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DISCUSSIONS

Probabilistic cost modeling as a basis for optimizing inspection and maintenance of support structures in offshore wind farms

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Abstract

The operational management of offshore wind farms includes inspection and maintenance (I&M) of the turbine support structures. These activities are complex and influenced by numerous uncertain factors that affect their costs. The uncertainty in the I&M costs should be considered in decision and value of information analyses performed to optimize I&M regimes. In this paper, we present a probabilistic cost model for I&M activities in an offshore wind farm serviced by boats operating from a port base. The model is developed based on interviews with a wind farm operator, consultants, and operation and maintenance engineers, as well as on scientific literature. Various I&M methods are considered, and the model is evaluated to predict probabilistic I&M costs at different levels, i.e., wind farm, structural system, and structural component. A sensitivity analysis is performed to study the influence of the different model parameters on the overall I&M costs. Finally, the model is included in a numerical example in which the I&M regime for a steel frame subject to fatigue is optimized using risk-informed methods. The frame's characteristics are comparable to those of a jacket structure supporting an offshore wind turbine. In the example, we demonstrate that the I&M costs can be considered deterministically as expected values since they are included in the optimization on a linear basis.

Keywords: offshore wind farms, turbine support structures, inspection and maintenance, probabilistic cost modeling, decision analysis, value of information

1 Introduction

The offshore environment is characterized by harsh conditions that have an impact on the condition and integrity of the support structures in offshore wind farms. The integrity management improves the condition of structural components by performing maintenance. Maintenance activities are classified as preventive when carried out proactively before the system fails. Preventive maintenance activities are systematic/periodic when performed at regular or fixed intervals, condition-based when scheduled based on the current condition of the system inferred from inspection and/or monitoring outcomes, and predictive when carried out based on the predicted system condition where the predictions are informed by the available inspection and/or monitoring outcomes (Straub, 2018). Unscheduled maintenance activities can take longer and incur higher costs due to additional engineering, planning, utilization of extra equipment and materials, accessibility, complexity of the damage, and weather downtime.

Typically, operation and maintenance (O&M) of an offshore wind farm corresponds to 25% - 30% of the levelized cost of energy (LCoE) (Ambuhl and Sorensen, 2017; Kolios and Brennan, 2018; Maples et al., 2013; Röckmann et al., 2017). One option to reduce the LCoE, is to optimize the inspection and maintenance (I&M) regime for the turbine support structures. The uncertainties in the costs of the I&M activities should be considered in such an optimization.

The overall expected I&M costs for an offshore wind farm depends on the I&M strategy. An inspection strategy is typically defined in terms of inspection method, inspection times, the number of wind turbines (WT) to be inspected in the wind farm and the number of components to be inspected in a WT support structure. In case the wind farm is serviced from a port base, the overall inspection costs are influenced by the distance between the port to the wind farm, the choice of vessel, the number of personnel, equipment, mobilization/demobilization activities, the location of the inspected components in the support structure, and the time to complete an inspection work package. The maintenance strategy is generally defined in terms a maintenance criterion, method, and time (following an indication of potentially critical damage). Like inspection costs, the maintenance costs are affected by the component location, the time to complete a maintenance activity on site, equipment/materials, the distance between the port to the wind farm, the choice of vessel, the number of personnel, and the engineering effort required to prepare an intervention (i.e., designing and testing of a repair solution).

In the literature, deterministic (normalized) cost models are generally utilized in probabilistic reliability or risk-informed optimizations of I&M strategies (Agusta et al., 2020; Ali et al., 2020; Ambuhl and Sorensen, 2017; Bismut and Straub, 2021; Farhan et al., 2021; Florian and Sorensen, 2017; Long et al., 2020; Madsen et al., 1991; Martinez-Luengo and Shafiee, 2019; Moan, 2005; Nielsen and Sorensen, 2010; Pozzi and Kiureghian, 2011; Schneider et al., 2019; Straub, 2004; Thöns, 2018). Although such cost models enable an optimization of I&M activities, they lack the ability to fully quantify the effect of the uncertainties in the I&M costs on the total expected costs of an I&M strategy.

In this paper, we present a probabilistic cost model of I&M of support structures in an offshore wind farm serviced by boats operating from a port base. The model is developed based on interviews with a wind farm operator, consultants, and O&M engineers, as well as on scientific literature. It is employed to evaluate the probabilistic I&M costs at the level of a wind farm, structural system, and structural component. In addition, a risk-informed decision and value of information (VoI) analysis is performed in which we optimize the I&M regime of a steel frame subject to fatigue and utilize the probabilistic cost model. In the numerical example, we demonstrate that the I&M costs can be considered deterministically as expected values in the analysis since they are included in the model on a linear basis.

The paper is organized as follows: Section 2 presents a generic decision-theoretical framework considering probabilistic I&M costs, which forms the basis for optimizing I&M regimes. In Section 3, different types of I&M methods for support structures in offshore wind farms are discussed. Based on this discussion, different factors are identified that influence the overall cost of an I&M regime and make it uncertain. Furthermore, different ranges of these variables are also presented, as estimated by wind farm operators. To quantify the overall cost of an I&M regime, first a deterministic cost model is established in Section 4. Subsequently, in Section 5, a probabilistic I&M model is constructed by combining the deterministic cost model with a probabilistic model of its uncertain parameters. In Section 6, sensitivity analyses are performed to identify the variables driving the overall I&M costs. Section 7 presents the numerical example. A summary is presented at the end, followed by conclusions in Section 8.

2 Generic framework for optimizing I&M of support structures in offshore wind farms considering probabilistic I&M costs

In this section, a generic decision-theoretic framework for optimizing I&M of support structures in offshore wind farms is presented. The presentation of the material closely follows our previous work (Farhan et al., 2021). Note, however, that our current contribution explicitly considers the uncertainties in the I&M costs in the decision-making.

2.1 Decision analysis

The identification of an optimal I&M regime for support structures in offshore wind farms is a decision problem under uncertainty and risk (Farhan et al., 2021). This class of problems can be solved based on Bayesian decision theory (Raiffa and Schlaifer, 1961). This decision problem can be represented by the generic decision tree shown in Figure 1. Each branch of the decision tree corresponds to a realization of decisions represented by square nodes and events/random variables represented by circular nodes. As an example, the lower path in the decision tree in Figure 1 corresponds to the realization of (a) a decision i concerning the information acquisition strategy, (b) the corresponding probabilistic inspection/monitoring outcomes $\mathbf{Z}_i$, (c) the decisions $\mathbf{a}$ concerning maintenance actions, (d) the probabilistic parameters $\mathbf{Y}$ influencing the outcomes of maintenance actions, (e) the probabilistic parameters $\mathbf{X}$ influencing the system state and (f) the probabilistic parameters $\mathbf{W}$ influencing the I&M costs. Each of these realizations is associated with a utility u represented by diamond shaped nodes. The optimal decisions concerning information acquisition and maintenance actions are determined by maximizing the expected utility and/or value of information (VoI) (Thöns, 2018).

According to utility theory (Von Neumann and Morgenstern, 1947), the expected value of the utility u quantifies the optimality of decisions (Farhan et al., 2021). With respect to the structural integrity management of support structures in offshore wind farms, the utility u may be generically expressed as a function of the economic benefits b from operating the wind farm and the total lifetime costs, broken down into monitoring costs c_{SHM}, inspection costs c_I, maintenance costs c_M and failure costs c_F (see also Sorensen, 2009):

$$\begin{aligned} u(i, \mathbf{Z}_i, \mathbf{a}, \mathbf{Y}, \mathbf{X}, \mathbf{W}) \\ = b(i, \mathbf{Z}_i, \mathbf{a}, \mathbf{Y}, \mathbf{X}, \mathbf{W}) - c_{SHM}(i, \mathbf{Z}_i, \mathbf{a}, \mathbf{Y}, \mathbf{X}, \mathbf{W}) - c_I(i, \mathbf{Z}_i, \mathbf{a}, \mathbf{Y}, \mathbf{X}, \mathbf{W}) \\ - c_M(i, \mathbf{Z}_i, \mathbf{a}, \mathbf{Y}, \mathbf{X}, \mathbf{W}) - c_F(i, \mathbf{Z}_i, \mathbf{a}, \mathbf{Y}, \mathbf{X}, \mathbf{W}) \end{aligned} \quad (1)$$

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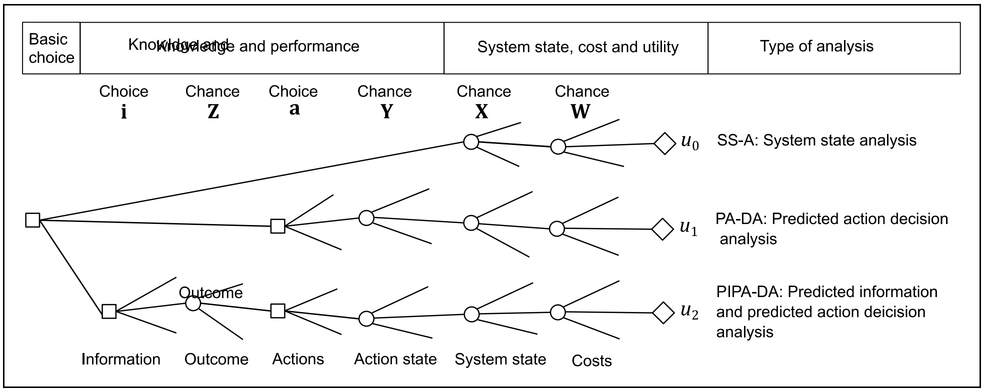

