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Operation and maintenance strategies for wave energy converters

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Abstract

Inspection and maintenance costs are a significant contributor to the cost of energy for wave energy converters. There are different operation and maintenance strategies for wave energy converters. Maintenance can be performed after failure (corrective) or before a breakdown (preventive) occurs. Furthermore, a helicopter and boats can be used to transport equipment and personnel to the device, or the whole device can be towed to a harbour for operation and maintenance actions. This article describes, among others, a risk-based inspection and maintenance planning approach where the overall repair costs including costs due to lost electricity production are minimized. The risk-based approach is compared with an approach where only boats are used and another approach where the target is to minimize the downtime of the device. This article presents a dynamic approach for total operation and maintenance costs estimations for wave energy converter applications including real weather data and damage accumulation. Furthermore, uncertainties related with costs, structural damage accumulation, inspection accuracy and different maintenance strategies can be included. This article contains a case study where different maintenance strategies are applied for the Wavestar device, and the influences of the different parameters, for example, failure rate, inspection quality and inspection interval, are evaluated for the overall costs and the number of repairs needed during its lifetime.

Keywords

Costs, damage modelling, inspections, operation and maintenance, wave energy converter

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Introduction

The cost of energy (COE) from wave energy converters (WECs) depends on the capital costs, the performance of the device (amount of produced electricity) and operation and maintenance (O&M) costs. In Carbon Trust,[1] the O&M costs reach 57% of the operational costs (operational expenditure (OPEX)) for a specific WEC.

Nowadays, different WECs are on the prototype level[2,3] and are being developed further to reach the commercial stage. The prototype level is needed to demonstrate working principles and proof efficiency as well as survivability. At the prototype level, O&M strategies are of minor focus. But when deploying commercial devices, which often are placed further offshore, O&M becomes an important cost driver for COE for WECs. Therefore, more focus on O&M is necessary in the WEC sector in the near future.

Maintenance actions and O&M costs for offshore structures strongly depend on the weather conditions which define the accessibility of the devices. Boats and helicopters are available for transporting crew and their equipment. Helicopters are faster but are also more expensive and bound to the wind speed, whereas boats are cheaper but are slower and mainly limited by the wave height. Also, limited availability of maintenance equipment may drive the O&M costs. The total resulting O&M costs can be minimized when considering risk-based O&M strategies.[4]

For WECs, cost optimal O&M strategies are important due to the fact that WECs are placed in locations with harsh environmental conditions, and the WEC might not be accessible for up to several weeks (mainly in winter time). This can have a large impact on the total levelized costs of energy (LCOE). Different studies[5,6] on weather windows analyses are performed in

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order to quantify the levels of access to marine renewables for O&M actions.

From the weather data, a methodology for O&M cost estimations can be developed as done for offshore wind turbines,[7,8] where weather data and failures of components are directly included and modelled. WEC-specific failure rates of components can be estimated directly from experiments[9] or can be adapted from failure rate data from nearby industries based on so-called adjustment factors[10] or by the use of Bayesian statistics.[11]

This article presents a methodology for WEC application which incorporates weather data and failure formation of the considered components (damage accumulation) directly in a dynamic simulation of O&M actions. The simulation tool simulates the whole lifetime. This article shows different O&M strategies applicable to WECs, where the availability and weather windows are considered. An example with focus on the Wavestar wave energy device, which is placed near Hanstholm at the Danish North Sea coast, shows how the methodology can be applied to existing concepts. Furthermore, a parametric study is performed in order to assess the influence of different parameters on the overall maintenance cost and the number of needed repairs during the lifetime.

This article is organized in different sections, where section 'Maintenance strategies' introduces different maintenance strategies applicable to WECs. Section 'Optimal planning of inspections and maintenance' focuses on general information about cost considerations for O&M considerations and time-dependent failure formation based on damage accumulation. Section 'Example – Wavestar device' presents the considered example including case-specific input variables which are different for other devices and locations. Section 'Results and discussion' presents the results of the example and the sensitivity of different important model input parameters. The conclusion of the work is given in section 'Conclusion'.

Maintenance strategies

When developing maintenance strategies for WECs, their different possible locations need to be considered. WECs can be shore-based, fixed offshore and floating offshore structures. Floating structures can be disconnected, towed to a harbour for maintenance actions and returned afterwards, or the repair actions can be performed directly on-site. Both strategies are dependent on the weather conditions. Repairs on fixed offshore WECs need to be done on-site. In this case, experiences and approaches from offshore wind turbines can be applied. Shore-based WECs are accessible from shore, and maintenance strategies are less dependent on weather conditions. More information about downtime influences of different WEC concepts can be found in Wolfram.[12] Figure 1 shows possible sources for on-site repairs which may impact the downtime (mean time to recover (MTTR)) and the repair costs given faults in the system. In order to reduce MTTR, spare components could be stored at the harbour or

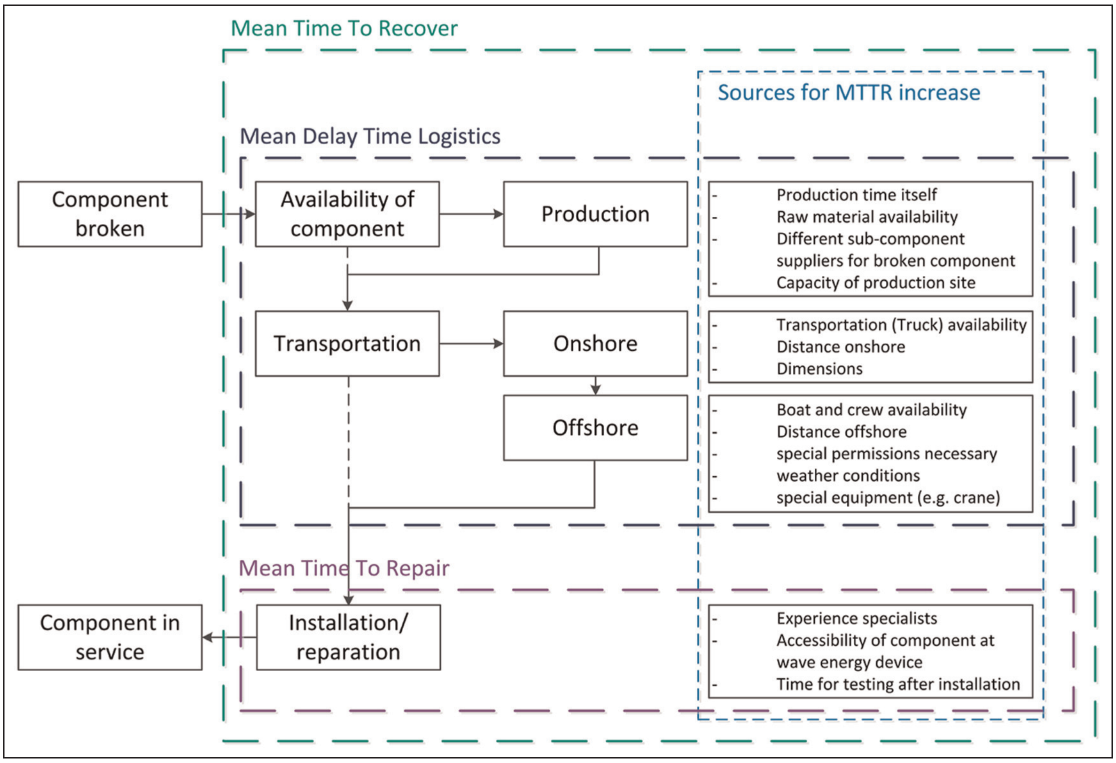

Figure 1. Sources which may affect the downtime of a fixed offshore WEC when a component has to be replaced.[13]

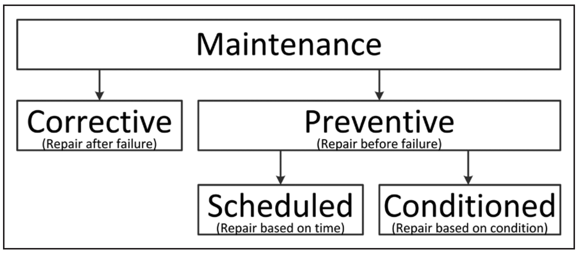

Figure 2. Different maintenance (repair) strategies.[7]

stored on the device offshore. In this case, the delivery time of the component can be reduced.

In general, multiple strategies to maintain systems exist (see Figure 2). 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 may, on the other hand, increase the number of performed maintenances or repairs.

Scheduled maintenance is based on a certain expected lifetime and could include, for example, lubrication, changing filters, check cooling systems or tightening bolts. Conditioned maintenance includes monitoring of, for example, corrosion or wear-out, and is based on measuring damage. In addition, damage and forthcoming failure of a component could be indicated during inspections, for example, by the following:

- Increased or unusual noise level;
- Oil condition (e.g. pollution);
- Detection of cracks and deformation;
- Vibrations;
- Oil leakages;
- Functionality of control system;
- Functionality of safety system (e.g. movement into storm protection mode).

Diagnosis of one of the above-mentioned identifications could necessitate a more detailed damage analysis of an affected component. Furthermore, remote condition monitoring (CM) and structural health monitoring (SHM) techniques could be used to detect the health condition of the component and to define conditional maintenance and find the events leading up to a fault due to its buffer history capability.[14]

When damage is found before a corrective replacement, the device is still able to produce electricity but not during or just partly during its replacement or repair action on-site. Furthermore, when taking components from nearby industries (e.g. wind turbines or oil and gas platforms), the influence of possible different environmental conditions (e.g. salinity, humidity or load characteristics) needs to be accounted for. The different conditions may lead to different inspection conditions due to, for example, different corrosion rates. The focus during inspections and for monitoring by sensors should be on the components located at key positions, custom-made components and where new technologies with no or limited experience are used. More information when using new technology and the same technology for different applications can be found in DNV-RP-A203.[15]

When applying preventive maintenance strategies, the number of replaced components during a lifetime is higher compared with corrective maintenance strategies due to the fact that the component is sometimes replaced before failure occurs. Corrective maintenance is the simplest strategy but may lead to large costs due to cascaded failure effects. This cascade effect may damage the main component and lead to large repair or replacement costs. Therefore, the costs for corrective maintenance are associated with larger uncertainties than preventive maintenance. Furthermore, component failures and loss of electricity production may often happen during storm conditions where the device is not accessible.

When a component failure appears, there are costs involved in replacing the component, and the time in which the machine is out of use due to the component failure influences the income because of the loss of harvested energy. A risk-based O&M approach will consider both repair costs and lost income from no electricity production in order to minimize the overall cost.

O&M actions on a WEC near-shore or offshore can be performed onshore or offshore. For onshore actions, which are mainly of importance for floating WECs, the device needs to be towed to a harbour where the maintenance actions can be performed. This maintenance strategy is limited by the operational range of the tug boat and potential sea-state limitations for disconnecting and reconnecting the WEC from the device's mooring system to the tug boat.

When focusing on offshore maintenance actions, one can take a boat (e.g. so-called crew transfer vessels) or a helicopter to access the device. In order to decide how transportation should be performed, different strategies can be used. The following strategies shown in a flow chart in Figure 3 can be used:

- Only use boat (helicopter not available, for example, boat owned by the operator);
- Repair or replacement as soon as possible (ASAP) in order to minimize downtime;
- 'Risk-based' strategy where the overall costs are minimized for this specific replacement using perfect weather forecast.

For the ASAP strategy, the use of boats is prioritized because as shown in the offshore wind sector, the WEC (farm) operators will most probably own their own vessels and will, therefore, prioritize the use of their own boats instead of paying for hiring a

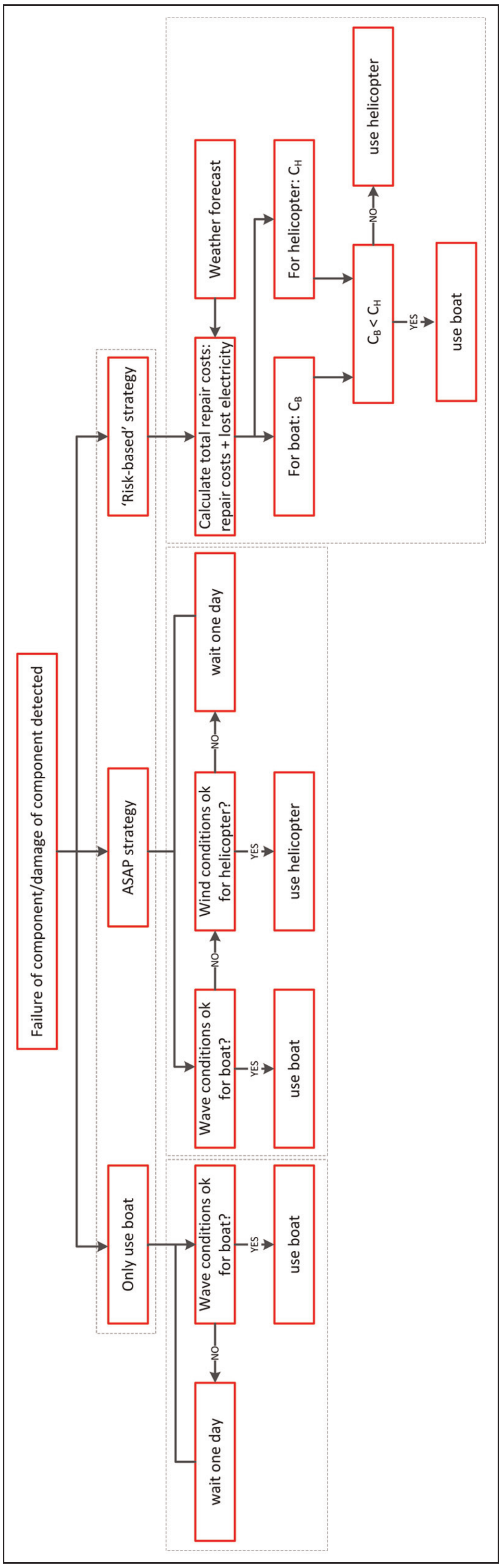

Figure 3. Three different transport strategies when performing maintenance actions offshore – 'Only use boat': no helicopter used, 'ASAP strategy': as soon as possible strategy and 'Risk-based' strategy: minimization of overall repair or replacement costs.

helicopter. Helicopters are often chartered on hourly basis, whereas O&M workboats are rented on a daily basis. The operational costs for helicopters and O&M workboats depend, among others, on the following:

- Distance from shore;
- Transfer speed of helicopter and vessel;
- Fuel consumption and fuel price;
- Chartered from subcontractor or helicopter or workboat operator's property.

