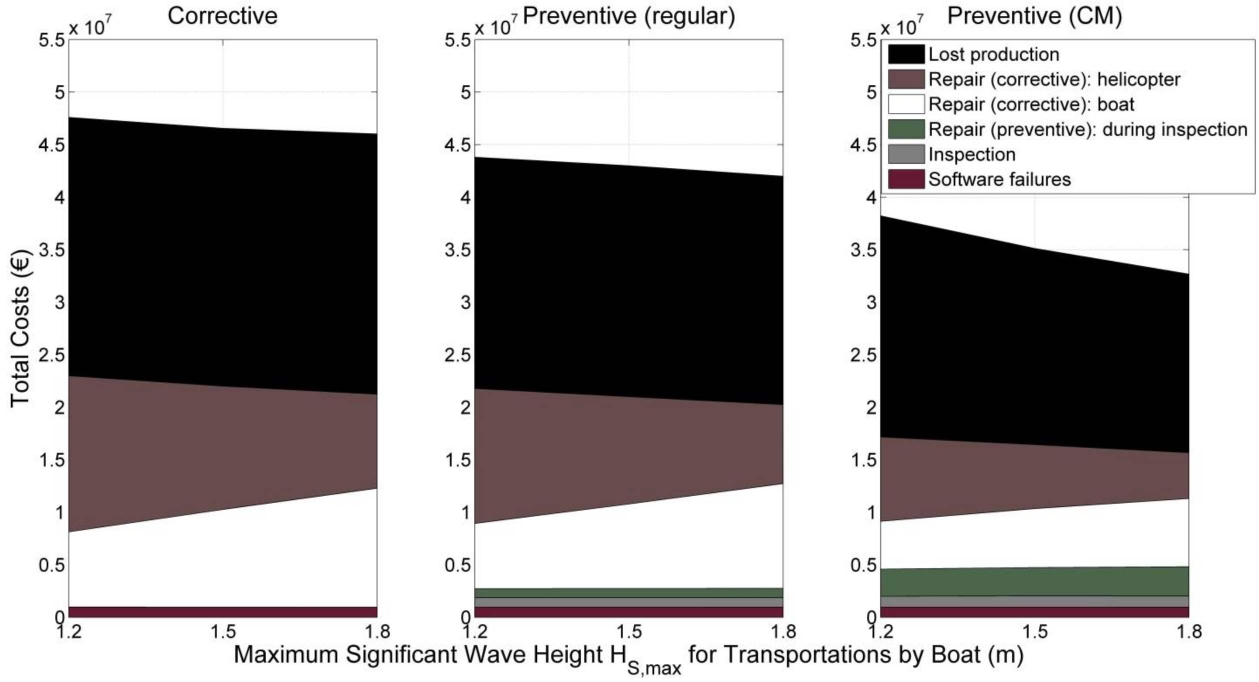

Figure 23 Influence of maximum significant wave height $H_{S,\,max}$ for transportations by boat on the total expected maintenance costs during one lifetime for different maintenance strategies following a risk-based transportation strategy. 'regular': Annual inspections; 'CM': Condition monitoring system. V_{max}=20 m/s.

Table 18 shows the relative impact on maintenance expenses per produced KWh of electricity for different transportation and maintenance strategies dependent on the maximum significant wave height with which the boat can reach the wind turbine. This table illustrates that the dominating impact on the maintenance costs per produced unit of electricity is the transportation strategy. For a given maintenance strategy, the maintenance expenses can be more than 2 times more expensive depending on the choice of transportation strategy. When increasing the maximum significant wave height the boat can access the wind turbines by 20%, the maintenance expenses per produced KWh will decrease between 1% and 17% for a given maintenance and transportation strategy.

Table 18 Relative impact on maintenance expenses per produced KWh of electricity (Normalized by using the risk-based transportation strategy and a maximum significant wave height for operation of 1.5 m) dependent on the maximum significant wave height where access to the wind turbine is possible for different transportation and maintenance strategies. CM: condition monitoring; regular: annual inspections.