Figure 1. *Generic decision tree for modeling decisions concerning information acquisition and maintenance actions (adapted from Thöns (2018)). The tree consists of square nodes representing decisions, circular nodes representing random events and diamond shaped nodes representing utility.*

The topmost branch of the generic decision tree in Figure 1 illustrates a system state analysis (SS-A) (see also Thöns and Kapoor, 2019), which establishes the expected utility $\mathbb{E}[U_0]$ based on the prior probabilistic system model as:

$$\mathbb{E}[U_0] = \mathbb{E}_{\mathbf{X},\mathbf{W}}[u_0(\mathbf{X},\mathbf{W})] \tag{2}$$

where $\mathbb{E}_{\mathbf{X},\mathbf{W}}[u_0(\mathbf{X},\mathbf{W})]$ is the expected value of the utility function $u_0(\mathbf{X},\mathbf{W})$ with respect to the random variables **X** and **W** that influence the system state and costs. $u_0(\mathbf{X},\mathbf{W})$ is defined as the difference between the total monetarized benefits and the failure costs:

$$u_0(\mathbf{X},\mathbf{W}) = b(\mathbf{X},\mathbf{W}) - c_F(\mathbf{X},\mathbf{W}) \tag{3}$$

The branch in the center of the tree represents a predicted action decision analysis (PA-DA) (see also Thöns and Kapoor, 2019). In this analysis, the expected utility $\mathbb{E}[U_1|\mathbf{a}]$ is conditional on the predicted maintenance actions **a,** and computed with respect to the random variables **Y**, **X** and **W**, which influence the associated action implementation states, system state and maintenance costs. The optimal maintenance actions $\mathbf{a}^*$ are identified by maximizing the expected value of U_1:

$$\mathbf{a}^* = \arg\max_{\mathbf{a}} \mathbb{E}[U_1|\mathbf{a}] \quad \text{with} \quad \mathbb{E}[U_1|\mathbf{a}] = \mathbb{E}_{\mathbf{Y},\mathbf{X},\mathbf{W}}[u_1(\mathbf{a},\mathbf{Y},\mathbf{X},\mathbf{W})] \tag{4}$$

where $\mathbb{E}_{\mathbf{Y},\mathbf{X},\mathbf{W}}[u_1(\mathbf{a},\mathbf{Y},\mathbf{X},\mathbf{W})]$ is the expected value of the utility function $u_1(\mathbf{a},\mathbf{Y},\mathbf{X},\mathbf{W})$ with respect to **Y**, **X**, and **W**. $u_1(\mathbf{a},\mathbf{Y},\mathbf{X},\mathbf{W})$ is expressed as the difference between the total monetarized benefits and the costs of maintenance actions and failure:

$$u_1(\mathbf{a},\mathbf{Y},\mathbf{X},\mathbf{W}) = b(\mathbf{a},\mathbf{Y},\mathbf{X},\mathbf{W}) - c_M(\mathbf{a},\mathbf{Y},\mathbf{X},\mathbf{W}) - c_F(\mathbf{a},\mathbf{Y},\mathbf{X},\mathbf{W}) \tag{5}$$

The expected utility U_1 conditional on the optimal maintenance action $\mathbf{a}^*$, $\mathbb{E}[U_1|\mathbf{a}^*]$, is then calculated as:

$$\mathbb{E}[U_1|\mathbf{a}^*] = \mathbb{E}_{\mathbf{Y},\mathbf{X},\mathbf{W}}[u_1(\mathbf{a}^*,\mathbf{Y},\mathbf{X},\mathbf{W})] \tag{6}$$

The lower branch of the decision tree constitutes a predicted information and predicted action decision analysis (PIPA-DA) (see also Thöns and Kapoor, 2019), which optimizes the decision on the information acquisition strategy together with decisions on the maintenance actions. In

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this analysis, the utility is maximized based on (a) predicted information on the system condition and performance, (b) predicted maintenance actions and (c) corresponding benefits and costs. When applying the extensive form of the analysis (Raiffa and Schlaifer, 1961), the optimization is progressed from the leaf of the branch towards the node representing the decision on the information acquisition strategy i. The analysis starts by determining the optimal action $\mathbf{a}^*_{|\mathbf{z}_i}$ conditional on a certain realization of the inspection/monitoring outcomes $\mathbf{Z}_i = \mathbf{z}_i$ corresponding to a given information acquisition strategy i as:

$$\mathbf{a}^*_{|\mathbf{z}_i} = \arg\max_{\mathbf{a}} \mathbb{E}_{\mathbf{Y},\mathbf{X},\mathbf{W}|\mathbf{Z}_i=\mathbf{z}_i}[u_2(i, \mathbf{z}_i, \mathbf{a}, \mathbf{Y}, \mathbf{X}, \mathbf{W})] \tag{7}$$

wherein $\mathbb{E}_{\mathbf{Y},\mathbf{X},\mathbf{W}|\mathbf{Z}_i=\mathbf{z}_i}[u_2(i, \mathbf{z}_i, \mathbf{a}, \mathbf{Y}, \mathbf{X}, \mathbf{W})]$ is the conditional expected value of the utility function $u_2(i, \mathbf{z}_i, \mathbf{a}, \mathbf{Y}, \mathbf{X}, \mathbf{W})$ with respect to $\mathbf{Y}$, $\mathbf{X}$ and $\mathbf{W}$ conditional on $\mathbf{Z}_i = \mathbf{z}_i$. $u_2(i, \mathbf{Z}_i, \mathbf{a}, \mathbf{Y}, \mathbf{X}, \mathbf{W})$ is equal to the utility function u defined in Eq. (1).

Subsequently, the optimal information acquisition strategy i^* is obtained as:

$$i^* = \arg\max_{i} \mathbb{E}_{\mathbf{Z}_i}[\mathbb{E}_{\mathbf{Y},\mathbf{X},\mathbf{W}|\mathbf{Z}_i}[u_2(i, \mathbf{Z}_i, \mathbf{a}^*_{|\mathbf{Z}_i}, \mathbf{Y}, \mathbf{X}, \mathbf{W})]] \tag{8}$$

where $\mathbb{E}_{\mathbf{Z}_i}[\cdot]$ is the expectation with respect to $\mathbf{Z}_i$. The maximum expected value of U_2 conditional on i^*, $\mathbb{E}[U_2|i^*]$, is calculated as:

$$\mathbb{E}[U_2|i^*] = \mathbb{E}_{\mathbf{Z}_{i^*}}[\mathbb{E}_{\mathbf{Y},\mathbf{X},\mathbf{W}|\mathbf{Z}_{i^*}}[u_2(i^*, \mathbf{Z}_{i^*}, \mathbf{a}^*_{|\mathbf{Z}_{i^*}}, \mathbf{Y}, \mathbf{X}, \mathbf{W})]] \tag{9}$$

From Eq. (7), (8) and (9), it can be seen that a PIPA-DA cannot be summarized in a single optimization problem if the extensive form of the analysis is applied. As shown in Eq. (7), the optimal decisions on the maintenance actions $\mathbf{a}^*_{|\mathbf{z}_i}$ can only be determined conditional on a certain realization of the inspection/monitoring outcomes $\mathbf{Z}_i = \mathbf{z}_i$. In addition, Eq. (8) and (9) imply that the decision maker upon knowing the inspection/monitoring outcomes $\mathbf{Z}_i = \mathbf{z}_i$ will always make the optimal maintenance decisions $\mathbf{a}^*_{|\mathbf{z}_i}$.

2.2 Value of information analysis

The root node in the decision tree in Figure 1 represents the basic decision concerning the adoption of an integrity management strategy (Thöns, 2018). This decision can be informed by a VoI analysis. Following Thöns and Kapoor (2019), three different VoI's may be formulated based on the decision tree shown in Figure 1. The first type of VoI i.e., $VoI_{PA\text{-}DA}^{PIPA\text{-}DA}$ is defined as the difference between the expected utility maximized with the PIPA-DA, $\mathbb{E}[U_2|i^*]$, and the expected utility maximized with the PA-DA, $\mathbb{E}[U_1|\mathbf{a}^*]$, i.e.:

$$VoI_{PA\text{-}DA}^{\text{PIPA-DA}} = \mathbb{E}[U_2|i^*] - \mathbb{E}[U_1|\mathbf{a}^*] \tag{10}$$

The second type $VoI_{SS\text{-}A}^{PIPA\text{-}DA}$ is defined as the difference between the expected utility maximized with the PIPA-DA, $\mathbb{E}[U_2|i^*]$, and the expected utility of the SS-A, $\mathbb{E}[U_0]$:

$$VoI_{SS\text{-}A}^{\text{PIPA-DA}} = \mathbb{E}[U_2|i^*] - \mathbb{E}[U_0] \tag{11}$$

According to the third type, the $VoI_{SS\text{-}A}^{PA\text{-}DA}$ is the difference between the expected utility maximized with PA-DA and the expected utility of SS-A given as:

$$VoI_{SS\text{-}A}^{\text{PA-DA}} = \mathbb{E}[U_1|\mathbf{a}^*] - \mathbb{E}[U_0] \tag{12}$$

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In the essence, an integrity management strategy should be implemented based on the VoI analyses given that the value of $VoI_{PA\text{-}DA}^{PIPA\text{-}DA}$, $VoI_{SS\text{-}A}^{PIPA\text{-}DA}$ or $VoI_{SS\text{-}A}^{PA\text{-}DA}$ is positive.