Boats and helicopters for O&M may be leased from specialist marine and aviation contractors on a long-term basis. For large distances from shore, an offshore accommodation could be used in order to decrease daily transfer time. The different transportation technologies may also lead to additional investment costs. For access by helicopter, a landing platform or a place where the technicians can be roped down and a weather station and additional navigation installations are necessary. When using the boat, technicians need to have an installation (e.g. ladder or crane), where they can access the device. The technicians may need additional training for both transportation strategies. Furthermore, there may be different insurance rates due to different possible effects of helicopter or boat collisions with the device.

Before starting to find the optimal maintenance strategy, an analysis of the working principle and the considered or involved mechanical or electrical components and the control system needs to be performed in order to find the high-risk failure modes. A procedure outlined in Figure 4 can be followed. High-risk failure modes are of importance for defining the inspection plan and estimating the overall costs. Therefore, the working principle of the systems needs to be analysed by either a failure mode and effect analysis (FMEA) or a fault tree analysis (FTA). In the next step, the failure modes and combinations of component failure modes

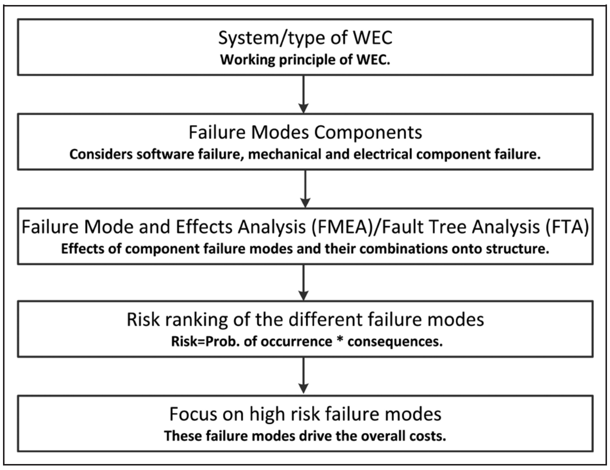

Figure 4. Flow chart of how to find and define the most important failure modes of a certain WEC concept.

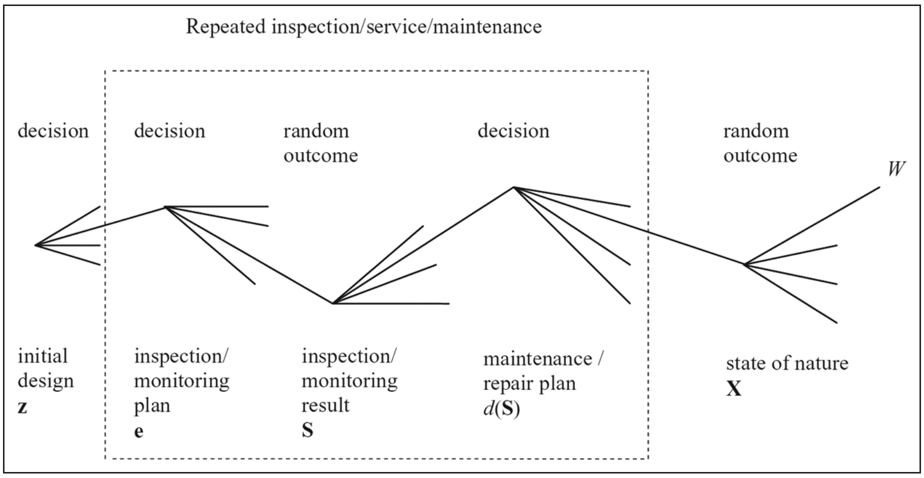

Figure 5. Decision tree for optimal planning of inspections and maintenance.[4]

leading to the most expensive failures or high occurrence rates should be detected based on risk ranking. How risk ranking can be performed based on a risk matrix is shown in DNV-RP-A203.[15]

Thies et al.[16] show an example of important failure modes and their failure rates for a generic hydraulic WEC. An FMEA for the Wavestar WEC prototype is performed in Ambühl et al.[13] Furthermore, it should be accounted for that partial failure of the device may also occur, for example, one floater of the Wavestar prototype, which consists of two floaters, can fail, and the other floater still produces electricity.

Optimal planning of inspections and maintenance

Optimal planning of inspection and maintenance actions may be based on the application of risk-based methods where information or experience from the past, inspections and monitoring results are taken into account. The theoretical background is described in Sørensen[4] for offshore wind turbines and can be transferred directly to WECs.

Figure 5 shows a typical decision tree for optimal planning. Risk-based inspection (RBI) and maintenance planning depends on the initial design decisions, z, of the device. The initial design may include, for example, the design lifetime of the different components and whether the inspections are done offshore or the device is tugged to a harbour for inspections and maintenance. The inspection or 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 or monitoring results S. Based on the inspection or monitoring results, a maintenance or repair plan, $d(S)$, is developed. Together with the realization of uncertain parameters, X, a certain total gain minus costs, W, is calculated. Realizations of uncertain parameters include, for example, wind and wave climate and model uncertainties.

The application of risk-based decision models for maintenance considerations requires that the condition of the different considered components can be described, for example, with damage models where the uncertain parameters X are included. Another way to decrease maintenance expenses is based on reducing the number of installed components and, therefore, lowering the expected time, in which the device is out of order. Furthermore, the O&M expenses per produced kilowatt hour may decrease when increasing the installed capacity because many tasks associated with O&M of a single machine are the same, irrespective of its capacity. The strategy of increasing the number of installed megawatt per device in order to decrease O&M expenses per produced kilowatt hour is followed by the offshore wind turbine industry. When focusing on a WEC farm, the maintenance strategy should be optimized by considering the whole farm and not just a single device.

Cost model

Which O&M strategy should be chosen is driven by the total costs, W, which should be minimized in order to maximize the total income minus the total cost, W

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

where B is the expected benefit; C_I are the initial (investment) costs; C_{IN} are the expected service and inspection costs (man-hours, special tools, etc.); C_{REP} are the repair and maintenance costs; C_F are the expected failure costs; z are the design parameters; e are the inspection parameters; and d is the decision rule for repairs

When a WEC farm is considered, the total income minus costs, W, should be maximized for the whole farm and not a single WEC. The discounted present values, C_0, are always important in cost considerations

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

where C is the real cost, T is the time in years when the cost occurs and r is the annual real rate of interest. In order to be able to use a decision model, which defines when and how inspections should be performed, an additional model leading to the parameter used as decision parameter for the decision model should be developed. In this case, the damage growth with time is used as damage model and described in the next section.

Damage model

A damage model can be used to model the time-dependent damage of a component or structural part. Furthermore, the damage model should be able to model the influences from inspections (e.g. reparation of detected crack). The damage model presented here is used in the example shown in section 'Example – Wavestar device'. Also other damage accumulation models can be included equivalently in the presented methodology for total repair cost estimations. 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 or repaired.

For modelling inspections, the damage needs to be measurable. The general damage accumulation for components is assumed to be described by an initial value problem with the following differential equation[7]

$$\frac{dD}{dt} = C \cdot F^{m_1} \cdot D^{m_2} \tag{3}$$

where dD/dt is the rate of damage growth, F is a measure for the load and D is the damage size. The parameters C, m_1 and m_2 are model parameters. This damage accumulation model uses an exponential damage model, which can be used, for example, for fatigue driven damages where the differential equation used is based on Paris Law.[17] The damage accumulation rate is given as

$$\frac{dD}{dt} = \frac{dN}{dt} \cdot C \cdot \Delta K^m \tag{4}$$

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

$$\Delta K = \beta \cdot \Delta s \cdot \sqrt{\pi D} \tag{5}$$

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

$$\Delta s = H_S \cdot x_S \tag{6}$$

where x_S is the proportionality factor which also models the uncertainty about estimation of Δs. It is assumed that the mean zero-crossing wave period, T_Z, drives the number of cycles

$$\frac{dN}{dt} = \frac{3600}{T_Z} \tag{7}$$

The damage, D, is calculated and summed up over time with time-steps equal to (Euler method)

$$D_{t+\Delta t} = D_t + \frac{dD}{dt} \cdot \Delta t \tag{8}$$

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.

When inspections are performed, the damage may not be detected. The probability that damages of a certain size will be detected depending, among others, on the technique used to detect the damage[18] and 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. Components such as bearings or weldings can be inspected using so-called non-destructive testing (NDT) techniques such as magnetic particle inspection (MPI) or ultrasonic and eddy current techniques. The uncertainty whether damages (cracks) are detected is often modelled using a probability of detection (PoD) curve. One possibility of defining such a curve is using a one-dimensional exponential threshold model[19]

$$\mathrm{PoD}(D) = P_0\left(1 - \exp\left(-\frac{D}{\lambda}\right)\right) \tag{9}$$

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

A replacement decision criteria (the decision rule $d(S)$ in Figure 5) could be that replacement will take place when a detected damage, D_{ins}, is larger than a certain threshold D_{rep}. In case D_{rep} is set equal to 0, all detected damages are repaired. The repair decision is equal to

$$D_{ins} \geqslant D_{rep} \tag{10}$$

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 in Nielsen et al.[8] for RBI planning for offshore wind turbines. Also, information from preventive or corrective maintenance and monitoring results will

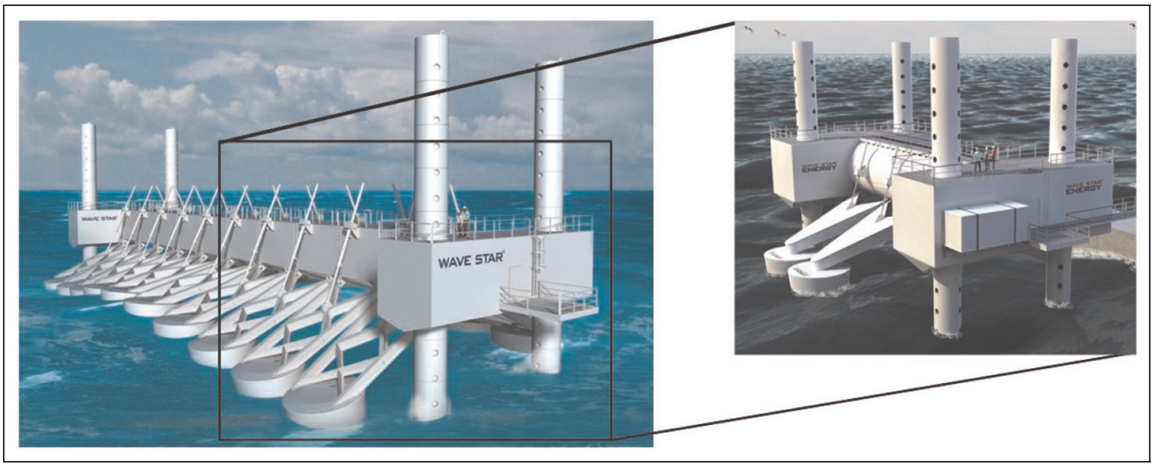

Figure 6. Planned commercial converter with 20 floats (left) and test section at Hanstholm (Denmark) with two floaters (right).[2]

be used for inspection planning. This RBI procedure is also considered in the oil and gas industry.[20]

There are further uncertainties which should be addressed when dealing with PoD curves:

- Possibility of false detection;
- Uncertainty of measurement devices including measurement errors of the equipment and the used technology and human errors. The measurement uncertainty includes the ability and sensitivity of detecting cracks or defects or damages and interpreting the detected cracks or defects or damages.

A probability of false indication (PFI) represents the probability of obtaining damage where no damage is actually present. The values for PoD and PFI can be combined with the probability of inspection (PoI), which defines whether or not preventive replacement is performed. The PoI can be written as

$$\mathrm{PoI}(D) = \mathrm{PoD}(D) + (1 - \mathrm{PoD}(D))\mathrm{PFI} \tag{11}$$

where D is the damage (crack size). Error in measurements of the crack size (damage) itself can be formulated by a normal distributed[21] variable ε_m. The resulting damage from an inspection (D_{ins}) can be estimated in the following way

$$D_{ins} = D + \varepsilon_m \tag{12}$$

The measurement uncertainty needs to be estimated based on measurements and depends on the considered technology and the competence of the technician detecting the crack. 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.

It has to be mentioned that no damage accumulation can be formulated for electrical components and the control system. For these components, scheduled preventive or corrective maintenance can be used instead.