Transportation strategy	Maintenance strategy								
	corrective			Preventive, regular			Preventive, CM		
	1.2 m	1.5 m	1.8 m	1.2 m	1.5 m	1.8 m	1.2 m	1.5 m	1.8 m
Only boat	2.911	2.246	1.877	2.568	1.997	1.653	1.623	1.407	1.347
ASAP	1.422	1.393	1.364	1.301	1.274	1.236	1.136	1.047	0.984
Risk-based	1.389	1.361	1.344	1.264	1.242	1.211	1.084	1.000	0.943

The influence of the maximum wind speed where the helicopter can operate on the total expected maintenance costs during one lifetime is shown in Figure 24 for different maintenance strategies following a risk-based transportation strategy. The expected maintenance costs can be decreased when increasing the operational range of the helicopter as mainly the costs representing the lost electricity is decreasing meaning that the waiting times given a certain broken component is decreased. The total amount of performed repairs depends on the maintenance strategy, but is not changed when adapting the operational range of the helicopter.

Table 19 presents the relative expenses per unit of produced electricity for different transportation and maintenance strategies. Increasing the maximum wind speed for operation by helicopter from 20 m/s to 24 m/s, a reduction potential in the range of 4% - 7% is possible to be reached when following a certain maintenance and transportation strategy.