3 I&M of support structures in offshore wind farms

3.1 I&M methods

Inspections are performed to obtain information on the condition of structural components. Inspections of offshore wind turbine support structures look for (indicators of) damages (e.g., corrosion and/or fatigue cracks), that pose a risk to the integrity of the structural system. In this contribution, a probabilistic cost model is developed for I&M actions performed to detect and repair fatigue cracks in welded connections in steel support structures of wind turbines in offshore wind farms (e.g., monopiles, jackets, etc.). In such structural systems, the welded components subject to fatigue can be located above and below water level. The components located above water are typically part of the turbine tower, transition piece, main access platform, and access systems, which can be inspected via rope access and getting closer to the structure, while in the areas of the transition piece and sub structure below water, inspections are carried out by a dive, or by utilizing a remotely operated vehicle (ROV). This division has an effect on the required personnel, vessels, equipment, and logistics.

Two types of inspection methods to identify fatigue damage in welded components located above and/or below water level are considered: visual inspection, and electromagnetic (EM) inspection methods such as eddy current (EC), magnetic particle inspection (MPI) and alternating current field measurement (ACFM). Visual inspection is a coarse method capable to detect only relatively large surface breaking defects in welds or fatigue failures of welded connections. It can be performed with the help of a camera mounted on an ROV or by naked-eye observation. In contrast, EM inspection methods detect smaller surface breaking defects in welds. They can also be applied by a diver below water.

After an inspection campaign, if any fatigue damage is detected, a subsequent maintenance action (e.g., a repair) is performed on the basis of the inspection results. Depending on the criticality of the identified fatigue damage, the maintenance campaign is launched in the same year or the following year.

During an inspection campaign, the length and depth of a detected surface-breaking defect is measured to inform decisions on the repair methods. With regards to possible repairs for welded joints, we consider two methods. The first repair method is referred to as welding (Rodriguez-Sanchez et al., 2011). In this method, the welded joint is repaired by removing a surface crack through grinding and subsequent filling of the resulting groove with wet welding. This method is applied if the measured depth of the surface crack is greater than a defined percentage of the section thickness. Any surface crack with a measured depth less than the defined percentage of the section thickness may be repaired by grinding, which is the second repair method (Rodriguez-Sanchez et al., 2004).

3.2 Cost-affecting factors for I&M

There are several factors that influence the total cost of an I&M regime for support structures in an offshore wind farm. The influencing factors have been identified and their costs have been estimated based on scientific literature and interviews with experts on the I&M: a wind farm operator, consultants, and operational engineers—who may not be representative of all wind farms of this category but were able to provide an approximate estimation. The precise figures always depend on the actual wind farm layout and the existing operational constraints. In this study, we assume a case in which the wind farm is serviced by boats operating from a nearby port base. Therefore, other forms of wind farm access such as Heli-support, are not considered in this study.

Accessibility is the main factor influencing the I&M regime of turbine support structures. Depending on the locality of the offshore wind farm, the I&M activity (above water level (AW) and/or below water level (BW)), the operational duration of the I&M activity, a certain type of vessel is employed. The choice of vessel for port-based operations could be a crew transfer vessel (CTV) or a service operation vessel (SOV). CTV are usually used for frequent operations and are generally small aluminum catamarans employed to transfer personnel to and from offshore sites on a daily basis. CTV do not have sufficient dynamic positioning redundancies to keep still during rough sea conditions. Their carrying capacity is usually 12 crew members who do 12-hour shifts. SOV are bigger vessels designed and equipped to be present for a longer duration at the offshore wind farm for subsea or extensive I&M operations. These vessels have a capacity of around 40 technicians and can perform 24-hour operations with multiple shifts (each shift is 12 hours), which means that they come back to port only approximately once every two weeks (Martinez-Luengo and Shafiee, 2019). Table 1 shows the range of mobilization and demobilization costs and daily rates for both CTV and SOV.

Table 1. *Estimates of vessel costs*

	Type of vessel	
Type of vessel cost	**CTV**	**SOV**
Mobilization / demobilization (€)	2,000 - 20,000	15,000 – 80,000
Operational rate (€/shift)	1,000 - 15,000	10,000 – 50,000

The mobilization and demobilization costs of the vessels cover several aspects like commuting time to the offshore wind farm and back, fuel consumption of the vessel, and project management costs, which account for logistics organization and reporting. The operational rate of the vessel per shift comprises how many people can intervene in the operation, the personnel costs per shift, equipment costs, and the operational cost of the vessel during the I&M activity.

I&M also include the additional effort for engineering the required repairs. This effort is associated with costs as summarized in Table 2. The engineering costs usually dependent on the type of repair. In the case of grinding, the extra cost of engineering and preparation entails the design of the repair, laboratory tests, etc. In the case of welding, the cost entails the design of the repair, chambers for underwater repair work if required, special equipment and/or materials, laboratory tests, etc. This additional cost is usually incurred once during the service life of a wind farm because the type of hotspots/components is known; thus, if any repair is performed, the implementation of the repair has already been planned for the specific type of hotspot in the support structures.

Table 2. *Estimates of engineering costs*

Type of repair	Engineering cost (€)
Grind repair	5,000 – 35,000
Weld repair	10,000 – 100,000

The duration to complete a I&M activity is another factor that strongly influences the total I&M cost. It depends, for example, on the weather conditions, the experience of the personnel, the condition of the asset and the existence of marine growth. The total time to complete a I&M activity usually entails transit time between WT, the time required to complete the work

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package once stationed at a WT, and additional weather downtime due to unfavorable weather conditions. An increase in I&M activity time due to the aforementioned factors can lengthen the offshore time within a campaign. While this may not seem crucial, the time increase has an effect on other costs, such as the costs of the deployment of a vessel, personnel, and equipment. Table 3 shows the estimation of the time that each of the I&M activities takes for a single component in a support structure. A component is here defined as a hotspot in a welded connection (i.e., a certain section of a weld).

Table 3. *I&M activity: type, location, and estimates of the duration per component*

Type of activity	Location	hrs./component
Weld repair	Above water	50 – 58
	Below water	60 – 70
Grind repair	Above water	14 – 18
	Below water	24 – 30
Visual inspection	Above water	1 – 2
	Below water	5 – 8
EM inspection	Above water	4 – 6
	Below water	10 – 15

Weather downtime is mostly dependent on the type of vessel utilized and is given in Table 4. In the case of CTV, the weather downtime is usually higher because they are small in size and lighter compared to SOV and can easily lose position, especially if there are large waves and strong currents, while SOV can safely withstand the harshest conditions even in winter.

Table 4. *Estimates weather downtime in function of the vessel type*

Type of vessel	Weather downtime
CTV	30 – 40%
SOV	10 – 15 %

The transit time between turbines also influences the inspection maintenance cost. It is here estimated based Martinez-Luengo and Shafiee (2019), and usually varies between 15 to 30 minutes.

4 Deterministic cost model

Taking into account the factors influencing the I&M, we develop a cost model that estimates the total cost of I&M for an offshore wind farm. The cost of I&M can be generally broken down into a campaign cost C_C, engineering cost C_E, and operational cost C_{Op}. In a case I&M are performed simultaneously (mixed I&M), the total cost $C_{I\&M}$ is given as:

$$C_{I\&M} = C_{I\&M_C} + C_{I\&M_E} + C_{I\&M_{Op}} \tag{13}$$

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where $C_{I\&M_C}$ is the campaign cost, $C_{I\&M_E}$ is the engineering cost, and $C_{I\&M_{Op}}$ is the operational cost.

In the usual case where inspections and maintenance are performed in separate campaigns, the total cost of inspection C_I and the total cost of maintenance C_M is given by:

$$\begin{aligned} C_I &= C_{I_C} + C_{I_{Op}} \\ C_M &= C_{M_C} + C_{M_E} + C_{M_{Op}} \end{aligned} \tag{14}$$

where C_{I_C} and C_{M_C} are the campaign costs for inspection and maintenance. The campaign cost is usually the fixed one-time cost of initiating the I&M activities, which includes the cost of commuting to the wind farm and back, necessary equipment for the offshore environment, fuel cost, and project management costs. All these components of campaign costs are here included in the mobilization and demobilization cost of the vessel. The choice of vessel could be CTV or SOV depending on the nature and extent of the I&M activities as discussed in Section 3.2. In the case of maintenance, an additional cost of planning and engineering the repair C_{M_E} is included and is dependent on the choice of repair method (welding or grinding).