Example – Wavestar device

This section investigates the different maintenance strategies for the Wavestar wave energy device. A Wavestar prototype is located near Hanstholm (Denmark). This device has been feeding electricity into the grid between January 2010 and September 2013. It consists of two floaters and is actually a test section of a planned commercial converter with 20 floaters (see Figure 6), which is considered in this example. The device is secured at the sea bottom with steel piles. Moving the device to a harbour for maintenance actions (onshore O&M strategy) is costly for this device. Therefore, only so-called offshore O&M strategies are considered in this example. The lifetime of the device is expected to be 20 years, and the location is assumed to be circa 30 km off the coast. Furthermore, the helipad is assumed to be located in the harbour such that the distance the helicopter and the boat need to conquer in order to reach the Wavestar device is the same.

The approach to estimate the total costs for O&M activities presented in this article considers among other uncertainties related with modelling failure of the considered components (damage accumulation), the time required to repair or replace the broken component and the quality of inspections (represented by the PoD curve).

Failures of large structural parts, such as the arm or one pile, which need a large transportation vessel and jack-up or crane vessel, are not considered here. The focus in this example is on failure of system components such as generator or hydraulic motor and valves.

The electricity feed-in tariff for this example is chosen to be 0.12 €/KWh, which is equal to the feed-in tariff for electricity in the long term produced by WECs in Denmark.[22]

It needs to be mentioned that the purpose of this article is to show different O&M technologies which can be applied to WECs based on a generic example. If values other than the ones presented here are used, other results will be obtained. For each condition, 1000 lifetimes are simulated, and the following figures show the average values. Figure 7 shows a flow chart for preventive maintenance, which shows how the methodology is implemented and simulations are performed. If failure of more than one component occurs at the same time, the transportation costs can be shared.

Weather data

Weather data are available for the period 1979–2009 with 1-h values of significant wave height (H_S), mean zero-crossing wave period (T_Z) and wind speed (V). In order to make the weather a pseudo-random variable, the available weather data are bootstrapped based on yearly steps. Bootstrapping enables resampling of a data set. In this case, a data set L consists of M annual sets including wind and wave data from simulations or measurements

$$L = [X_1, \ldots, X_M] \quad (13)$$

where X_i represents an annual data set of wave and wind conditions. A wave and wind data set ($\hat{L}$) for a lifetime of N years can be generated from

$$\hat{L} = \left[\hat{X}_1, \ldots, \hat{X}_N\right] \quad (14)$$

where $\hat{X}_i$ of a certain year i is equal to a random data set X from data set L. The data $\hat{L}$ in equation (14) can be repeated, and different combinations of weather conditions over the lifetime are generated.

In order to get an idea about the wave characteristics at the considered location, Table 1 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, the electricity production (see section 'Power matrix') and the calculation of the accumulated damage (see section 'Damage model').

Power matrix

The power of a WEC is often dependent on the significant wave height and the peak, mean zero-crossing or energy wave period. Table 2 illustrates the produced electricity scatter diagram. The data are taken from Kramer[23] using reactive control strategies. A conversion efficiency from harvested power to electricity of 70%[24] is assumed.

In significant wave heights higher than 3.25 m, the floaters are taken out of the water and moved into storm protection mode in order to decrease the wave loads on the floaters.

Operational range of 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. In this article, boat operations are assumed to be wave condition limited, but boats can

Table 1. 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 (m)	Mean wave period 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

Table 2. Electricity power matrix[23] in kilowatt for one floater of the Wavestar device using reactive control dependent on the significant wave height H_S and the mean zero-crossing wave period T_Z.

H_S (m)	Mean wave period T_Z (s)					
	2.5	3.5	4.5	5.5	6.5	7.5
0.25	0.11	0.32	0.62	0.93	1.15	1.23
0.75	0.95	2.86	5.07	5.92	5.88	5.67
1.25	2.64	7.88	11.80	17.54	11.56	10.84
1.75	5.17	14.89	19.73	19.44	17.79	16.07
2.25	8.55	23.40	28.55	27.20	24.50	21.92
2.75	5.78	33.10	30.09	35.45	31.61	28.11

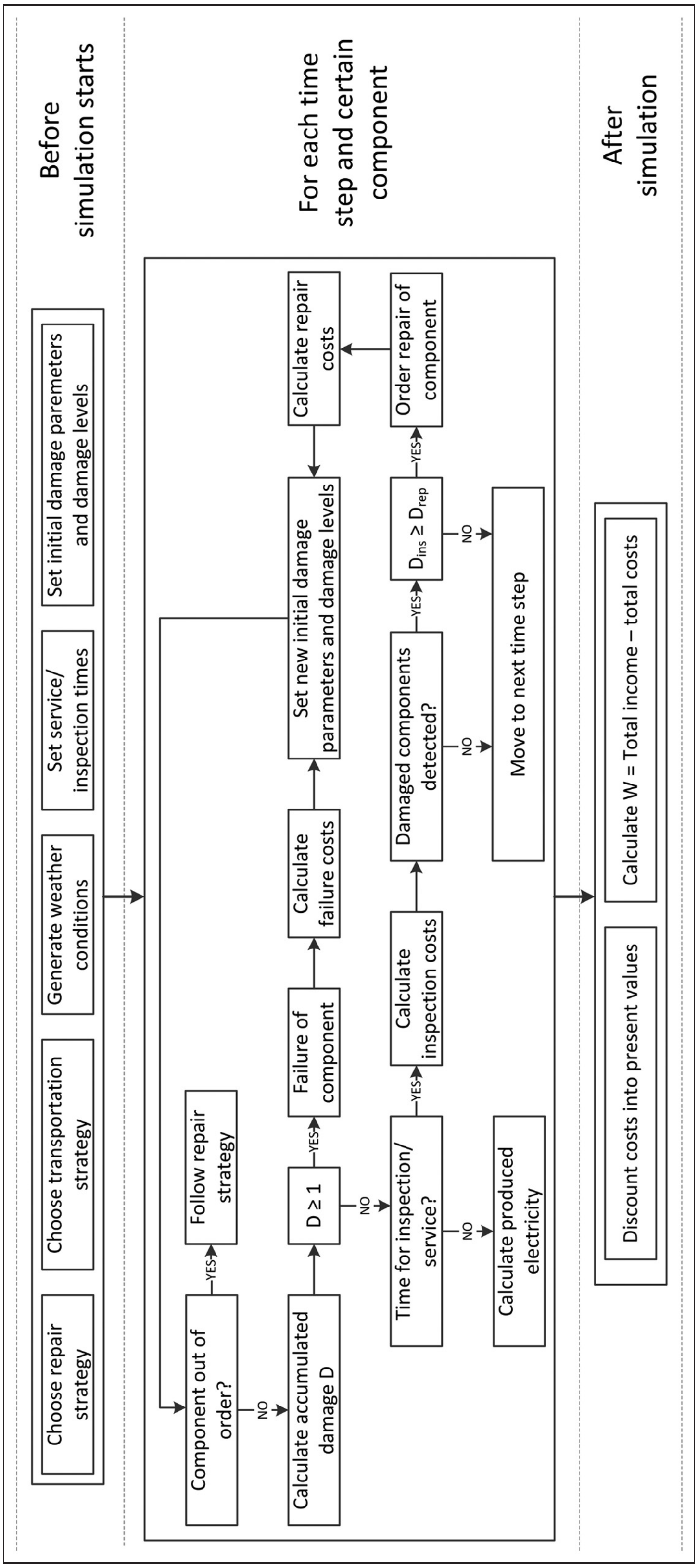

Figure 7. Exemplar flow chart for O&M simulation considering preventive maintenance.

Table 3. Repair costs, inspection costs, transportation costs, interest rate and duration for repairing the two considered failure modes.

			Failure mode 1	Failure mode 2
Repair cost C_R (€)			2000	4000
Inspection cost C_{ins} (work on board) (€)			1000	
Transportation costs by boat C_{tb} (€/day)			1200	
Transportation costs by helicopter C_{th} (€/day)			2400	
Interest rate r (%)			5	
Repair time (days)	Lognormal distributed	Mean	2	3
		COV	0.5	0.5

COV: coefficient of variation.

additionally be wind speed limited. Cradden et al.[5] show that the limitation due to significant wave height is more prohibitive than limitations due to the wind speed. There exist different types of boats, which have different wave height operational limits.[6] Support vessels designed to access offshore wind turbines can also be used for maintenance actions on WECs. These boats are highly manoeuvrable, 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;[25]
- Helicopter: maximum wind speed = 20 m/s.[8]

The access limitation does not only depend on whether boat or helicopter is used but also on the following:

- The need for a crew and small hand-held components;
- The need for a crane vessel;
- The ability for the boat to dock to the device;
- The ability for the helicopter to land on the device or whether the crew or components need to be lowered down onto the device.

Also, other parameters that are not considered here may affect the use of boats (e.g. strong current velocities) and helicopters (e.g. fog) for transportation.

Considered system

The 20-floater Wavestar device is assumed to have two different failure modes. One failure mode can occur at the power take-off (PTO) system, which harvests the energy from the waves. Another failure mode occurs at the system which produces electricity. Figure 8 shows a block diagram including the different failure modes. The first failure mode (failure mode 1) only affects one floater, whereas the second one (failure mode 2) affects the whole system and includes failure of the turbine, the generator, the transformer and the grid connection to shore. It is assumed that all 21 components considered are statistically independent, and failure of one component does not affect the other components.

Costs and time for repair, inspection and transportation

Table 3 shows the repair costs and the duration for reparation on board of the device for the two failure modes shown in Figure 8 and the considered costs for transportation and inspection together with the considered interest rate. It is assumed that failure in the PTO system (failure mode 1) can easily be repaired (e.g. broken valve) and replaced. Therefore, it needs less time for replacement, whereas the failure of the turbine–generator system (failure mode 2) needs longer repair time. Replacement and repair of a broken component starts the day after the damage occurs. The rest of the day is used to order the new component, the crew and the boat or helicopter. The total time for replacement and repair is assumed to be lognormal distributed[8] in order to prevent negative values. The repair time can only reach integer values. The repair cost, C_R, is assumed to be fixed here but different for the two failure modes. The inspection cost, C_{ins}, only contains the work on board. Therefore, the transportation costs by boat, C_{tb}, are also added for each inspection. The transportation cost reflects the daily operational costs for a workboat. Besnard et al.[26] show that operational costs of a crew transfer vessel are equal to 1200 €/day. The ratio between transportation by helicopter and boat is chosen according to Van Bussel and Schöntag,[27] where the transportation cost by helicopter is roughly two times larger than by boat when the offshore wind farm is placed 30 km off the coast.

Table 4 shows the total repair costs for different damage levels and transportation types. Preventive replacement ($D < 1$) takes place during inspections, which are performed in constant time sequences. For preventive replacements, no transportation costs occur due to the fact that they are already included in the total inspection costs. The total repair costs for corrective replacements consist of the cost for repair, the installation costs at the site and the total transportation costs. The repair costs, C_R, contain the supply cost of the component. The installation costs ($C_R \cdot 0.5 \cdot$repair days) depend on the duration of the repair (man-hours,

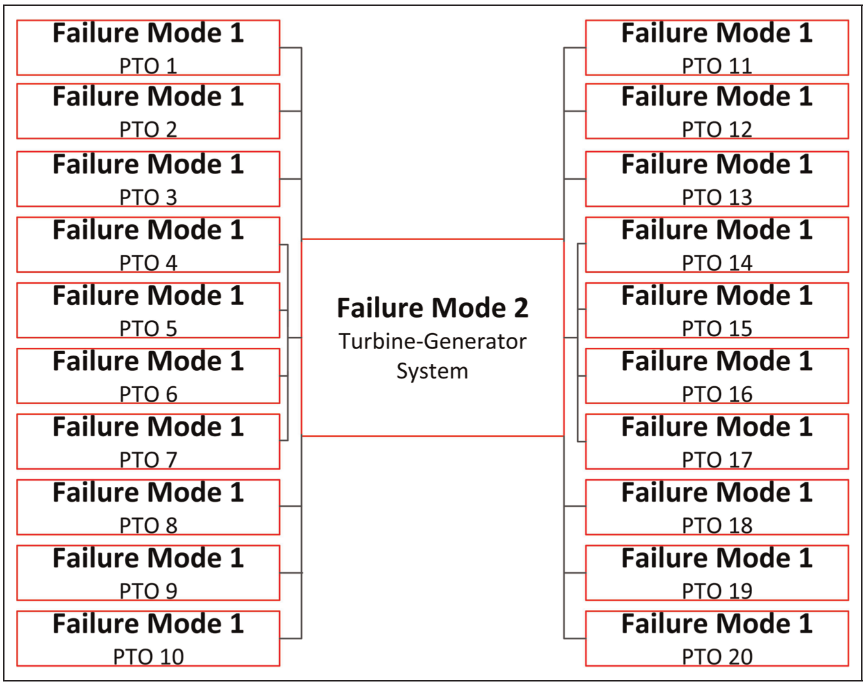

Figure 8. Block diagram including two different failure modes for the Wavestar device with 20 floaters.

Table 4. Total cost of repairs depends on the damage and transportation type.