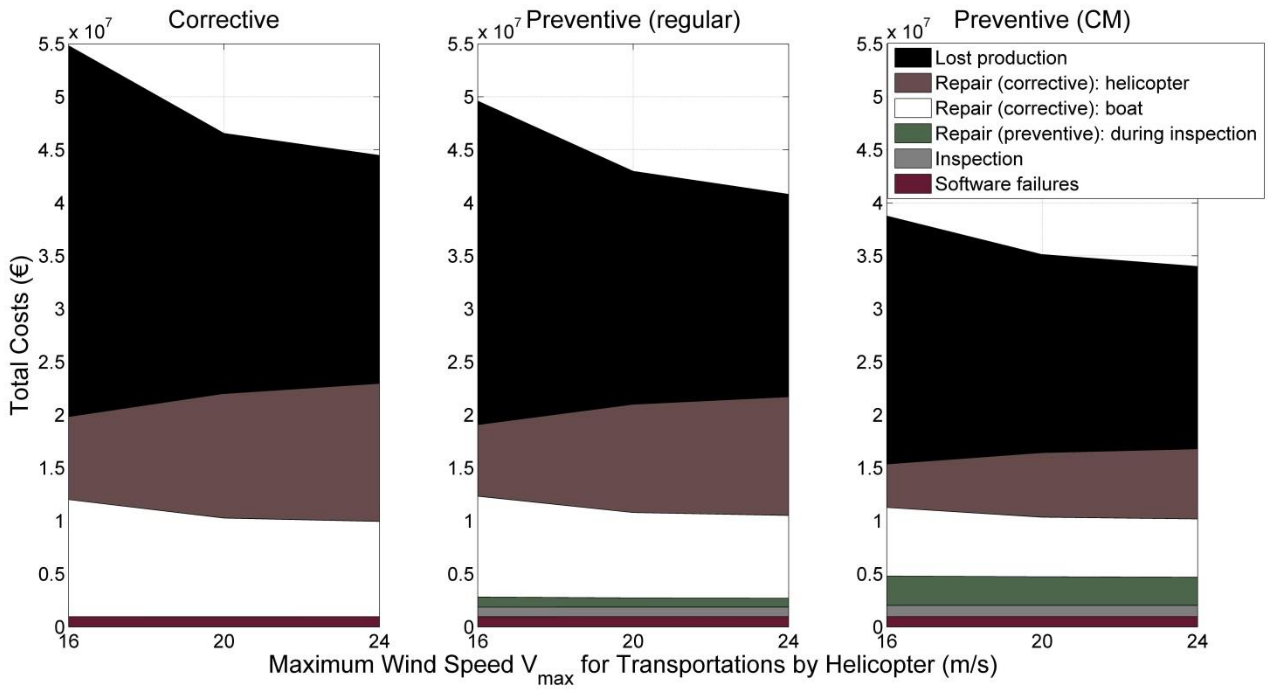

Figure 24 Influence of maximum wind speed V_{max} for transportations by helicopter on the total expected costs during one lifetime for different maintenance strategies following a risk-based transportation strategy. 'regular': Annual inspections; 'CM': Condition monitoring system. H_{Smax}=1.5 meters.

Table 19 Relative impact on maintenance expenses per produced KWh of electricity (Normalized by using the risk-based transportation strategy and a maximum mean wind speed of 20 m/s) dependent on the maximum wind speed where access to the wind turbine is possible for different transportation and maintenance strategies. CM: condition monitoring; regular: annual inspections.

Transportation strategy	Maintenance strategy								
	corrective			Preventive, regular			Preventive, CM		
	16 m/s	20 m/s	24 m/s	16 m/s	20 m/s	24 m/s	16 m/s	20 m/s	24 m/s
ASAP	1.712	1.393	1.295	1.531	1.274	1.191	1.174	1.047	1.006
Risk-based	1.672	1.361	1.280	1.485	1.242	1.167	1.126	1.000	0.964

In general, there is larger potential for decreasing the maintenance expenses when increasing the maximum significant wave height with which the boat can access the wind turbines by 20% instead of focusing on the maximum wind speed that the helicopter can handle.

5.5 Influence of Electricity Price

The electricity price is an important value for the operator of an offshore wind turbine farm as many countries have different subsidies like fixed feed-in-tariff or supplements to the actual market prize for electricity from offshore wind turbines, and it often decides whether or not a wind turbine farm is making profit or it cannot be realized. This example will consider a fixed feed-in tariff and its influence on the overall maintenance costs as well as include investigation of the relative impact on the maintenance expenses per produced unit of electricity.

Figure 25 shows the total expected maintenance expenses for different maintenance strategies using a risk-based transportation strategy dependent on the electricity price. The overall maintenance expenses increase when increasing the electricity price as the costs for lost electricity increase. Table 20 shows the relative impact on the total expected maintenance expenses per produced KWh of electricity for different maintenance and transportation strategies dependent on the electricity selling price. When increasing the electricity price, the income per produced KWh increases, but the relative maintenance expenses per produced unit of electricity decrease as the income increases more than the maintenance expenses. The electricity price has a large impact on the relative maintenance expenses per produced electricity and becomes more important than the impact of the transportation strategy.