Moreover, $C_{I_{op}}$ and $C_{M_{op}}$ is the operational cost of inspection and maintenance, which is the cost of conducting the inspection or maintenance operation when the vessel is mobilized at the offshore wind farm. The total operational cost further depends on the time to complete the maintenance operation, the vessel utilized, and its shift pattern. The total time to complete the operation depends on the extent of the I&M activity and where it is carried out, i.e., above or below water. The operational cost of inspection $C_{I_{op}}$ and maintenance $C_{M_{op}}$ activity is given by:

$$\begin{aligned} C_{I_{op}} &= \frac{t_{I_{op}}}{t_{shift_{vessel}}} \times C_{vessel/shift} \\ C_{M_{op}} &= \frac{t_{M_{op}}}{t_{shift_{vessel}}} \times C_{vessel/shift} \end{aligned} \tag{15}$$

where $C_{vessel/shift}$ is the operational rate of the vessel (CTV or SOV) per shift, $t_{shift_{vessel}}$ is the duration of a shift (in hours) in which a vessel can operate with the crew present in it, $t_{I_{op}}$ is the total time (in hours) to complete the inspection operation, and $t_{M_{op}}$ is the total time to complete the maintenance operation. The total operational time for I&M is estimated as:

$$\begin{aligned} t_{I_{op}} &= \left[\left[\sum_{i=1}^{n_{I_{WT}}} n_{I_c,i} \cdot t_{I_c}\right] + (n_{I_{WT}} - 1) \cdot t_{transit}\right] \cdot (1 + WD_{vessel}) \\ t_{M_{op}} &= \left[\left[\sum_{i=1}^{n_{M_{WT}}} n_{M_c,i} \cdot t_{M_c}\right] + (n_{M_{WT}} - 1) \cdot t_{transit}\right] \cdot (1 + WD_{vessel}) \end{aligned} \tag{16}$$

where $n_{I_{WT}}$ is the total number of WT to be inspected in an offshore wind farm during an inspection campaign, $n_{M_{WT}}$ is the total number of WT to be repaired in the offshore wind farm during a maintenance campaign, $n_{I_c,i}$ is the number of components to be inspected in the ith WT support structure in the offshore wind farm, $n_{M_c,i}$ is the number of components to be repaired in the ith WT support structure in the offshore wind farm, $t_{transit}$ is the transit time between the different WT, t_{I_c} is the time to inspect a component above or below the water, and

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t_{M_c} is the time to repair a component above or below water. Furthermore, WD_{vessel} is the weather-related downtime dependent on the type of vessel utilized.

5 Probabilistic cost model

The cost model developed in Section 4 provides deterministic estimates of I&M costs. However, due to the uniqueness of each operation, and the complexity of the individual activities involved, the different parameters governing Eq. (13), (14), (15), and (16) – i.e., the campaign cost, the vessel costs, the engineering costs, the inspection duration, the repair duration, the transit time, and the weather downtime – are uncertain and their values are typically only known in terms of intervals, as estimated in Section 3.2. To capture these uncertainties, the parameters of the cost model are modeled as random variables. By probabilistically modeling the uncertainties in the parameters and propagating them through the deterministic cost model, a probabilistic description of the I&M costs is obtained.

Let $\mathbf{W}$ denote the vector of random parameters influencing the total I&M costs. Based on Eq. (14), (15), and (16), the probabilistic cost model of inspection $C_I(\mathbf{W})$ can now be written as:

$$C_I(\mathbf{W}) = C_{I_C} + \frac{\left[\left[\sum_{i=1}^{n_{I_{WT}}} n_{I_C,i} \cdot t_{I_c}\right] + (n_{I_{WT}} - 1) \cdot t_{transit}\right] \cdot (1 + WD_{vessel})}{t_{shift_{vessel}}} \times C_{vessel/shift} \tag{17}$$

Similarly, the probabilistic cost model of maintenance $C_M(\mathbf{W})$ can be formulated as:

$$C_M(\mathbf{W}) = C_{M_C} + C_{M_E} + \frac{\left[\left[\sum_{i=1}^{n_{M_{WT}}} n_{M_c,i} \cdot t_{M_c}\right] + (n_{M_{WT}} - 1) \cdot t_{transit}\right] \cdot (1 + WD_{vessel})}{t_{shift_{vessel}}} \times C_{vessel/shift} \tag{18}$$

Due to the lack of data on the parameters in $\mathbf{W}$, their marginal probability distributions are assumed to be lognormal. The parameters of the different probability distributions are determined based on the intervals provided in Table 1, Table 3 and Table 4, where 1% of the parameter values are assumed to be smaller than minimum value of the corresponding interval and 5% of the parameter values are assumed to be larger than maximum value of the corresponding interval. Figure 2 illustrates a fitted lognormal distribution based on the estimated intervals.

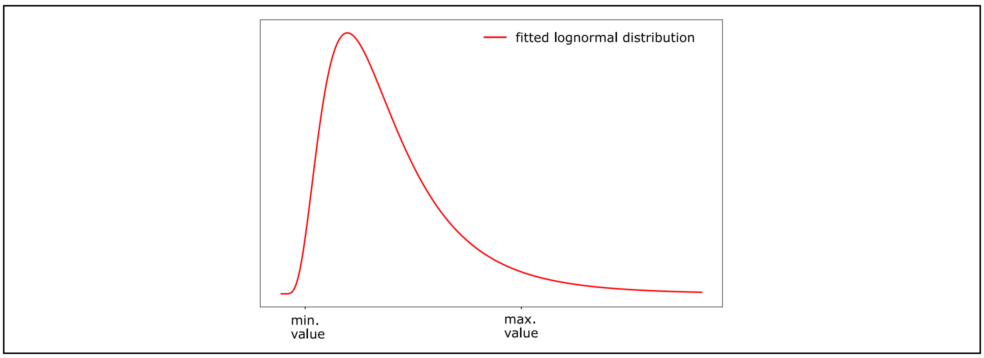

Figure 2. *Lognormal distribution fitted based on the minimum and maximum value of the estimated parameter interval*

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The estimated mean and coefficient of variation (CoV) of each probabilistic parameter of the cost models are summarized Table 5.

Table 5. *Mean and coefficient of variation (CoV) of the probabilistic parameters of the cost model*

Parameter	Description	Unit	Distribution	Mean	CoV
$C_{I_{C_{CTV}}}$	Campaign cost (CTV)	[€]	lognormal	9111.04	0.63
$C_{I_{C_{SOV}}}$	Campaign cost (SOV)	[€]	lognormal	43771.22	0.44
$C_{CTV/shift}$	Vessel cost per shift (CTV)	[€/shift]	lognormal	6220.67	0.78
$C_{SOV/shift}$	Vessel cost per shift (SOV)	[€/shift]	lognormal	27744.47	0.42
$t_{I,EM_{c.BW}}$	Duration of component inspection (EM, below water)	[hrs.]	lognormal	12.73	0.10
$t_{I,EM_{c.AW}}$	Duration of component inspection (EM, above water)	[hrs.]	lognormal	5.10	0.10
$t_{I,V_{c.BW}}$	Duration of component inspection (visual inspection, below water)	[hrs.]	lognormal	6.63	0.12
$t_{I,V_{c.AW}}$	Duration of component inspection (visual inspection, above water)	[hrs.]	lognormal	1.53	0.17
$C_{E,weld}$	Engineering cost (welding)	[€]	lognormal	45719.43	0.63
$C_{E,grind}$	Engineering cost (grinding)	[€]	lognormal	17584.96	0.51
$t_{M,weld_{c.BW}}$	Duration of component repair (welding, below water)	[hrs.]	lognormal	65.74	0.03
$t_{M,weld_{c.AW}}$	Duration of component repair (welding, above water)	[hrs.]	lognormal	54.59	0.03
$t_{M,grind_{c.BW}}$	Duration of component repair (grinding, below water)	[hrs.]	lognormal	27.41	0.05
$t_{M,grind_{c.AW}}$	Duration of component repair (grinding above water)	[hrs.]	lognormal	16.24	0.06
$t_{transit}$	Transit time between turbines	[hrs.]	lognormal	0.38	0.17
WD_{CTV}	Weather downtime (CTV)	-	lognormal	0.35	0.07
WD_{SOV}	Weather downtime (SOV)	-	lognormal	0.12	0.10

6 Quantification of probabilistic I&M costs and sensitivity analysis

6.1 Probabilistic analysis of I&M costs

The probabilistic cost model for I&M of turbine support structures in the offshore wind farm defined in Equations (17) and (18) can be applied for different combinations of input parameters. The different combinations are defined by the type of vessel, the inspection and repair methods, the number of inspected and/or repaired components above and/or below water

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level, and the number of inspected and/or repaired wind turbine support structures. For the purpose of illustration, the probabilistic I&M costs are in the following estimated at wind farm, wind turbine and component level.

First, the total I&M costs are estimated at wind farm level. To this end, it is assumed that $n_{I_{c,BW}} = 10$ components of $n_{I_{WT}} = 10$ support structures are inspected below water. In addition, it is assumed that $n_{M_{c,BW}} = 5$ components of $n_{M_{WT}} = 5$ support structures are repaired below water. Inspections are performed using EM and visual inspection methods, while welding and grinding are applied as repair methods. Moreover, a CTV is utilized as transport vessel in each scenario. For each considered scenario, the probabilistic distributions of the total I&M costs are determined using Monte Carlo (MC) simulations with $n_{MC} = 10^6$ samples of the corresponding model parameters. In the analysis, the model parameters are assumed to be statistically independent. The resulting empirical probability distributions of the total I&M costs are shown in Figure 3.