Damage	Transport type	Repair cost (total)
$D < 1$	Boat	C_R
$D \geqslant 1$	Boat	$C_R.(1 + 0.5 \cdot \text{repair days}) + C_{tb}.\text{repair days}$
$D \geqslant 1$	Helicopter	$C_R.(1 + 0.5 \cdot \text{repair days}) + C_{th}.\text{repair days}$

C_R: repair cost; C_{tb}: transportation cost by boat; C_{th}: transportation cost by helicopter.

needed equipment, etc.). For corrective replacements, the resulting daily transportation costs (C_{tb} and C_{th}) depend on the means of transportation, and the considered values are given in Table 3.

There might be seasonal change in hiring costs (not considered here) due to large demands for maintenance actions during summer months. It is assumed that all components are inspected during an inspection. The optimal inspection interval depends on the mean-time between failures (MTBF) of the different components.

Waiting time costs due to bad weather conditions are reflected by the lost electricity production. Waiting costs of the transportation vehicles are not considered in this example as the boat and helicopter are ordered based on perfect weather forecast. Furthermore, this example assumes that the boat and the helicopter are always available. Furthermore, the overall repair costs and inspection costs may vary over time due to improvements and gaining of knowledge. In this example, the hiring and inspection costs are assumed to be constant over the whole lifetime.

Considered damage model

Annual failure rates of offshore wind turbines are assumed to be between 0.9 and 1.2 in Van Bussel and Zaaijer.[28] In Van Bussel and Bierbooms,[29] 1.5 failures/year are assumed for offshore wind turbines. No failure rate data are available for the different components of the Wavestar device. Therefore, this example considers a general failure rate of 1.5/year for the whole WEC, which is in correspondence what is assumed for offshore wind turbines.[29] The failure rate is for illustration divided into 1 failure/year of failure mode 1 and 0.5 failures/year of failure mode 2 (see Figure 8). Table 5 shows the considered values for the damage parameters of the different considered components. The failure rate is used to calibrate the mean values of parameters C and x_S. These parameters are calibrated using a corrective maintenance strategy.

Table 6 shows the variables used for the PoD curve. The smallest detectable damage λ is modelled as a stochastic variable reflecting human uncertainties and measurement uncertainties. Due to the fact that the same crew and equipment are used for inspection of the whole device (21 components) and all components are inspected at the same day, the uncertainty about λ is assumed to be constant during a certain inspection. The coefficient of variation (COV) value for the λ value is assumed to be 0.1. When gaining experiences, the decision (threshold) when a repair is performed and the accuracy of inspections might change with time due to

Table 5. Values used for damage parameters of the different considered components.

Symbol	Meaning		Mean	COV	Distribution
m	Damage exponent		2	–	Deterministic
β	Geometry factor		1	–	Deterministic
C	Damage coefficient	Failure mode 1	5.5e–10	0.2	Lognormal
		Failure mode 2	8.7e–10		
x_S	Proportionality factor from H_S to load	Failure mode 1	4.5	0.1	Lognormal
		Failure mode 2	10.5		
D_0	Initial damage		0.02	0.02	Exponential

COV: coefficient of variation.
Distribution types are taken from Nielsen and Sørensen.[8]

Table 6. Values used for the PoD curve for all 21 components.

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 or replacement	0.3	–	Deterministic

COV: coefficient of variation; PoD: probability of detection.

new technologies. But in this example, the decision rule and the statistical values for the PoD curve are assumed to be constant over the whole lifetime.

Results and discussion

Figure 9 shows an example of failure occurrences of the whole system shown in Figure 8 during one lifetime. In this example, corrective and preventive maintenance strategies with a fixed inspection interval of 1 year are considered, and only boat access for maintenance is assumed. When applying preventive maintenance, some components are repaired before the component fails. During inspections, preventive replacements of more than one component can take place.

Figure 10 shows the damage accumulation of the component with failure mode 2 for both corrective and condition-based maintenance using risk-based transport strategies with annual inspection intervals. The use of preventive maintenance means that the component is sometimes repaired or replaced before failure occurs. Most of the repairs are performed during inspections when condition-based maintenance is applied.

Figures 11 and 12 show average numbers of the total maintenance cost and the number of replacements during one lifetime when considering different maintenance strategies. Preventive and corrective maintenance strategies are considered where transportation is performed only by boat ('only boat') or the target is to minimize the downtime of the device and replacement should be performed 'ASAP' or the transportation strategy where the overall costs are minimized ('risk-based'). The total maintenance cost when applying corrective maintenance is, in general, larger compared with preventive maintenance strategies for the considered example. The number of total repairs increases from around 29 to 40 when changing from corrective to preventive maintenance. The number of preventive repairs during inspection for this case is equal to 32.

In order to get an overview about the scattering of the total cost presented in Figure 11 and the average number of total repairs during one lifetime (see Figure 12), Tables 7 and 8 show the COV of the total cost for O&M actions and the total number of repairs. The COV value is the standard deviation of a certain data set divided by its mean value. The larger the COV values, the larger the scattering of the results. The COV value is around 0.145 when following a corrective maintenance strategy and increases to 0.18 when applying a preventive maintenance strategy. The scattering differences among the different transportation strategies are of minor importance. The COV values of the total number of repairs are in the range of 0.1 and are as expected not dependent on the maintenance and transportation strategy.

The resulting overall maintenance costs and the number of repaired components are dependent on the operational conditions for the boat and the helicopter, the time interval between two inspections and the condition when a detected damage should lead to replacement of the component, the used inspection technique and the economic situation (e.g. leading to different interest rates). How these factors affect the total maintenance costs and the number of repaired components are investigated in the following.

Influence of inspection or service interval

Figure 13 shows the influence of time intervals between maintenance actions on the total O&M costs for different transportation strategies. Increasing the inspection

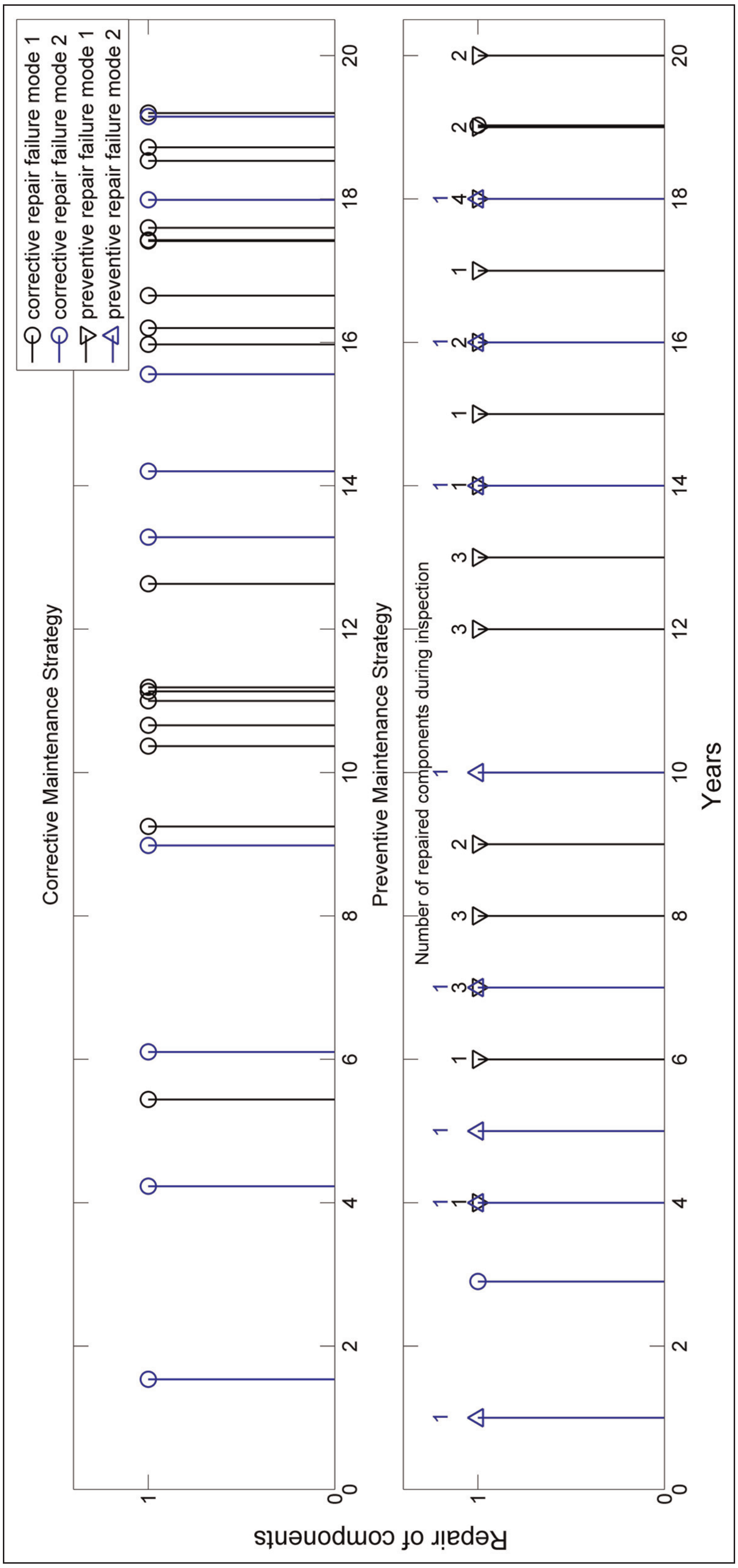

Figure 9. Example of preventive and corrective repairs of the whole system (including components with failure modes 1 and 2) using corrective and preventive maintenance strategies with boat access and annual inspection intervals.

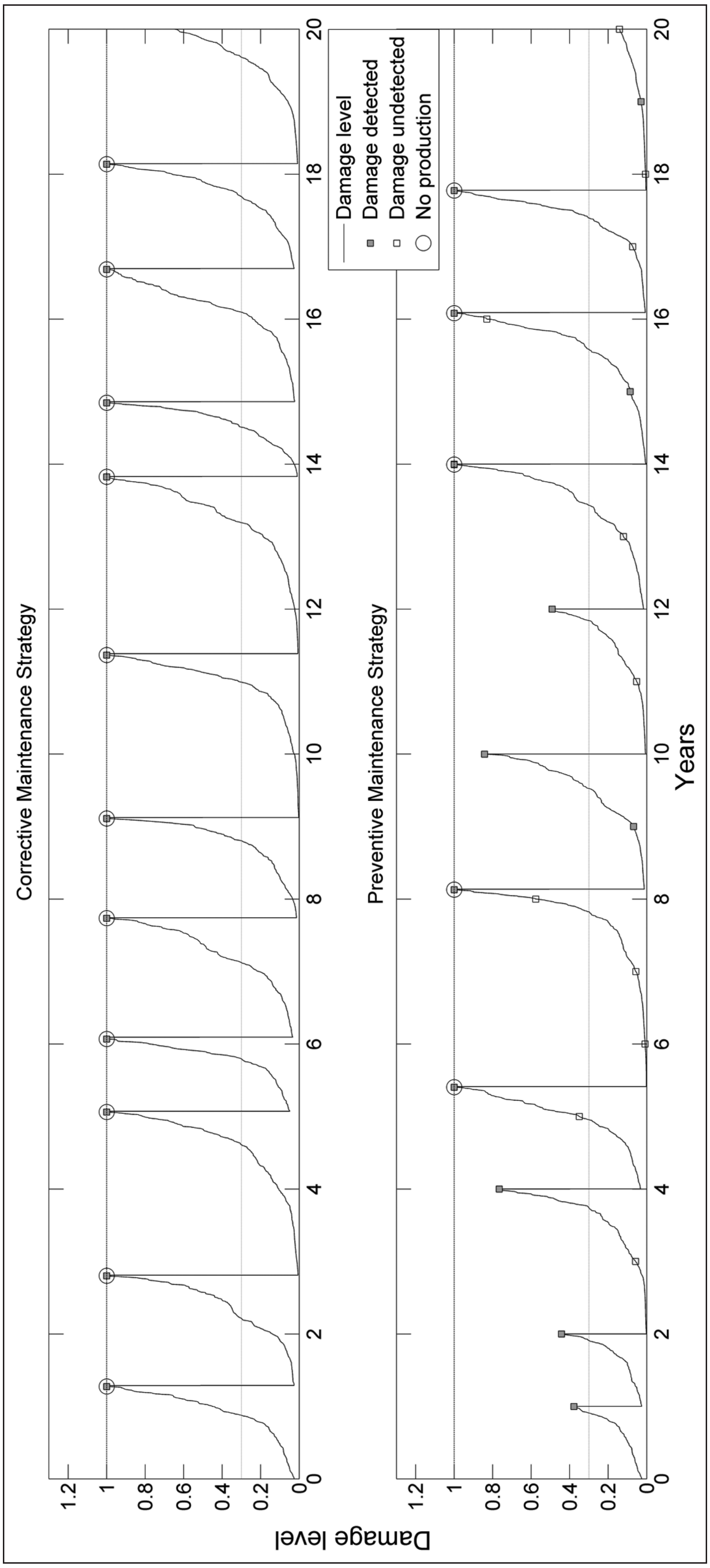

Figure 10. Damage development of a component with failure mode 2 for risk-based transport strategy and corrective and condition-based maintenance.