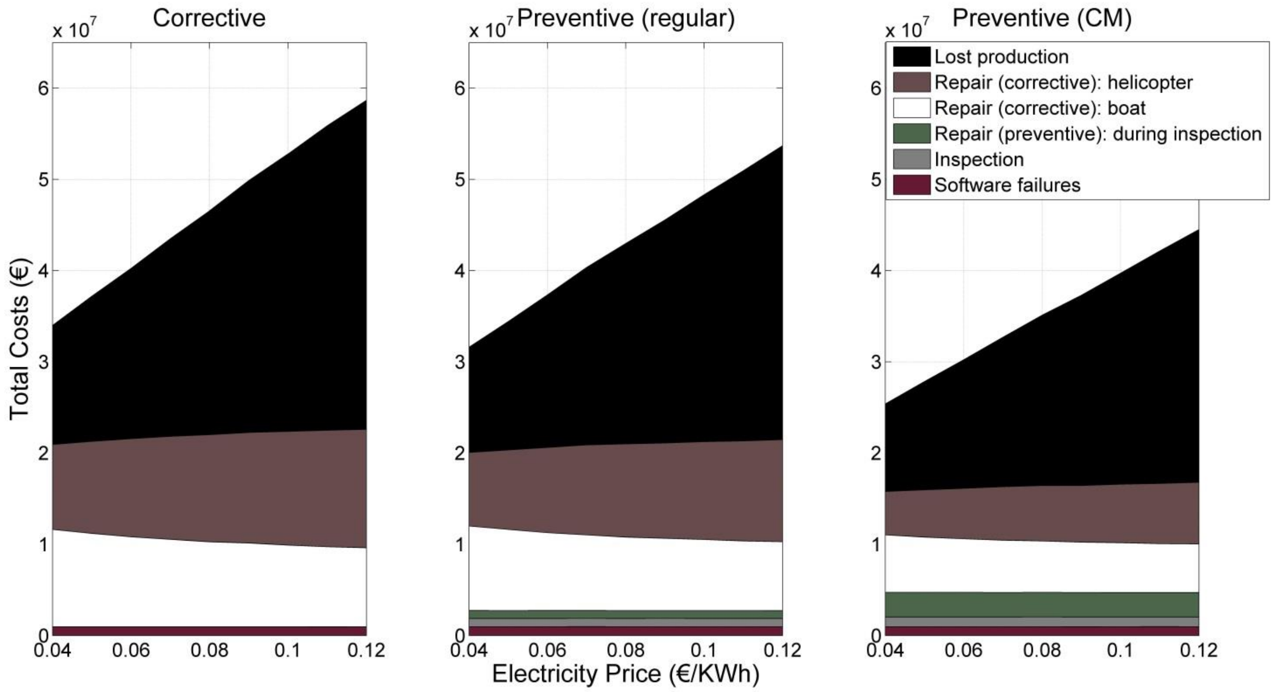

Figure 25 Influence of electricity price on the total expected maintenance costs during one lifetime for different maintenance strategies following a risk-based transportation strategy. 'regular': Annual inspections; 'CM': Condition monitoring system.

Table 20 Relative impact on maintenance expenses per produced KWh of electricity (Normalized by using the risk-based transportation strategy and an electricity price of 0.08 €/KWh) dependent on the electricity price for different transportation and maintenance strategies. CM: condition monitoring; regular: annual inspections.

Transportation strategy	Maintenance strategy								
	corrective			Preventive, regular			Preventive, CM		
	0.04 €/KWh	0.08 €/KWh	0.12 €/KWh	0.04 €/KWh	0.08 €/KWh	0.12 €/KWh	0.04 €/KWh	0.08 €/KWh	0.12 €/KWh
Only boat	2.839	2.245	2.060	2.563	1.997	1.795	1.852	1.407	1.260
ASAP	2.087	1.392	1.159	1.932	1.273	1.050	1.568	1.047	0.870
Risk-based	1.998	1.361	1.142	1.835	1.242	1.034	1.451	1.000	0.845

5.6 Influence of Real Rate of Interest

The interest rate is considered in this case study to calculate the discounted present value. Figure 26 shows the impact of the interest rate on the discounted present total maintenance expenses for different maintenance strategies using a risk-based transportation strategy. The impact of the interest rate on the maintenance expenses is high.

Table 21 shows the impact of the interest rate on the normalized maintenance expenses per produced unit of electricity. It can be seen that the maintenance expenses are nearly independent on the interest rate for a given transportation and maintenance strategy. This independence occurs because the maintenance costs as well as the income from producing electricity are discounted in this example with the same interest rate.