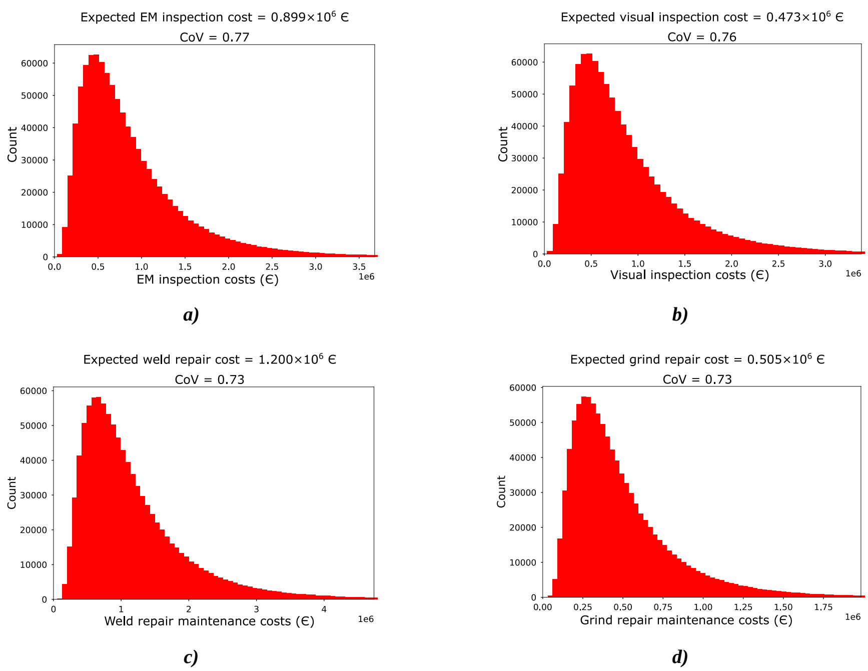

Figure 3. *Empirical probability distributions of the total I&M costs:* ***a)*** *10 components in each 10 support structures are inspected below water with EM inspection technique,* ***b)*** *10 components in each 10 support structures are visually inspected below water,* ***c)*** *5 components in each 5 support structures are repaired below water by welding,* ***d)*** *5 components in each 5 support structures are repaired below water by grinding*

Second, the total I&M costs are estimated at turbine level. In this case, it is assumed that 10 components of a support structure are inspected below water level, i.e., $n_{I_{WT}} = 1$, $n_{I_{c,BW}} = 10$; and 5 components in a support structure are repaired below water level, i.e., $n_{M_{WT}} = 1$, $n_{M_{c,BW}} = 5$. The assumptions regarding inspection and repair methods and the choice of vessel are the same as in the previous scenario considering I&M at wind farm level. The estimated empirical probability distributions of the total I&M costs together with their expected value and CoV are shown in Figure 4.

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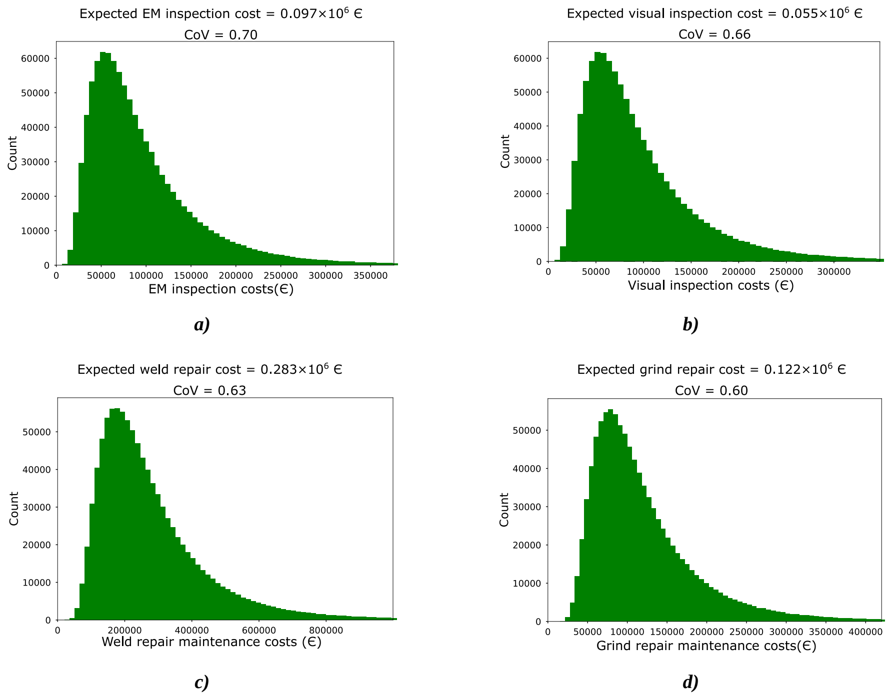
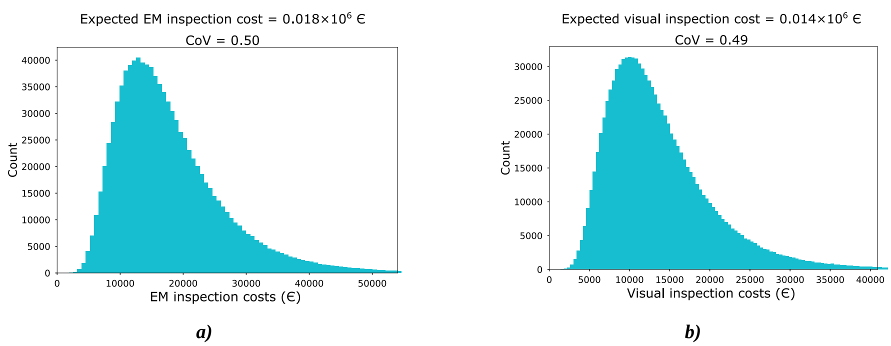


Figure 4. *Empirical distributions of the total I&M costs:* ***a)*** *10 components of a turbine support structures are inspected below water with EM inspection technique,* ***b)*** *10 components of a turbine support structures are visually inspected below water,* ***c)*** *5 components of a turbine support structures are repaired below water by welding,* ***d)*** *5 components of a turbine support structures are repaired below water by welding*

Finally, the total I&M costs are estimated at element level. In this scenario, $n_{I_{c,BW}} = 1$ components of $n_{I_{WT}} = 1$ turbines are inspected below water. The same is assumed for the maintenance campaign, i.e., only $n_{M_{c,BW}} = 1$ component of $n_{M_{WT}} = 1$ turbine support structure is repaired below water. The assumptions regarding inspection and repair methods and the choice of vessel are the same as in the scenario considering I&M at wind farm level. The empirical probability distributions of the total I&M costs are shown in Figure 5.



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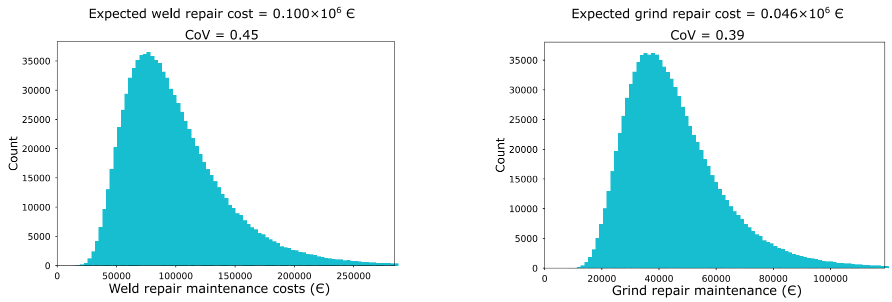

c) ***d)***

Figure 5. *Empirical distributions of the total I&M costs:* ***a)*** *EM inspection of a component in a support structure below water level,* ***b)*** *visual inspection of a component in a support structure below water level,* ***c)*** *welding repair maintenance of a component repaired below water level for a support structure,* ***d)*** *grinding repair maintenance of a component repaired below water level for a support structure*

A summary of the uncertainty quantification of the I&M costs from Figure 3, Figure 4 and Figure 5 is given in Table 6.

Table 6. *Summary of the uncertainty quantification of the total I&M costs*

		Wind farm	**Wind turbine**	**Component**
EM inspection	Expected value (10^6€)	0.899	0.097	0.018
	CoV	0.77	0.70	0.50
Visual inspection	Expected value (10^6€)	0.473	0.055	0.014
	CoV	0.76	0.66	0.49
Weld repair	Expected value (10^6€)	1.200	0.283	0.100
	CoV	0.73	0.63	0.45
Grind repair	Expected value (10^6€)	0.505	0.122	0.046
	CoV	0.73	0.60	0.39

6.2 Sensitivity analysis

As discussed in Sections 3 to 5, I&M costs are influenced by numerous uncertain parameters $\mathbf{W}$. To study the importance of each model parameter W_i, a variance-based sensitivity analysis is performed (Sobol, 1993), which quantifies W_i's effect on the variance of the inspection and maintenance costs in terms of the following first-order measure:

$$V_i = \mathrm{Var}_{W_i}\{\mathbb{E}_{\boldsymbol{W}_{-i}}[C(\mathbf{W})|W_i]\} \tag{19}$$

where $C(\mathbf{W})$ can be the probabilistic model of the inspection costs defined in Eq. (17) or the probabilistic model of the maintenance costs defined in Eq. (18), $\mathbb{E}_{\boldsymbol{W}_{-i}}[C(\mathbf{W})|W_i]$ is the expected value of the inspection or maintenance costs with respect to all parameters except W_i whose value is fixed, and $\mathrm{Var}_{W_i}\{\mathbb{E}_{\boldsymbol{W}_{-i}}[C(\mathbf{W})|W_i]\}$ is the variance of this average model. Normalizing V_i with the variance $\mathrm{Var}[C(\mathbf{W})]$ provides the first order sensitivity index S_i (Sobol, 1993):

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$$S_i = \frac{V_i}{\mathrm{Var}[C(\mathbf{W})]} = \frac{\mathrm{Var}_{W_i}\{\mathbb{E}_{\mathbf{W}_{-i}}[C(\mathbf{W})|W_i]\}}{\mathrm{Var}[C(\mathbf{W})]} \tag{20}$$

in which $\mathrm{Var}[C(\mathbf{W})]$ is the variance of the inspection or maintenance costs. S_i is here evaluated using a MC approach (Sobol, 2001).