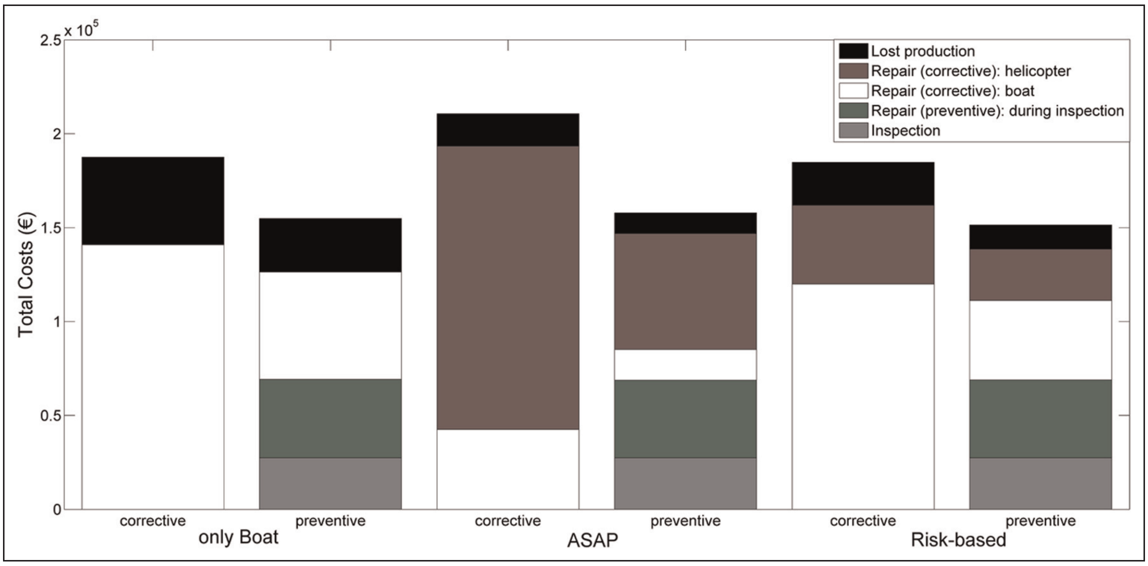

Figure 11. Influence of maintenance and transportation strategy on total maintenance costs during one lifetime –'only Boat': only boat used to access device; 'ASAP': replacement or repair as soon as possible considering both boat and helicopter for transportation and 'Risk-based': minimize overall costs considering boat and helicopter for transportation.

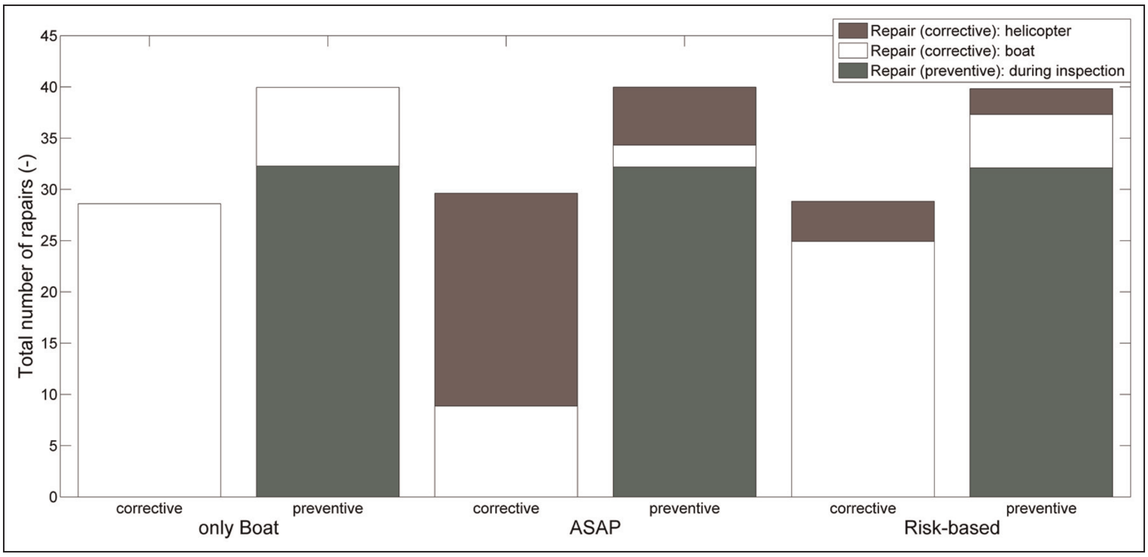

Figure 12. Average total number of repairs for different transportation and maintenance strategies during one lifetime –'only Boat': only boat used to access device; 'ASAP': replacement or repair as soon as possible and 'Risk-based': minimize overall costs.

Table 7. Coefficient of variation (COV) value of the total maintenance costs during one lifetime shown in Figure 11 for different maintenance and transportation strategies.

Corrective maintenance			Preventive maintenance		
Only boat	ASAP	Risk based	Only boat	ASAP	Risk based
0.154	0.139	0.139	0.192	0.169	0.176

ASAP: as soon as possible.

intervals decreases the costs used for preventive replacements and inspections but increases the corrective repair costs and the period of no electricity production. For inspection intervals between 9 months and 2 years, the total costs remain nearly constant, whereas the total cost increases for smaller inspection intervals. Figure 14 shows the number of total repairs dependent on the inspection interval for different transportation

Table 8. Coefficient of variation (COV) value of the total number of repairs during one lifetime shown in Figure 12 for different maintenance and transportation strategies.

Corrective maintenance			Preventive maintenance		
Only boat	ASAP	Risk based	Only boat	ASAP	Risk based
0.102	0.099	0.101	0.098	0.099	0.097

ASAP: as soon as possible.

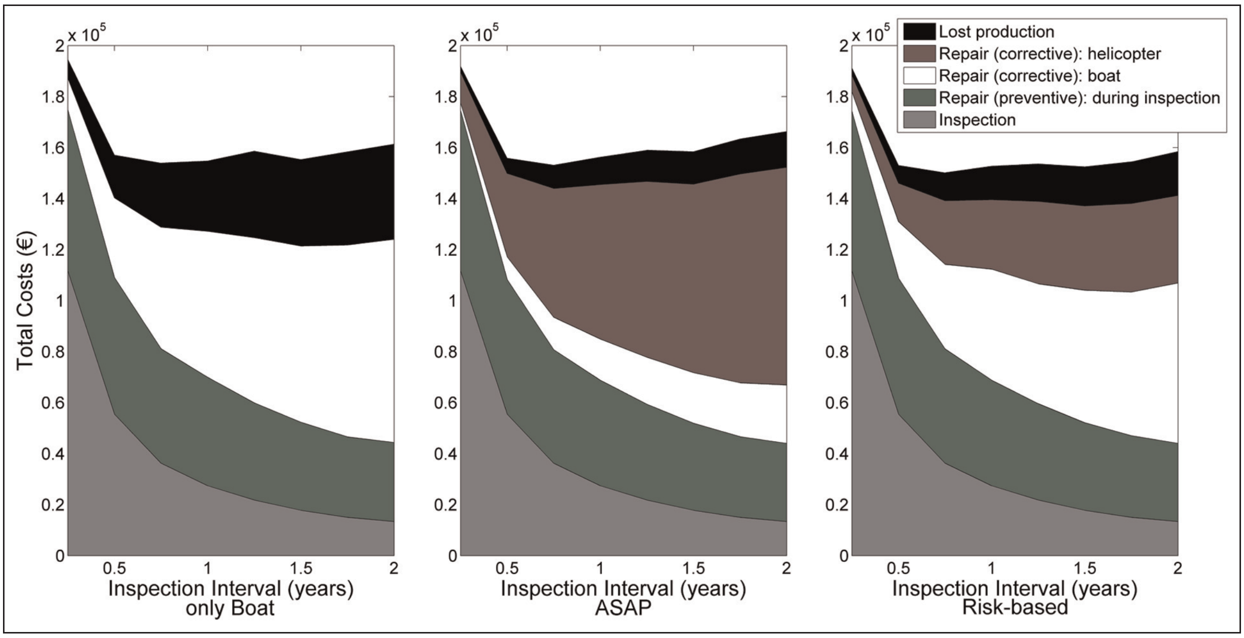

Figure 13. Total cost for different preventive maintenance strategies and different inspection intervals (time between two sequent inspections) –'only Boat': only boat used to access device; 'ASAP': replacement or repair as soon as possible and 'Risk-based': minimize overall costs.

strategies. The total number of repairs decreases when the inspection intervals are increased. With an inspection interval of 3 months, the number of repaired components is equal to 43 and with an inspection interval of 2 years, the total number of repaired components is roughly equal to 37.

Influence of damage threshold for repair (D_{rep}) during inspection

Figure 15 shows the influence of D_{rep}, which reflects the threshold when a detected damage should be repaired, on total maintenance costs during 20 years using the three different transportation strategies. The lowest total costs are reached with $D_{rep} = 0.3$. When all detected damages ($D_{rep} = 0$) are repaired, the total maintenance cost increases due to large preventive maintenance costs, whereas for large damage thresholds for repair ($D_{rep} = 0.9$), the corrective repair costs become dominant. Figure 16 shows the resulting total number of repairs dependent on the damage threshold for repair and different transportation strategies. The total number of repairs decreases in total when increasing D_{rep} for all three different transportation strategies. The larger the damage threshold is chosen, the more components are replaced based on corrective maintenance.

Influence of minimal detectable threshold during inspections

Different inspection technologies may lead to different sizes of the smallest detectable damages (λ). Here, mean values of minimal detectable damages of 0.2, 0.4 and 0.6 are chosen, and Figures 17 and 18 show their influence on the overall costs and number of repaired components. The total maintenance cost increases when the smallest detectable damage is increased. If only the boat is used to access the device, the total cost increases by 7.5% when λ is increased from 0.2 to 0.6. For the transportation strategy ASAP (replacement as soon as possible), the increase is equal to 6.2%, and it increases by 4.9% for the risk-based approach. Not considered here is the expected increase in inspection costs when using technologies leading to more accurate detection of damages, but these technologies might be more expensive. The number of repairs decreases from 42 (= 0.2) down to 38 for λ (= 0.6).

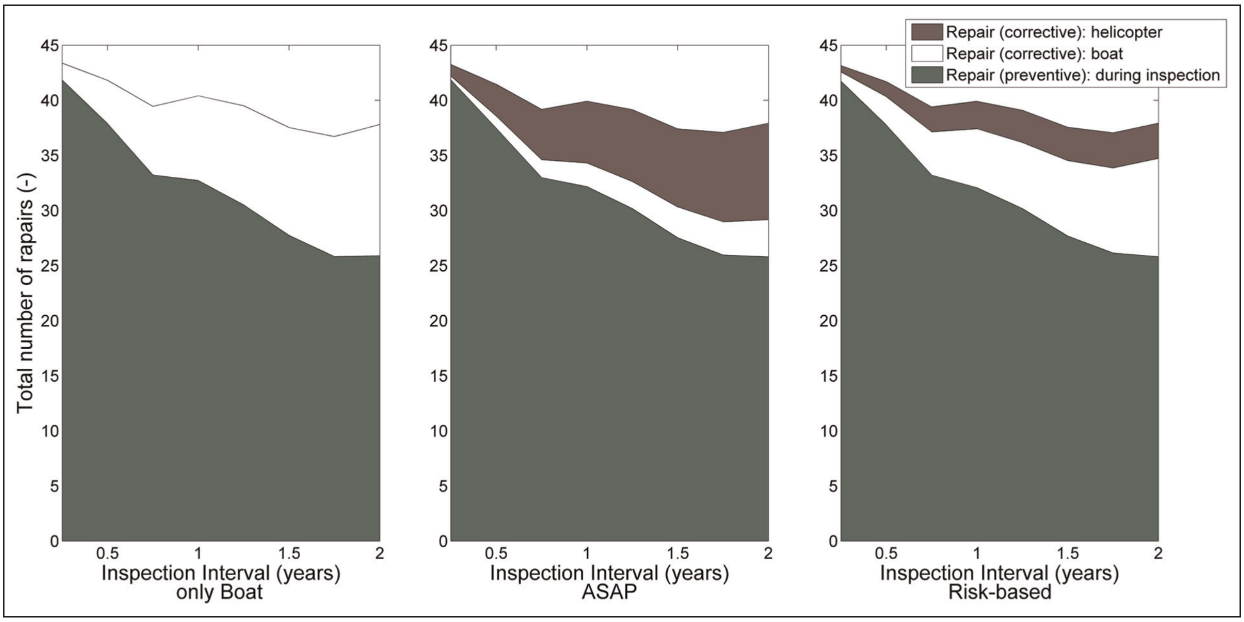

Figure 14. Total number of repairs during one lifetime dependent on the time between two inspections (inspection interval) for different preventive maintenance strategies –'only Boat': only boat used to access device; 'ASAP': replacement or repair as soon as possible and 'Risk-based': minimize overall costs.