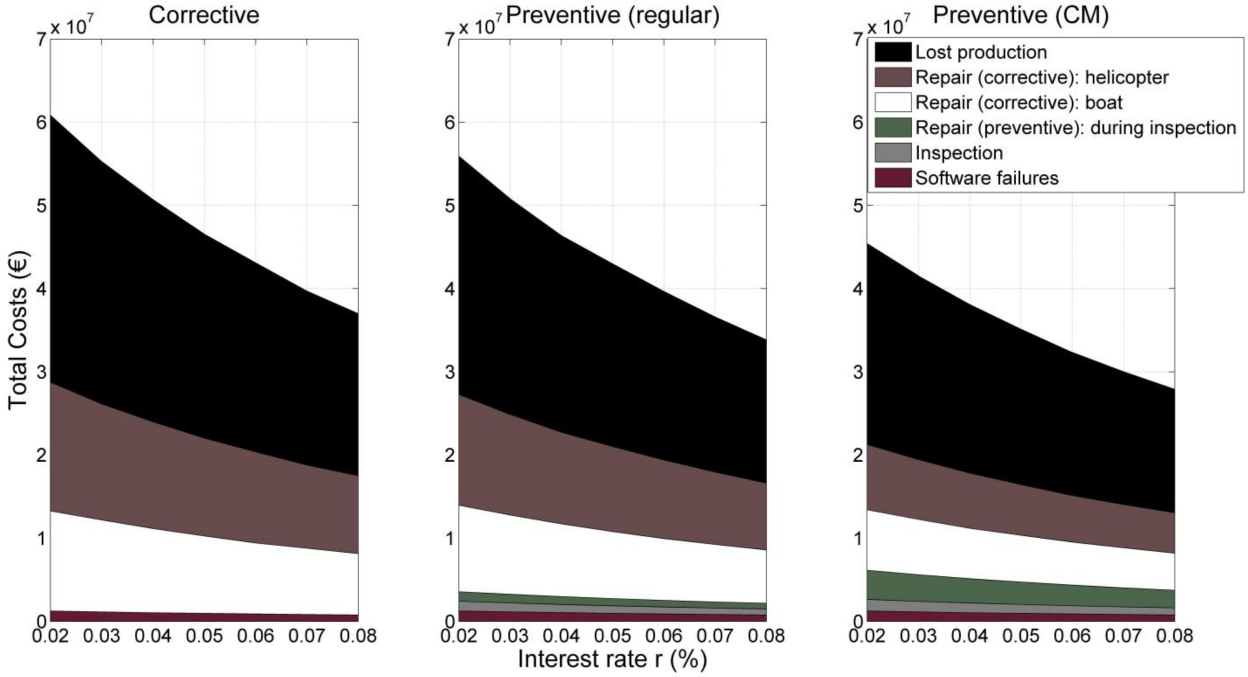

Figure 26 Influence of interest rate r for different maintenance strategies on the total expected maintenance costs during one lifetime following a risk-based transportation strategy. 'regular': Annual inspections; 'CM': Condition monitoring system.

Table 21 Relative impact on maintenance expenses per produced KWh of electricity (Normalized by using the risk-based transportation strategy and an interest rate of 5%) dependent on the considered interest rate for different transportation and maintenance strategies. CM: condition monitoring; regular: annual inspections.

Transportation strategy	**Maintenance strategy**								
	corrective			**Preventive, regular**			**Preventive, CM**		
	2%	**5%**	**8%**	**2%**	**5%**	**8%**	**2%**	**5%**	**8%**
Only boat	2.265	2.246	2.224	2.013	1.997	1.979	1.411	1.407	1.401
ASAP	1.401	1.392	1.380	1.281	1.273	1.263	1.049	1.046	1.037
Risk-based	1.374	1.361	1.352	1.247	1.242	1.225	1.001	1.000	0.9955

6 Conclusions

This article investigates the cost impact of different maintenance and transportation strategies for an offshore wind turbine farm consisting of 10 6 MW wind turbines. Corrective and preventive maintenance strategies using either fixed intervals for inspections or a condition monitoring system are considered. Transportation of technician and material needed to repair and replace broken components is either done by boat or by helicopter. Three different transportation cases are investigated. The first transportation strategy only considers access by boat, the second strategy focuses on short downtime of the device and the third transportation strategy considers a risk-based approach where the overall costs resulting from the downtime (lost electricity) as well as the costs for repair/replacement of the components are minimized. Failures of the main mechanical and electrical components of a wind turbine as well as software failures are considered.