6.2.1 Inspection costs

The first part of sensitivity study quantifies the effect of the campaign cost, vessel operation cost, and inspection operation time on the total inspection costs based on the probabilistic cost model defined in Eq. (17), where inspection operation time depends on the duration of a component inspection, the transit time between turbines, and the weather downtime. The analysis considers different scenarios which depend on the inspection method (visual or EM), the vessel type (CTV or SOV), the location of the inspected components (above or below water), the number inspected turbine support structures and the number of inspected components in each structure. The results are shown in Figure 6 and Figure 7, in which the columns correspond to the number of inspected turbines and the rows correspond to a certain combination of vessel type (SOV or CTV) and location of the inspected components (above or below water). In each subplot, the sensitivity index of the campaign cost, vessel operation cost, and inspection operation time is provided in function of the number of inspected components.

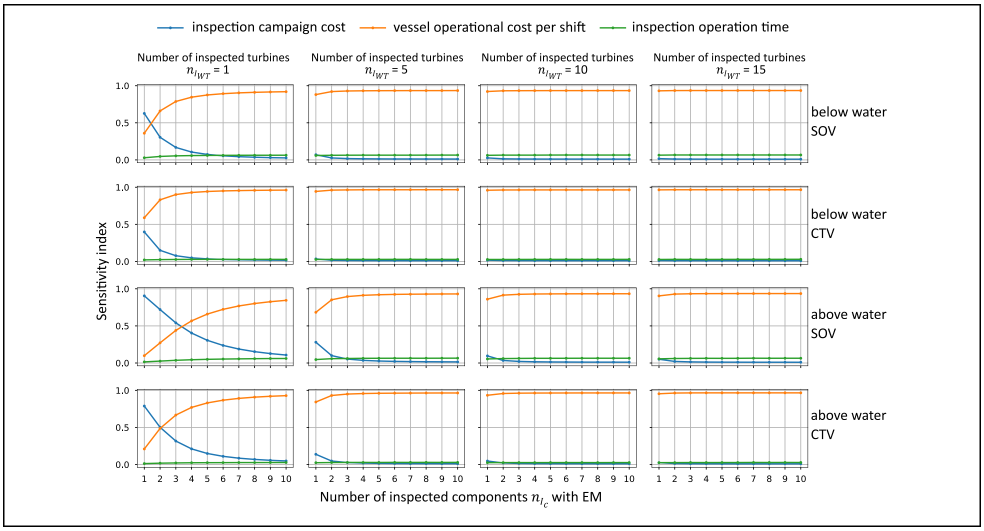

Figure 6. *Sensitivity indices of the campaign cost, vessel operation cost, and inspection operation time in function of the vessel type (CTV or SOV), the location of the inspected components (above or below water), the number inspected turbine support structures and the number of inspected components in each support structure. Inspections are performed with EM inspection method*

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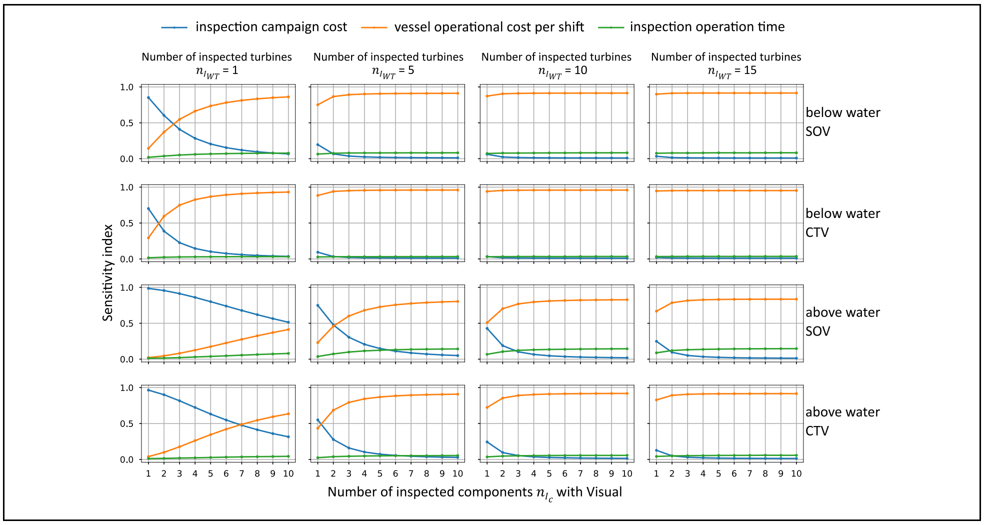

Figure 7. *Sensitivity indices of the campaign cost, vessel operation cost, and inspection operation time in function of the vessel type (CTV or SOV), the location of the inspected components (above or below water), the number inspected turbine support structures and the number of inspected components in each support structure. Inspections are performed with visual inspection method*

In Figure 6 and Figure 7, it can be observed that the campaign cost significantly impacts the overall inspection costs for both inspection methods (EM and visual) when fewer components are inspected within a single support structure. In contrast, the vessel operation cost has the largest effect on the total inspection costs when a larger number of turbines and components are inspected. These results confirm that the significance of different cost factors depends on the adopted inspection plan.

6.2.2 Maintenance costs

The second part of sensitivity study evaluates the impact of the uncertain parameters defined in Eq. (18). The sensitivity analysis considers different scenarios in terms of combinations of the repair method (grinding or welding), the vessel type (CTV or SOV), the location of the repaired components (above or below water), the number repaired turbine support structures and the number of repaired components in each structure.

Figure 8 illustrates the sensitivity results for the scenario in which repairs are performed using welding. It can be seen that, irrespective of the repair location (above or below water) and vessel type, the sensitivity indices of the campaign cost, engineering cost for repair solutions, vessel operation cost, and repair operation time are similar. Furthermore, when multiple components in different turbines are repaired, the vessel operation dominates the overall maintenance cost.

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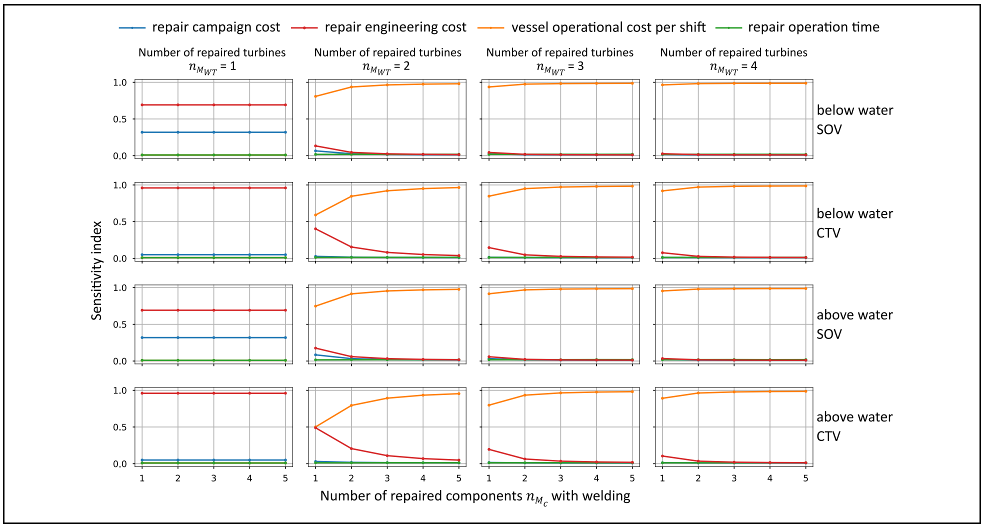

Figure 8. *Sensitivity indices of the campaign cost, the engineering cost for a repair, the vessel operation cost, and the repair operation time in function of the vessel type (CTV or SOV), the location of the repaired components (above or below water), the number repaired turbine support structures and the number of repaired components in each support structure. Repairs are performed using welding repair method*

Figure 9 presents the sensitivity indices for the case in which repairs are carried out through grinding. Similar to the results in Figure 8, the campaign and engineering cost have a significant influence on the total costs if a single turbine is repaired. The influence of the vessel operation cost increases with increasing number of repaired turbines and components.