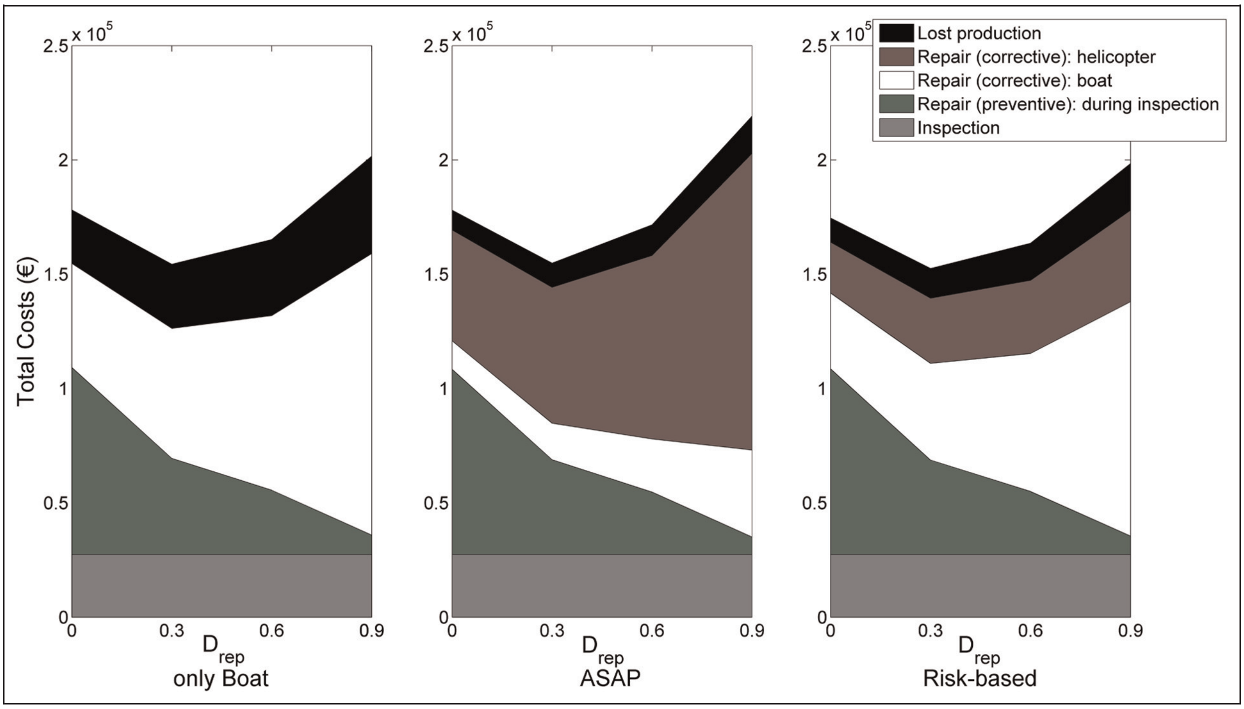

Figure 15. Total maintenance costs during one lifetime dependent on damage threshold for repair (D_{rep}) for preventive maintenance using different transportation strategies –'only Boat': only boat used to access device; 'ASAP': replacement or repair as soon as possible and 'Risk-based': minimize overall costs.

Influence of operational range of ship and helicopter

To investigate the impact of maximum operational range on total maintenance costs, maximum operational ranges of a helicopter and a boat are varied by ±20% from the values in section 'Operational range of boat and helicopter'. It is assumed that the transportation costs C_{bh} and C_{th} remain the same independent of the operational range of boat and helicopter.

Figure 19 shows the impact of the significant wave height limitations ($H_{S,max}$) on the total maintenance costs for corrective maintenance strategy with different

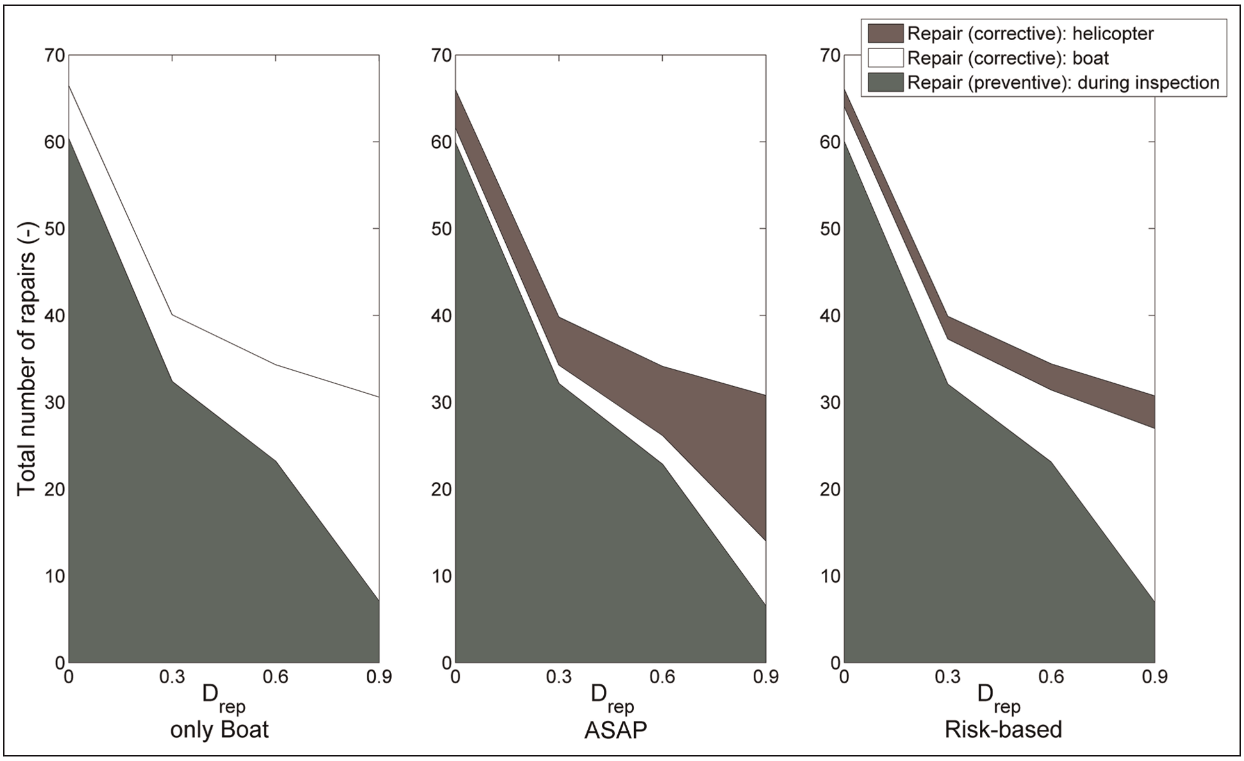

Figure 16. Number of repairs during one lifetime dependent on damage threshold for repair (D_{rep}) for different transport strategies using preventive maintenance strategies –'only Boat': only boat used to access device, 'ASAP': replacement or repair as soon as possible and 'Risk-based': minimize overall costs.

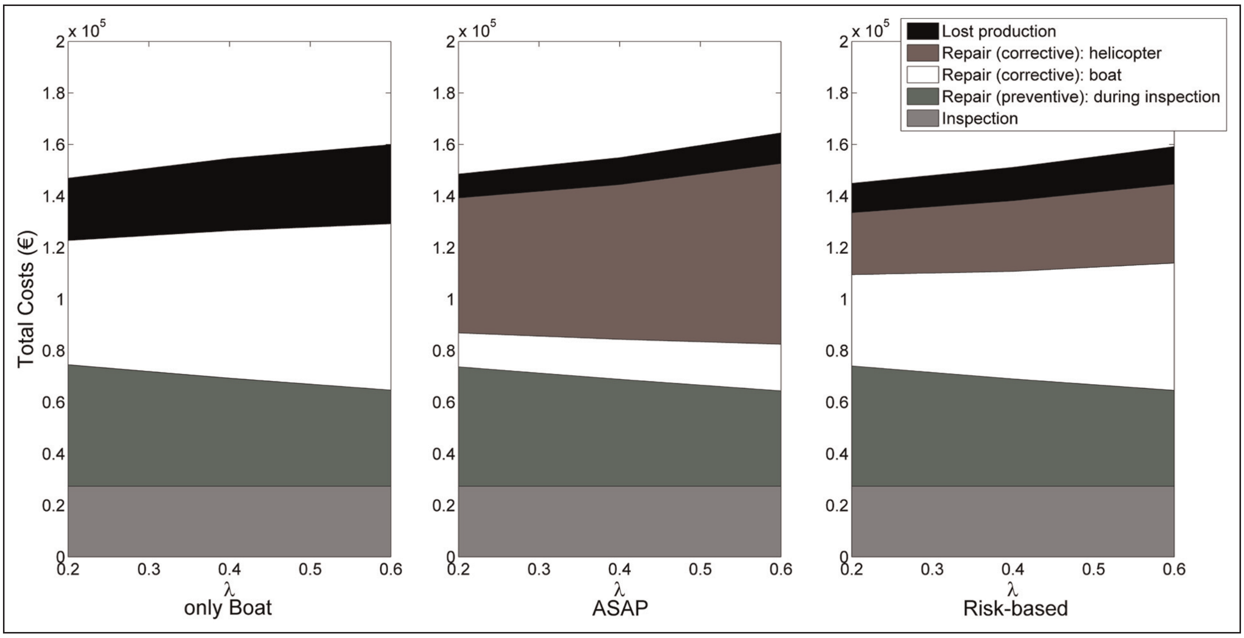

Figure 17. Total maintenance costs dependent on the smallest detectable damage λ for preventive maintenance and different transportation strategies –'only Boat': only boat used to access device; 'ASAP': replacement or repair as soon as possible and 'Risk-based': minimize overall costs.

transportation strategies. In general, the total cost tends to decrease for the transportation strategies 'only boat' and 'ASAP' when the limitation of boat operations is increased due to smaller waiting periods during strong wave conditions and increased number of repairs performed by boat. The 'risk-based' transport strategy with corrective maintenance shows that the total maintenance costs are nearly independent on maximum

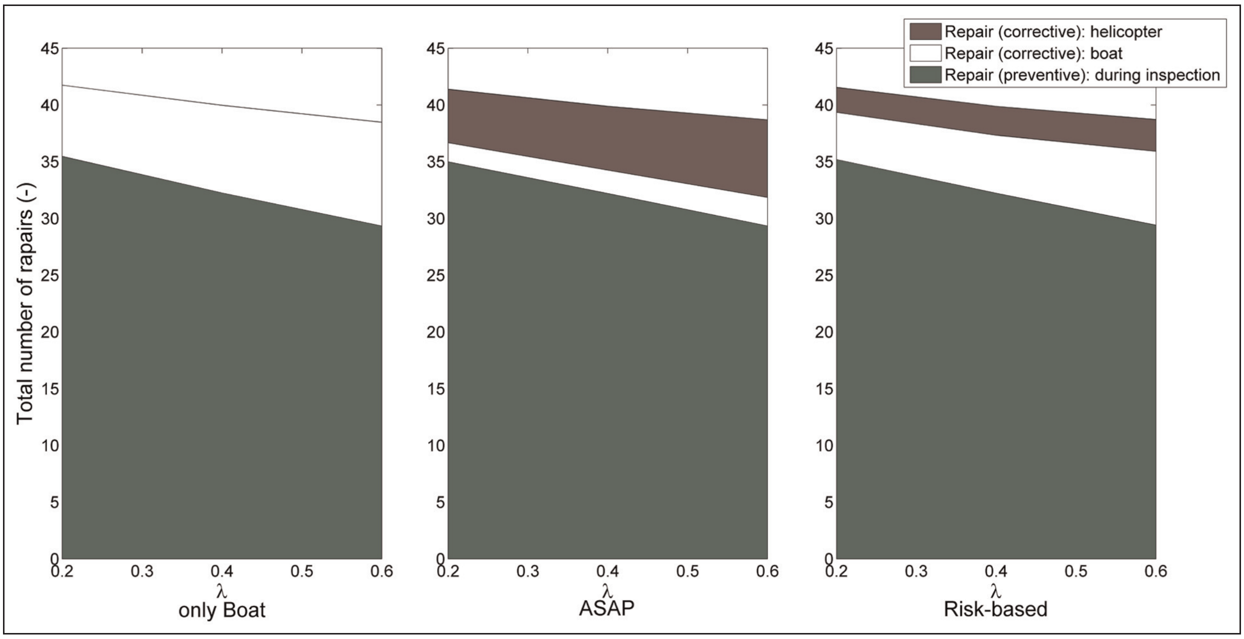

Figure 18. Total number of repairs dependent on smallest detectable damage λ using preventive maintenance and different transportation strategies –'only Boat': only boat used to access device; 'ASAP': replacement or repair as soon as possible and 'Risk-based': minimize overall costs.