The study results show that the main cost reduction potential is given by the transportation strategy, which defines which means of transportation (boat or helicopter) to be considered. Another important cost driver is the maintenance strategy. Optimizing the operation and maintenance schedule makes it possible to reduce the overall maintenance expenses from more than 30% of the levelized cost of energy (LCOE) when following a corrective maintenance strategy using boats to access the device to 15% of the LCOE when optimizing the maintenance actions by using a so-called risk-based approach and a condition monitoring system.

A parametric study is performed in order to assess the sensitivity of the different input parameters. The sensitivity analysis shows that the interest rate and the electricity price have large impact on the total maintenance costs. Therefore, it is fundamental to accurately predict the interest rate and the electricity price before doing maintenance optimizations. The total maintenance costs are increased by roughly 30% when decreasing the real rate of interest from 5% to 2%. When increasing the electricity price from 0.08 €/KWh to 0.12 €/KWh, the total expected maintenance expenses increase by 24% to 37%.

It can be concluded from the considered case that when following regular inspections (preventive maintenance), all detected damages should be immediately repaired independent on their severity whereas when using a condition monitoring system for indicating future failures of mechanical components, the small damages do not need to be repaired during inspections in order to reached lowest maintenance expenses. Furthermore, the inspection quality impacts the maintenance expenses. Detection of small damages makes it possible to decrease the total maintenance expenses. Decreasing the minimal detectable damage size by 50% enables to decrease the maintenance expenses per produced KWh by 2% - 5%.

Furthermore, increasing the operational range of ship leads to larger maintenance expense savings compared with increasing the operational range of the helicopter by the same percentage. Increasing the operational range of the boat by 20% decreases the maintenance expenses per produced KWh electricity by up to 17%. The lowest maintenance expenses result in this case study when following a preventive maintenance strategy with a condition monitoring system.

In general it needs to be mentioned that the resulting optimizations and cost reduction potentials depend on many factors like assumed costs, expected downtimes for the different failure types, the location (defining resource, accessibility and power production) of the wind turbine farm as well as the amount and type of considered wind turbines. Therefore, when considering different assumptions than used in this report, other results and conclusions might be obtained.

References

[1] Central Intelligence Agency (2013). *The CIA World Factbook 2013-14*. CIA, Washington, DC, USA. Online: http://www.odci.gov/cia/publications/factbook/

[2] Shell International BV (2008). *Shell energy scenarios to 2050*. Technical report. Online: www.shell.com/scenarios

[3] Esteban, M.D.; Diez, J.J; López, J.S.; Negro, V. (2011). Why offshore energy? *Renewable Energy*, 36, pp. 444-450. DOI: 10.1016/j.renene.2010.07.009

[4] GL Garrad Hassan (2013). Offshore wind - Operations & Maintenance opportunities in Scotland - An insight into opportunities for Scottish ports and the O&M chain. Scottish Enterprise and GL Garrad Hassan.

[5] Yang, W.; Tavner, P. J.; Crabtree, C. J.; Feng, Y.; Qiu, Y. (2012). Wind Turbine Condition Monitoring: Technical and Commercial Challenges. *Wind Energy*, 17, 673-693. DOI: 10.1002/we.1508

[6] Hofmann, M. (2011) A Review of Decision Support Models for Offshore Wind Farms with Emphasis on operation and Maintenance Strategies, Wind Engineering, Vol. 35, No. 1, 1-16.