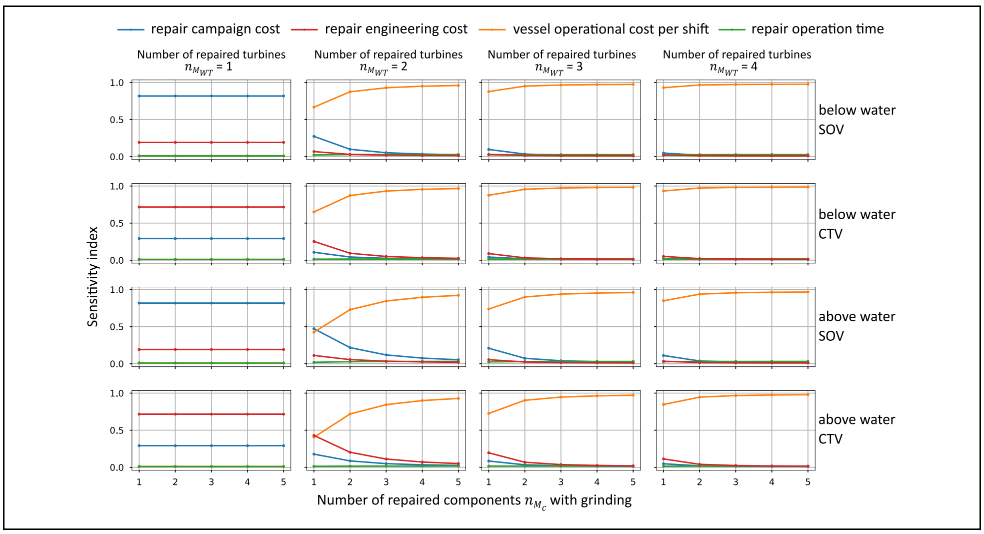

Figure 9. *Sensitivity indices of the campaign cost, the engineering cost for a repair, the vessel operation cost, and the repair operation time in function of the vessel type (CTV or SOV), the location of the repaired components (above or below water), the number repaired turbine support structures and the number of repaired components in each support structure. Repairs are performed using grinding repair method*

7 Numerical example

The proposed probabilistic model for estimating I&M costs presented in Sections 3 to 5, is applied in a risk-informed optimization of I&M strategies for the two-dimensional steel frame

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shown in Figure 10. The optimization is performed before the frame is commissioned. The frame has been studied in numerous publications and in the following we provide a brief summary of the underlying models and assumptions. A detailed description can be found in (Eichner et al., 2023; Schneider, 2020; Schneider et al., 2017).

The steel frame is made of welded tubular members. It resembles a jacket support structure of an offshore wind turbine. The planned lifetime of the steel frame is 25 years, which is divided into $j = 1, \ldots, m$ intervals of one year length. In addition to gravity, the steel frame is exposed to a time-dependent lateral force, represented by its annual maximum L. Moreover, the frame is subject to fatigue at locations marked with red dots (the fatigue hotspots) in Figure 10. A Paris-Erdogan fatigue crack growth model is used to model the evolution of fatigue cracks at each hotspot. At the system level, the frame's braces are in a functioning or failed condition based on the size of the fatigue cracks at the respective hotspots. The fatigue hotspots are inspected with MPI and repaired by welding if a fatigue crack is identified and fulfills the repair criterion as described in Section 3.1. It is assumed that hotspots 1 to 8 are above water, while hotspots 9 to 22 are located below water. The cost of inspection and maintenance depends on the location of the hotspot (above or below water). The applied repair model is documented in detail in (Farhan et al., 2021). The maximum capacity of the damaged steel frame under the applied load is assessed with the help of pushover analyses. Further information regarding the applied inspection, structural performance, and fatigue models as well as the methods employed to compute the time-variant failure probability of the frame are documented in (Eichner et al., 2023; Schneider, 2020; Schneider et al., 2017).

All consequences in the current application – including the consequences of structural failure – are expressed as monetary costs C to facilitate quantitative decision and VoI analyses. Furthermore, following Nielsen and Sorensen (2021), the benefits from the existence of the wind turbine are assumed to be independent of the structural reliability and I&M actions. They are thus constant and consequently, they can be neglected in the optimization of I&M for the support structure. It follows that the utility U is proportional to $-C$.

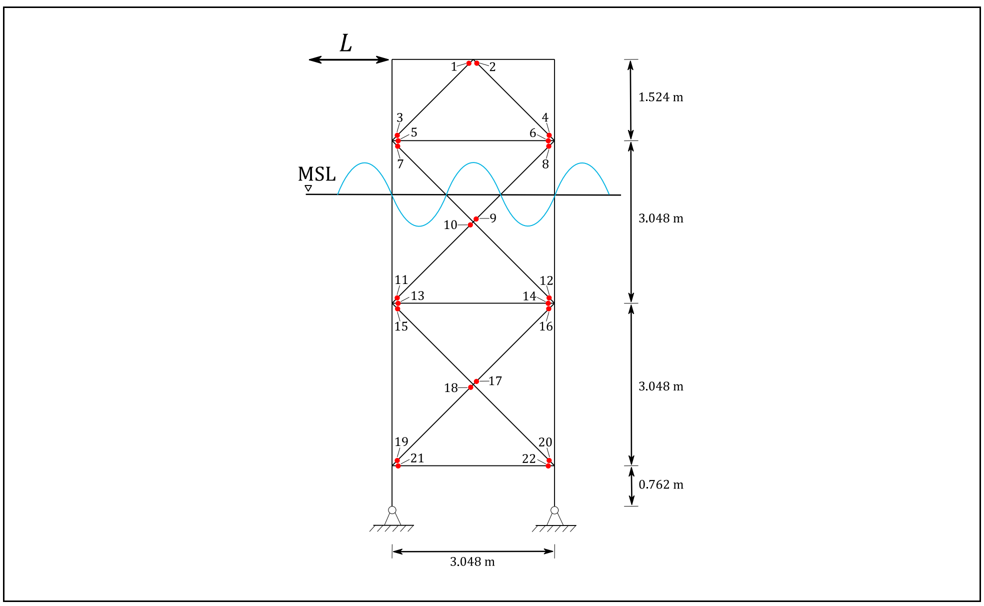

Figure 10. *Steel frame with 22 fatigue hotspots indicated as red dots (adopted from Schneider et al. (2017))*

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7.1 System state analysis

The SS-A determines the expected total lifetime cost $\mathbb{E}[C_0]$ assuming that no inspections and no maintenance actions are performed during the lifetime of the support structure. $\mathbb{E}[C_0]$ is equal to the expected total lifetime cost of system failure $\mathbb{E}[C_F]$ (lifetime risk of failure), i.e.:

$$\mathbb{E}[C_0] = \mathbb{E}[C_F] = \sum_{j=1}^{m} c_F \cdot \gamma_j \cdot [\Pr(F_j) - \Pr(F_{j-1})] \tag{21}$$

where $c_F = 2 \cdot 10^7$€ is the failure cost, which is here assumed to be deterministic and equal to the investment cost of one wind turbine (Thöns et al., 2017); $\Pr(F_j)$ is the probability of failure up to the end of year j; $\Pr(F_j) - \Pr(F_{j-1})$ is the probability of failure in year j; and all costs are discounted to time $j = 0$ using a discounting function $\gamma_j = 1/(1+r)^j$, wherein $r = 0.02$ is the discount rate. The expected total lifetime cost $\mathbb{E}[C_0]$ of the case study related to steel frame is $7 \cdot 10^5$€.

7.2 Predictive information and predictive action decision analysis considering probabilistic I&M costs

The PIPA-DA for jointly optimizing I&M is performed using the normal form of analysis as proposed in (Bismut and Straub, 2021; Luque and Straub, 2019), which is computationally tractable compared to the extensive form of analysis described in Section 2.1. In this method, the I&M strategy $\mathcal{S}$ is defined by parameterized rules that specify what, when, and how to inspect and repair in accordance with the available system information. The optimal strategy $\mathcal{S}^*$ results in the minimum expected lifetime cost, i.e.:

$$\mathcal{S}^* = \arg\min_{\mathcal{S}} \mathbb{E}[C_2|\mathcal{S}] \tag{22}$$

with

$$\begin{aligned}\mathbb{E}[C_2|\mathcal{S}] &= \mathbb{E}_{\mathbf{X},\mathbf{Y},\mathbf{Z},\mathbf{W}}[c_2(\mathcal{S},\mathbf{X},\mathbf{Y},\mathbf{Z},\mathbf{W})] \\ &= \int_{\mathbf{X}}\int_{\mathbf{Y}}\int_{\mathbf{Z}}\int_{\mathbf{W}} c_2(\mathcal{S},\mathbf{X},\mathbf{Y},\mathbf{Z},\mathbf{W})\, f(\mathbf{x},\mathbf{y},\mathbf{z}|\mathcal{S})\, f(\mathbf{w}|\mathcal{S})\, \mathrm{d}\mathbf{x}\, \mathrm{d}\mathbf{y}\, \mathrm{d}\mathbf{z}\, \mathrm{d}\mathbf{w}\end{aligned} \tag{23}$$

where

$$c_2(\mathcal{S},\mathbf{X},\mathbf{Y},\mathbf{Z},\mathbf{W}) = c_I(\mathcal{S},\mathbf{X},\mathbf{Y},\mathbf{Z},\mathbf{W}) + c_M(\mathcal{S},\mathbf{X},\mathbf{Y},\mathbf{Z},\mathbf{W}) + c_F(\mathcal{S},\mathbf{X},\mathbf{Y},\mathbf{Z},\mathbf{W}) \tag{24}$$

in which $c_I(\mathcal{S},\mathbf{X},\mathbf{Y},\mathbf{Z},\mathbf{W})$ are the total lifetime inspection costs, $c_M(\mathcal{S},\mathbf{X},\mathbf{Y},\mathbf{Z},\mathbf{W})$ are the total lifetime maintenance costs and $c_F(\mathcal{S},\mathbf{X},\mathbf{Y},\mathbf{Z},\mathbf{W})$ are the total lifetime failure costs; $f(\mathbf{x},\mathbf{y},\mathbf{z}|\mathcal{S})f(\mathbf{w}|\mathcal{S})$ is the joint probability density function (PDF) of **X**, **Y**, **Z** and **W**. Eq. (23) implies that the uncertain parameters **W** governing the I&M costs are modeled as statistically independent of the uncertain parameters **X** influencing the system state, the uncertain parameters **Y** affecting the repair outcomes and the probabilistic inspection outcomes **Z**.