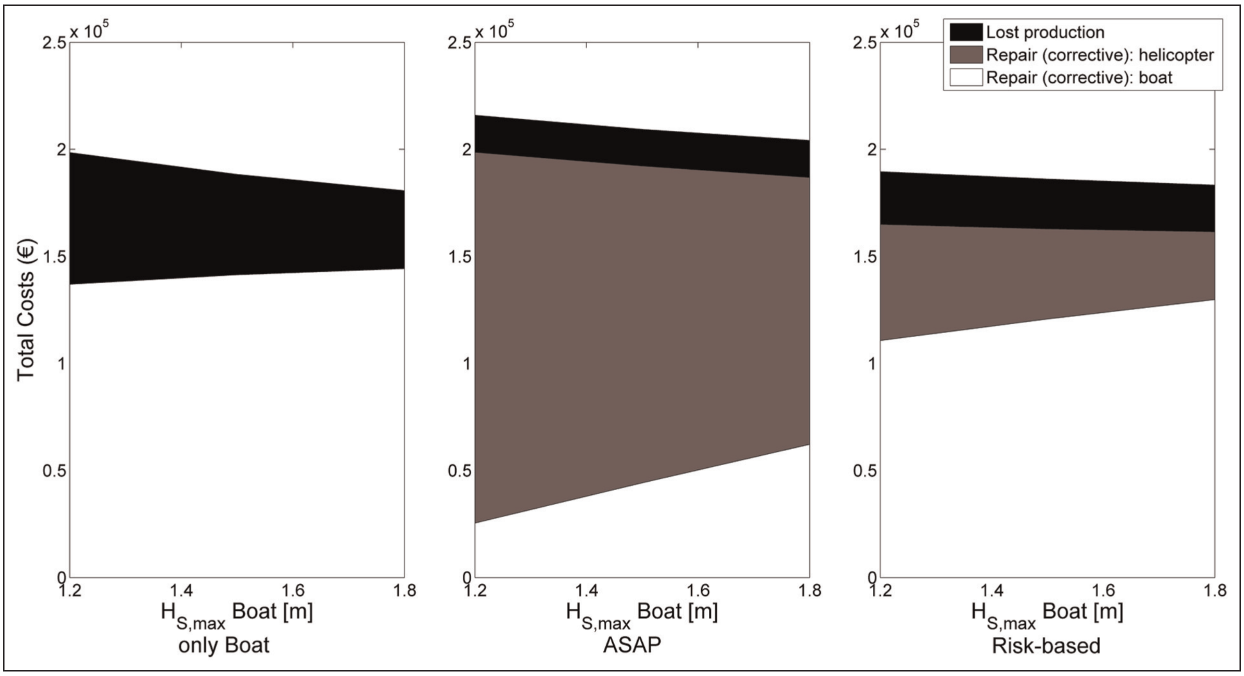

Figure 19. Total maintenance costs for corrective maintenance strategy and different transportation strategies dependent on maximum significant wave height ($H_{S,max}$), which limits boat operation. Maximum wind speed for helicopter operation: 20 m/s.

operational range of the boat. When preventive maintenance strategies are applied (see Figure 20), the total costs decrease with the 'only boat' transportation strategy, whereas the 'ASAP' and 'Risk-based' transportation strategies lead to more or less the same total maintenance costs for different maximum significant wave height limitations.

Larger operational ranges might lead to more expensive transportation costs because another type of boat or helicopter needs to be taken. How much the hiring price can be increased for the different transportation and maintenance strategies when the maximum significant wave height for the boat is increased from 1.2 to 1.8 m is shown in Table 9. A transportation cost

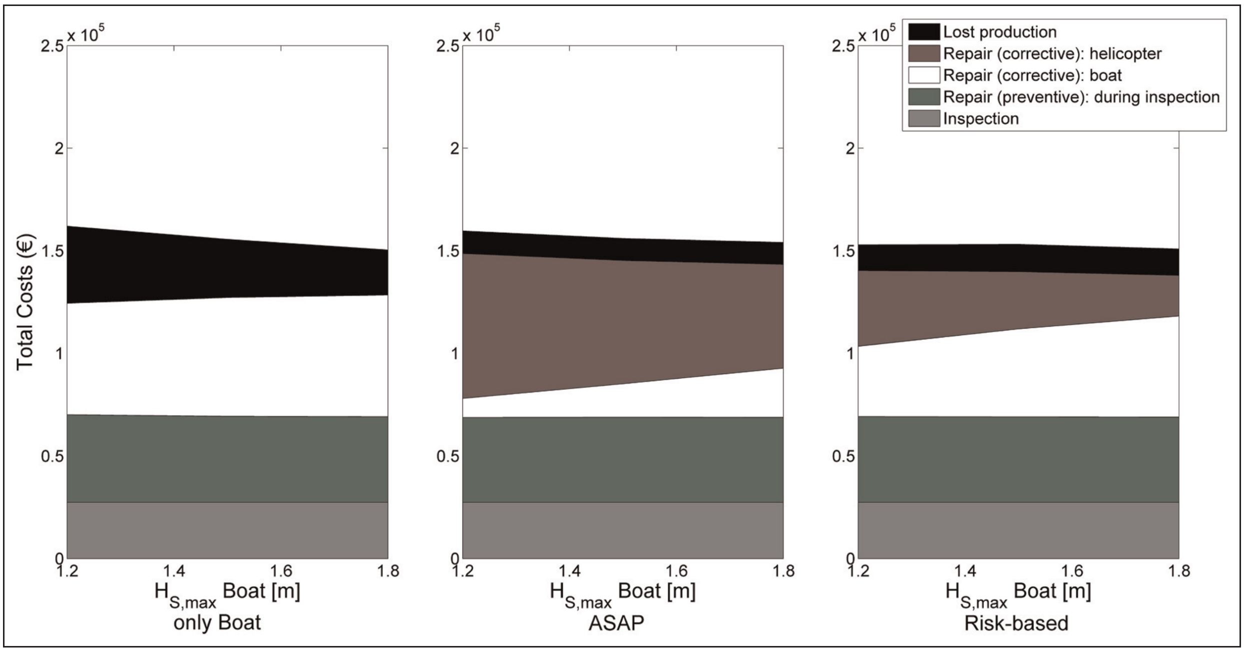

Figure 20. Total maintenance costs for preventive maintenance strategy and different transportation strategies dependent on maximum significant wave height ($H_{S,max}$), which limits boat operation. Maximum wind speed (V_{max}) for helicopter operation: 20 m/s.

Table 9. Relative acceptable transportation cost increase when maximum significant wave height where boat operation is possible is increased from 1.2 to 1.8 m.

Corrective maintenance			Preventive maintenance		
Only boat	ASAP	Risk based	Only boat	ASAP	Risk based
9.0%	5.5%	3.5%	7.2%	3.6%	1.3%

ASAP: as soon as possible.

increase between 9% and 1.3% can be accepted in order to reach the same or lower total O&M expenses when increasing the maximum significant wave height value where operation is possible.

Figure 21 shows the impact of the helicopter operation range (limited by the wind speed) on the total maintenance costs for corrective maintenance. The impact for preventive maintenance is shown in Figure 22. Both figures show that changes in the helicopter operation limitations have a negligible impact on the total maintenance costs for all three different transportation strategies.

Influence of real rate of interest

Figure 23 shows the total maintenance costs for corrective and preventive maintenance strategies when risk-based transportation strategies are used. Real rates of interest are set at 2%, 5% and 10%. The costs discounted into present values are smaller for larger rates of interest. A 10% real rate of interest increases the discounted maintenance costs by roughly a factor of 2, compared with a real rate of interest equal to 2%. However, also the costs using corrective maintenance relative to the total costs from preventive maintenance costs are of interest. Figure 24 shows the total maintenance costs using 'risk-based' transportation strategies normalized by the total costs using corrective maintenance strategies. The relative costs are almost the same for all three different cases. The difference between corrective and preventive maintenance strategies is between 20% (for real rate of interest equal to 2%) and 16% (for real rate of interest equal to 10%).

Influence of electricity price

The feed-in tariff for electricity produced by WECs is location dependent due to different support strategies of different countries.[30] The feed-in tariff affects the total costs for O&M because the costs due to loss of electricity production in case of failure need to be considered in the total costs. In this section, the influences of different feed-in tariffs are assessed for the total costs and the number of repairs performed using the boat and the helicopter to assess the device. The feed-in tariff is of importance for the risk-based transportation

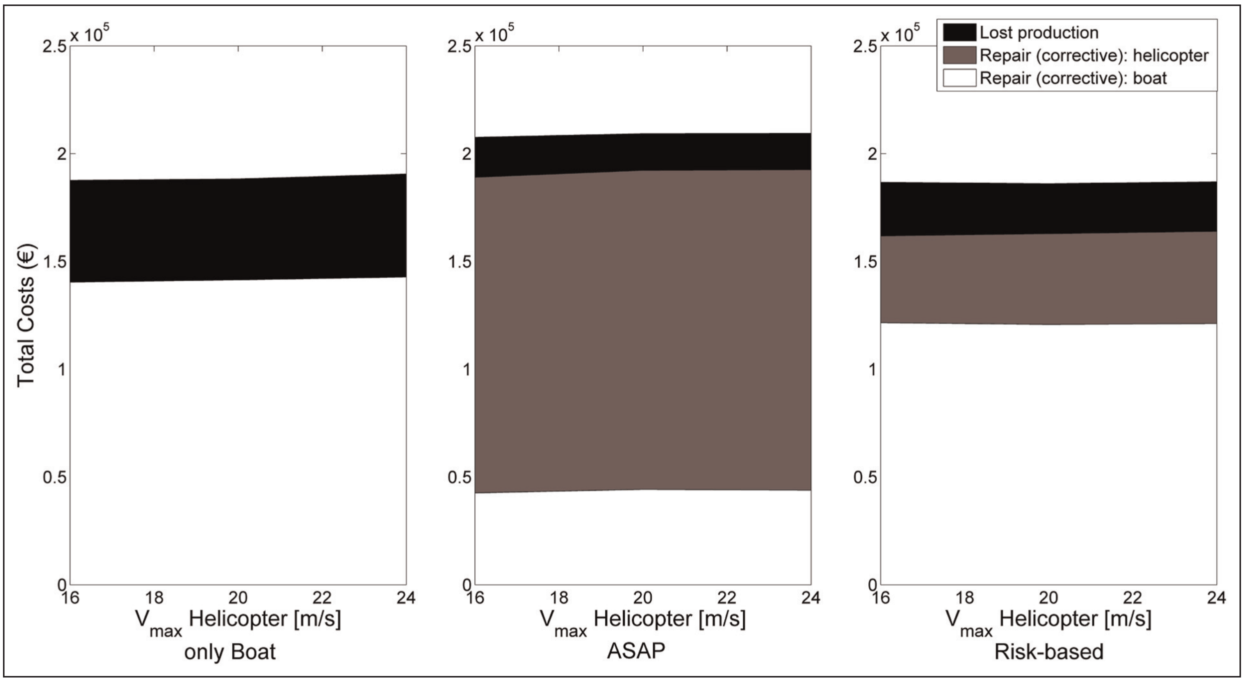

Figure 21. Influence of maximum wind speed (V_{max}) for transportations by helicopter on total costs for corrective maintenance with different transportation strategies. Maximum significant wave height ($H_{S,max}$) for boat operation: 1.5 m.

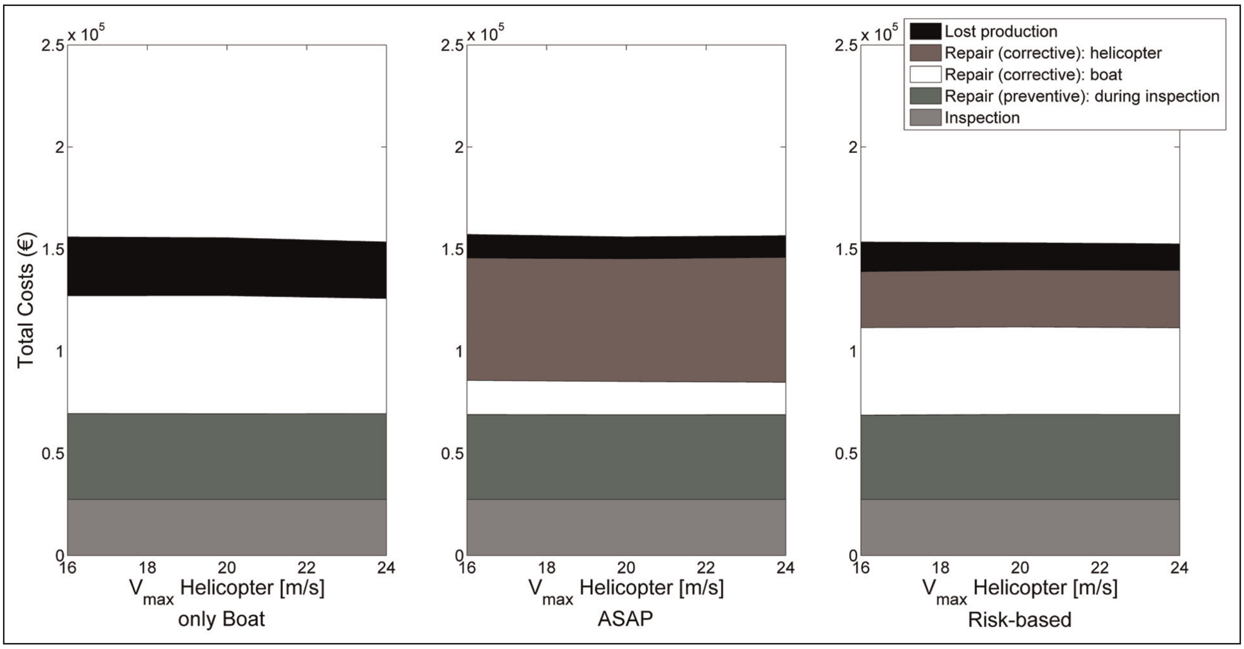

Figure 22. Influence of maximum wind speed (V_{max}) for transportations by helicopter on total costs for preventive maintenance with different transportation strategies. Maximum significant wave height ($H_{S,max}$) for boat operation: 1.5 m.

strategy, whereas for the two other transportation strategies, the decision which means of transportation to take is not driven by the feed-in tariff.

Figure 25 shows the total maintenance costs for corrective maintenance dependent on the feed-in tariff, which is varied from 0.08 to 0.16 €/KWh for the different transportation strategies. When the electricity price is increased, the total maintenance expenses increase for all three transportation strategies. Larger electricity prices make it necessary to quickly replace the broken component. Therefore, for the risk-based approach, larger electricity prices lead to more repairs performed by helicopters. When the electricity price is increased from 0.08 to 0.16 €/KWh, the total corrective maintenance expenses increase between 9% ('Risk-based' strategy) and 16% ('only boat' strategy).