[7] Ribrant, J.; Bertling, L. (2007). Survey of failures in wind power systems with focus on Swedish wind power plants during 1997-2005. *2007 IEEE Power Engineering Society General Meeting*, Tampa, FL, 2007, pp. 1-8. DOI: 10.1109/PES.2007.386112

[8] Spinato,F.; Tavner, P. J.; Bussel G. J. W. V.; Koutoulakos,E. (2009) Reliability of wind turbine subassemblies. *IET Renewable Power Generation*, vol. 3, no. 4, pp. 387-401, December 2009. DOI: 10.1049/iet-rpg.2008.0060

[9] Tavner, P.J.; Xiang, J.; Spinato, F. (2007) Reliability Analysis for Wind Turbines. *Wind Energy*, 10, 1-18. DOI: 10.1002/we.204

[10] Faulstich, S.; Hahn, B,; Tavner, J. P. (2011) Wind Turbine Downtime and its Importance for Offshore Deployment. *Wind Energy*, 14, 327-337. DOI: 10.1002/we.421

[11] Nielsen, J. J.; Sørensen, J. D. (2011). On Risk-Based Operation and Maintenance of Offshore Wind Turbine Components. *Reliability Engineering and System Safety*, *96*(1), 218-229. DOI: 10.1016/j.ress.2010.07.007

[12] Rangel-Ramírez, J. G.; Sørensen J. D. (2012). Risk-based Inspection Planning Optimisation of Offshore Wind Turbines, *Structure and Infrastructure Engineering*, 8:5,473-481, DOI: 10.1080/15732479.2010.539064

[13] Sørensen, J. D. (2009). Framework for Risk-based Planning of Operation and Maintenance for Offshore Wind Turbines. *Wind Energy*, *12*(5), 493-506. DOI: 10.1002/we.344

[14] Nielsen, J. S. (2013). *Risk-based operation and maintenance of offshore wind turbines*, PhD thesis, Aalborg University, Department of Civil Engineering.

[15] SAND2006-1100 (2006). *Wind Turbine Reliability: Understanding and Minimizing Wind Turbine Operation and Maintenance Costs*, Technical Report, Sandia National Laboratories.

[16] Ambühl, S.; Sørensen, J. D. (2017) *On Different Maintenance Strategies for Casted Components of Offshore Wind Turbines*. DCE Report No. 222, Aalborg University, Denmark.

[17] Ambühl, S.; Marquis, L.; Kofoed, J. P.; Sørensen, J. D. (2015). Operation and Maintenance Strategies for Wave Energy Converters. *Proc IMechE Part O: J Risk and Reliability*, 1-25. DOI: 10.1177/1748006X15577877

[18] Paris, P. C.; Erdogan, F. (1963). A critical analysis of crack propagation laws, *Journal of Basic Engineering,* 85, 528-533.

[19] Burton, T.; Jenkins, N.; Sharpe, D.; Bossanyi, E. (2011) *Wind Energy – Handbook*. John Wiley & Sons Ltd., 2nd Edition, United Kingdom.

[20] Straub, D. (2004). *Generic approaches to risk-based inspection planning for steel structures*, PhD thesis, Swiss Federal Institute of Technology, ETH Zürich.

[21] Sørensen, J.D.; Toft, H.S. (2010) Probabilistic Design of Wind Turbines. *Energies*, 3, pp- 241-257. DOI: 10.3390/en3020241

[22] Sørensen, J. D.; Faber, M. H.; Rackwitz, R.; Thoft-Christensen, P. (1991). Modelling in optimal inspection and repair, I Proceedings of the 10th International Conference on Ocean, Offshore and Arctic Engineering (OMAE). Stavanger, Norway, 1991, Vol 2, pp. 281-288.

[23] McMillan, D.; Ault, G.W. (2007) Quantification of Condition Monitoring Benefit for Offshore Wind Turbines. Wind Engineering, 31(4), 2007, pp 267-285. DOI: 10.1260/030952407783123060

[24] Wilkinson, M.; Harman, K.; Hendriks, B.; Spinato, F.; van Delft, T. (2010). *Methodology and results of the ReliaWind reliability field study*, Scientific Track Proceedings, European Wind Energy Conference 2010, Warsaw, Poland.

[25] van Brussel, J. W.; Zaaijer , M. B. (2003). *Estimation of turbine reliability figures within the DOWEC project,* Technical report, DOWEC, 2003.