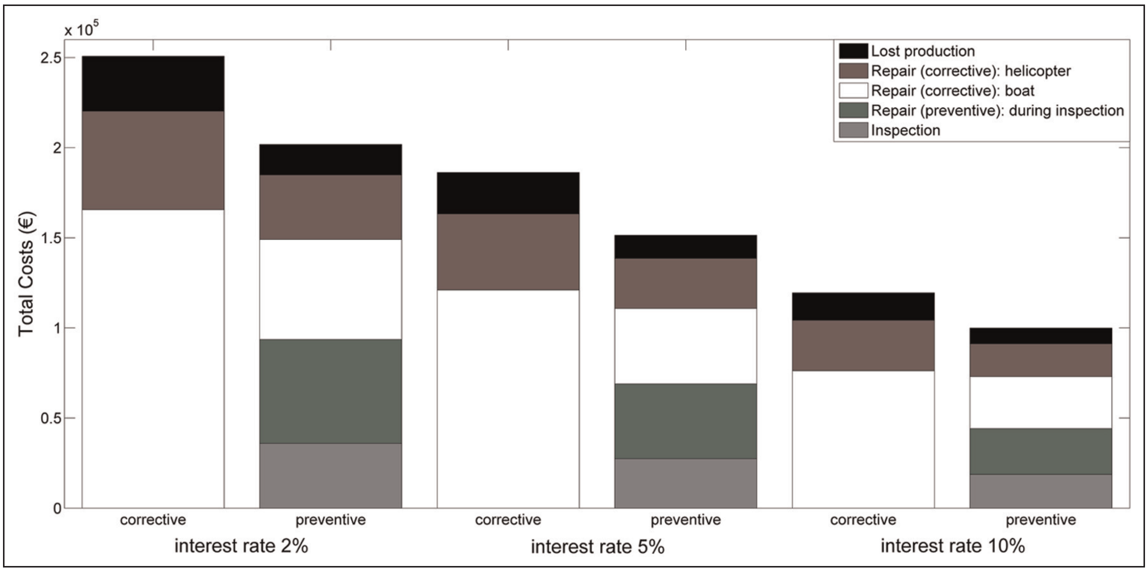

Figure 23. Influence of real rate of interest for 'risk-based' transportation strategies on total maintenance costs.

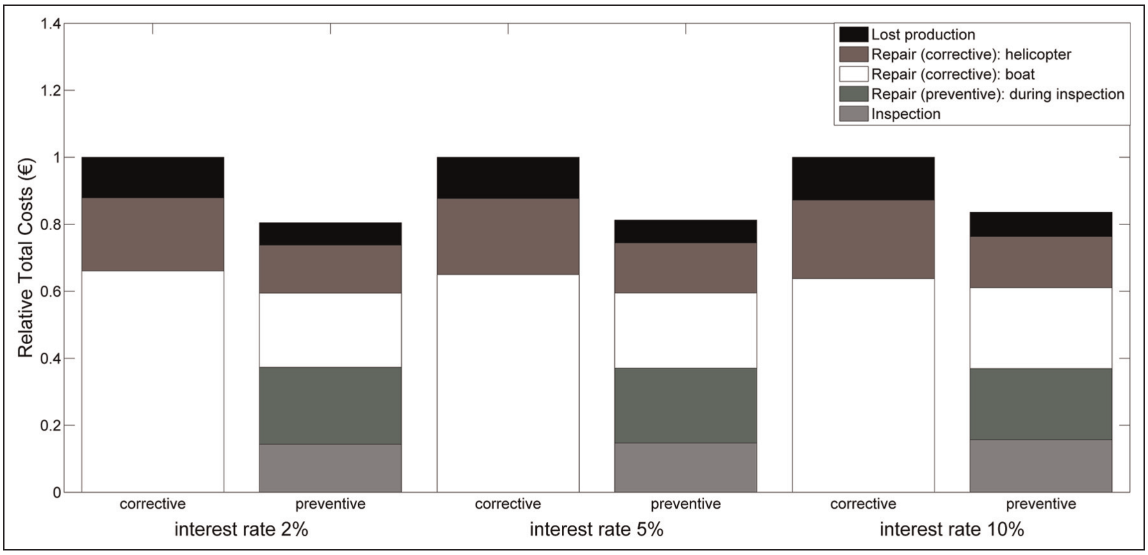

Figure 24. Relative total maintenance costs for corrective and preventive maintenance and 'risk-based' transportation strategies. The total costs for a certain real rate of interest are normalized by the total costs using corrective maintenance strategy.

Figure 26 shows the average total maintenance expenses when using preventive maintenance for different electricity prices and transportation strategies. Also, here, the total maintenance costs increase when the electricity price is increased. The total maintenance expenses following a preventive maintenance strategy increase between 4.5% ('Risk-based' strategy) and 13% ('only boat' strategy) when the electricity price is increased from 0.08 to 0.16 €/KWh. The impact of electricity prices has larger impact on corrective maintenance strategies compared with preventive maintenance strategies.

Change in feed-in tariff also changes the expected income from selling electricity. Therefore, also of importance is the ratio between total O&M expenses and the expected total income from selling electricity. Table 10 shows the ratio between expected income from selling electricity and the total maintenance costs. Larger electricity prices give, in general, a larger ratio between income and maintenance expenses. Furthermore, preventive maintenance strategies lead to larger ratios compared with corrective maintenance strategies. The largest ratios for a given maintenance strategy are achieved when 'risk-based' transportation strategy is chosen.

Conclusion

This article compares preventive and corrective maintenance strategies using the 20-floater Wavestar WEC as

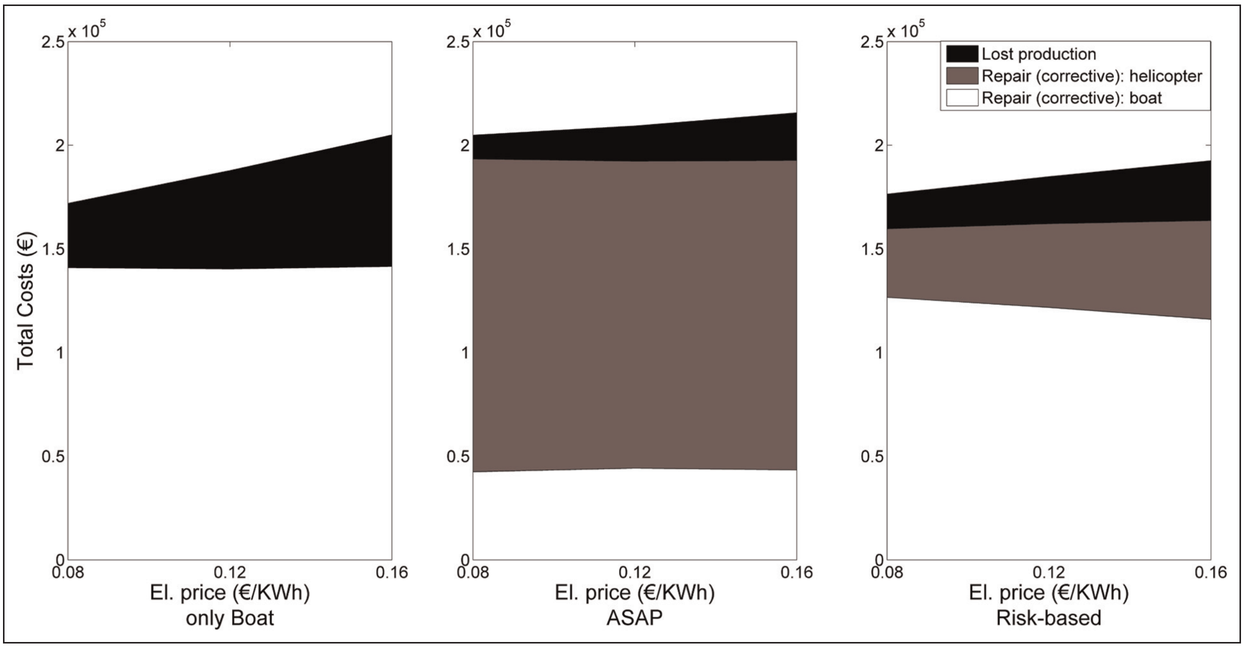

Figure 25. Total maintenance costs during one lifetime for corrective maintenance strategy considering different electricity prices and different transportation strategies.

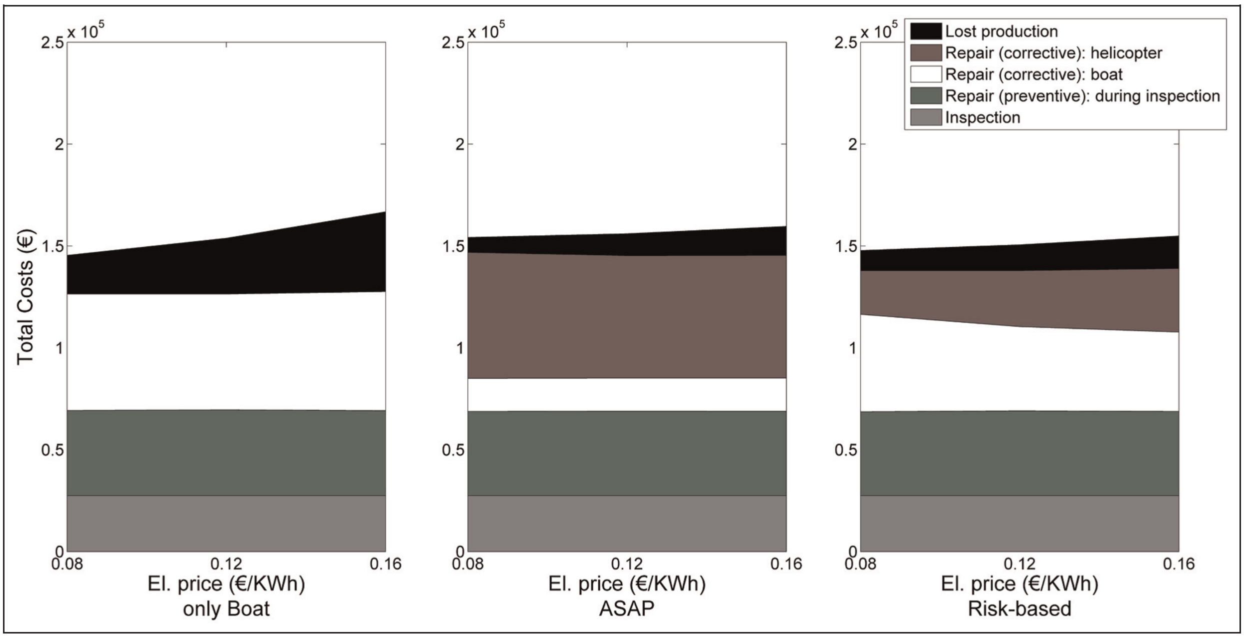

Figure 26. Total maintenance costs during one lifetime for preventive maintenance strategy considering different electricity prices and different transportation strategies.

Table 10. Normalized ratio between expected income during lifetime by selling electricity and total O&M costs.

Electricity price (€/KW h)	Corrective maintenance			Preventive maintenance		
	Only boat	ASAP	Risk based	Only boat	ASAP	Risk based
0.08	1.00	0.85	1.01	1.19	1.13	1.20
0.16	1.69	1.62	1.81	2.08	2.19	2.25

ASAP: as soon as possible.
Ratio resulting from an electricity price of 0.08 €/KWh and corrective maintenance where only the boat is used to access the devices is used as normalization factor.

a case study. Three different transportation strategies are considered to access the device. 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 minimization of the overall costs resulting from the downtime and repair or replacement of the component. The Wavestar case study is based on 21 components where fatigue is modelled by time-varying damage accumulation, and inspections are performed within a fixed time interval for preventive maintenance strategies. A parameter study is performed in order to assess the impact of different parameters on the overall costs and estimate their sensitivity in relation with costs needed for O&M. The parameter study showed that the total maintenance costs as well as the number of repaired or replaced components depend on the interval between two inspections and the damage threshold which leads to replacement of the component. Longer inspection intervals decrease the total maintenance costs and the total number of replaced or repaired components. A larger damage threshold for replacement decreases the amount of preventive repairs, but it increases the number of corrective repairs. The total maintenance costs are also influenced by the minimal detectable damage, which depends on the technology used to detect damages. Total maintenance costs are more sensitive to boat operation limitations (significant wave height dependent) than for helicopter operation limitations (wind speed dependent). Furthermore, the real rate of interest has large impact on total maintenance costs. An increase from real rate of interest equal to 10% down to 2% leads to doubled discounted total maintenance costs in the considered example. The generic example is based on estimated costs and failure rates. Due to the fact that many costs are estimated by the authors due to lack of data and knowledge, the absolute overall total costs have limited validity, whereas the sensitivity and dependence of the investigated parameters on the overall total O&M costs will be similar with different cost assumptions. Different results may occur if different costs and failure rates are used.

The considered example assumes a perfect weather forecast. A more realistic situation would be to assume an uncertain weather forecast. This can be performed by adding an uncertainty to the weather in the future when deciding whether to do the work or wait in the harbour. Furthermore, the presented framework can be used to optimize the overall costs of wave energy devices located in farms. When carrying out inspections within a WEC farm, the transportation cost per device decreases due to the fact that the ship or helicopter only needs to travel from the shore to the farm once. Crew hotel boat and the like may become of interest to decrease the time for inspection and the O&M costs when focusing on WEC farms.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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