[26] Ribrant, J.; Bertling, L. M. (2007). Survey of failures in wind power systems with focus on Swedish wind power plants during 1997 – 2005, *IEEE Transactions on Energy Conversion*, vol 22 (1), pp. 167 – 173.

[27] IEA Wind Task 33 (2012). *Reliability data standardization of data collection for wind turbine reliability and operation & maintenance analyses.* International Energy Agency.

[28] OREDA (2009), *Offshore Reliability Data Handbook*. SINTEF and OREDA participants.
[29] IEE Std 500-1984 (1984). *Reliability data for pumps and drivers, valve actuators and valves*. New York: Institute of Electrical and Electronics Engineers (IEEE).
[30] MIL-HDBK-271F (1991). *Reliability prediction of electronic equipment.* Washington: Department of Defense, Military Standardization Handbook.
[31] Ambühl S.; Sørensen, J. D. (2017) Sensitivity of Risk-Based Maintenance Planning of Offshore Wind Turbine Farms. *Energies*. 2017; 10(4):505. DOI: 10.3390/en10040505
[32] Green, R.; Vasilakos, N. (2010). The economics of offshore wind. *Energy Policy*, 39, pp. 496-502. DOI: 10.1016/j.enpol.2010.10.011
[33] Maples, B.; Saur,G. M.; Hand, R.; van de Pietermen, R.; Obdam, T. (2013*). Installation, Operation and Maintenance Strategies to reduce the Cost of Offshore Wind Energy*, Technical report NREL/TP-5000-57403, July 2013, National Renewable Energy Laboratory (NREL), Denver.
[34] Carroll, J.; McDonald, A.; McMillian, D. (2015). Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines. *Wind Energy*, 19, 1107-1119. DOI: 10.1002/we.1887
[35] Dalgic, Y., Lazakis, I.; Turan, O. (2015). Investigation of Optimum Crew Transfer Vessel Fleet for Offshore Wind Farm Maintenance Operations. *Wind Engineering*, 2015, Volume 39, No. 1, pp. 31-52. DOI: 10.1260/0309-524X.39.1.31
[36] Poore, R.; C. Walford (2008). *Development of an Operations and Maintenance Cost Model to Identify Cost of Energy Savings for Low Wind Speed Turbines*. Subcontract Report, NREL, NREL/SR-500-40581, June 2008.
[37] Fingersh; L.; Hand, M.; Laxson, A. (2006). *Wind Turbine Design Cost and Scaling*, Technical report, NREL, No. NREL/TP-500-40566, December 2006.
[38] Rademakers, L. W. M. M.; Braam, H. (2002). *O&M aspects of the 500 MW offshore wind farm at NL7*, ECN, Technical report, DOWEC-F1W2-LR-02-080/0.
[39] van Bussel, G. J. W.; Schöntag, C. (1997). Operation and Maintenance Aspects of Large Offshore Wind farms, I Proceedings of the European Wind Energy Conference (EWEC) 1997. Dublin, Ireland, pp. 272-279.
[40] O'Connor, M.; Lewis, T.; Dalton, G. (2013). Weather window analysis of Irish west coast wave data with relevance to operations & maintenance of marine renewables, *Renewable Energy*, Volume 52, pp. 57-66. DOI: 10.1016/j.renene.2012.10.021
[41] Rademakers, L. W. M. M.; Braam, H.; Zaaijer, M. B.; van Bussel, G. J. W. (2003). Assessment and optimisation of operation and maintenance of offshore wind turbines. I Proceedings of the European Wind Energy Conference (EWEC) 2003. Madrid, Spain.
[42] Dinwoodie, I.; Endrerud, O.-E. V.; Hofmann, M.; Martin, R.; Sperstad, I. B. (2015). Reference Cases for Verification of Operation and Maintenance Simulation Models for Offshore Wind Farms, *Wind Engineering*, Volume 39, No. 1, pp. 1-14. DOI: 10.1260/0309-524X.39.1.1

ISSN 1901-726X
DCE Technical Report No. 227