Eq. (23) can be rewritten as:

$$\mathbb{E}[C_2|\mathcal{S}] = \int_{\mathbf{Z}}\int_{\mathbf{W}} \mathbb{E}[C_2|\mathcal{S},\mathbf{z},\mathbf{w}]\, f(\mathbf{z}|\mathcal{S})\, f(\mathbf{w}|\mathcal{S})\, \mathrm{d}\mathbf{z}\, \mathrm{d}\mathbf{w} \tag{25}$$

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where $\mathbb{E}[C_2|\mathcal{S},\mathbf{z},\mathbf{w}]$ is the expected total lifetime cost conditional inspection outcomes $\mathbf{Z}=\mathbf{z}$ and corresponding repairs as prescribed by strategy $\mathcal{S}$ and $f(\mathbf{z}|\mathcal{S})$ is the marginal PDF of the lifetime inspection outcomes.

$\mathbb{E}[C_2|\mathcal{S},\mathbf{z},\mathbf{w}]$ is computed as:

$$\begin{aligned}\mathbb{E}[C_2|\mathcal{S},\mathbf{z},\mathbf{w}] &= \mathbb{E}_{\mathbf{X},\mathbf{Y}|\mathbf{Z}=\mathbf{z},\,\mathbf{W}=\mathbf{w}}[c_2(\mathcal{S},\mathbf{X},\mathbf{Y},\mathbf{z},\mathbf{w})] \\ &= \int_{\mathbf{X}}\int_{\mathbf{Y}} c_2(\mathcal{S},\mathbf{X},\mathbf{Y},\mathbf{z},\mathbf{w})\ f(\mathbf{x},\mathbf{y}|\mathcal{S},\mathbf{z})\,\mathrm{d}\mathbf{x}\,\mathrm{d}\mathbf{y}\end{aligned} \tag{26}$$

where $f(\mathbf{x},\mathbf{y}|\mathcal{S},\mathbf{z})$ is the conditional PDF of $\mathbf{X}$ and $\mathbf{Y}$ given $\mathbf{Z}=\mathbf{z}$. $\mathbb{E}[C_2|\mathcal{S},\mathbf{z},\mathbf{w}]$ can be decomposed as:

$$\mathbb{E}[C_2|\mathcal{S},\mathbf{z},\mathbf{w}] = \mathbb{E}[C_I|\mathcal{S},\mathbf{z},\mathbf{w}] + \mathbb{E}[C_M|\mathcal{S},\mathbf{z},\mathbf{w}] + \mathbb{E}[C_F|\mathcal{S},\mathbf{z},\mathbf{w}] \tag{27}$$

where $\mathbb{E}[C_I|\mathcal{S},\mathbf{z},\mathbf{w}]$ is the conditional expected lifetime inspection cost, $\mathbb{E}[C_M|\mathcal{S},\mathbf{z},\mathbf{w}]$ is the conditional expected lifetime maintenance cost, and $\mathbb{E}[C_F|\mathcal{S},\mathbf{z},\mathbf{w}]$ quantifies the conditional expected lifetime failure costs over the lifetime of the structure.

The conditional expected lifetime inspection cost $\mathbb{E}[C_I|\mathcal{S},\mathbf{z},\mathbf{w}]$ is computed as:

$$\mathbb{E}[C_I|\mathcal{S},\mathbf{z},\mathbf{w}] = \sum_{j=1}^{m} c_{I,j}(\mathcal{S},\mathbf{z},\mathbf{w})\cdot\gamma_j\cdot[1-\Pr(F_j|\mathcal{S},\mathbf{z})] \tag{28}$$

where the jth term represents the inspection costs in year j given that failure has not occurred up to the end of that year; $c_{I,j}(\mathcal{S},\mathbf{z},\mathbf{w})$ is the inspection cost in year j, which are estimated based on the model defined in Eq. (17); and $1-\Pr(F_j|\mathcal{S},\mathbf{z})$ is the probability of survival of the system up to the end of year j conditional on the inspection outcomes $\mathbf{Z}=\mathbf{z}$ and corresponding repairs as determined by the strategy $\mathcal{S}$.

Similarly, the conditional expected lifetime maintenance cost $\mathbb{E}[C_M|\mathcal{S},\mathbf{z},\mathbf{w}]$ is given by:

$$\mathbb{E}[C_M|\mathcal{S},\mathbf{z},\mathbf{w}] = \sum_{j=1}^{m} c_{M,j}(\mathcal{S},\mathbf{z},\mathbf{w})\cdot\gamma_j\cdot[1-\Pr(F_j|\mathcal{S},\mathbf{z})] \tag{29}$$

where $c_{M,j}(\mathcal{S},\mathbf{z},\mathbf{w})$ is the maintenance costs in year j, which are determined based on the model defined in Eq. (18).

The conditional expected lifetime failure cost $\mathbb{E}[C_F|\mathcal{S},\mathbf{z},\mathbf{w}]$ is evaluated as:

$$\mathbb{E}[C_F|\mathcal{S},\mathbf{z},\mathbf{w}] = \sum_{j=1}^{m} c_F\cdot\gamma_j\cdot[\Pr(F_j|\mathcal{S},\mathbf{z})-\Pr(F_{j-1}|\mathcal{S},\mathbf{z})] \tag{30}$$

where $\Pr(F_j|\mathcal{S},\mathbf{z})-\Pr(F_{j-1}|\mathcal{S},\mathbf{z})$ is the probability of failure for year j given $\mathbf{Z}=\mathbf{z}$.

$\mathbb{E}[C_2|\mathcal{S}]$ is estimated using a MC approach:

$$\mathbb{E}[C_2|\mathcal{S}] = \int_{\mathbf{Z}}\int_{\mathbf{W}} \mathbb{E}[C_2|\mathcal{S},\mathbf{z},\mathbf{w}]\ f(\mathbf{z}|\mathcal{S})\,f(\mathbf{w}|\mathcal{S})\,\mathrm{d}\mathbf{z}\,\mathrm{d}\mathbf{w}\ \approx \frac{1}{n}\sum_{i=1}^{n}\mathbb{E}[C_2|\mathcal{S},\mathbf{z}^{(i)},\mathbf{w}^{(i)}] \tag{31}$$

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where $\{\mathbf{z}^{(i)}\}_{i=1}^{n}$ are samples of the probabilistic inspection outcomes $\mathbf{Z}$ conditional on strategy $\mathcal{S}$, which are generated as discussed by Bismut and Straub (2021); $\{\mathbf{w}^{(i)}\}_{i=1}^{n}$ are samples of the uncertain cost model parameters $\mathbf{W} = [\mathbf{W}_1^T, \dots, \mathbf{W}_m^T]^T$, where $\mathbf{W}_j$ are the probabilistic parameters influencing the I&M costs in year j as defined in Table 5. In the current example, it is assumed that the different $\mathbf{W}_j$, $j = 1, \dots, m$ are independent and identical distributed. Thus, the joint PDF $f(\mathbf{w}|\mathcal{S})$ can simply be written as $f(\mathbf{w}|\mathcal{S}) = f(\mathbf{w}_1|\mathcal{S}) \cdot \dots \cdot f(\mathbf{w}_m|\mathcal{S})$. It is further assumed that repair solutions are engineered for each hotspot proactively before the frame is commissioned. Thus, the engineering costs are only incurred once at the beginning of the lifetime.

The parameterized decision rules (see also Bismut et al., 2017; Eichner et al., 2023; Schneider, 2019) that prescribe the I&M actions based on the available system information (inspection outcomes and corresponding repairs) are defined as follows:

1. Inspection campaigns are performed at fixed intervals Δt.
2. n_{I_c} hotspots are inspected during each inspection campaign.
3. Hotspots are prioritized for inspection according to a metric proposed by Bismut et al. (2017), which is a function of a parameter η as well as the structural importance and fatigue reliability of each hotspot.
4. An additional inspection campaign is launched if the annual system failure probability exceeds a threshold p_{th}.
5. A maintenance campaign is launched if fatigue cracks are indicated and measured to be deeper than a_R.

Therefore, a I&M strategy $\mathcal{S}$ is fully defined by the parameters $\boldsymbol{\theta} = [\Delta t, p_{th}, n_{I_c}, \eta, a_R]^T$. To highlight the dependence of $\mathcal{S}$ on $\boldsymbol{\theta}$, we write $\mathcal{S}_{\boldsymbol{\theta}}$ in the following. The optimal strategy $\mathcal{S}_{\boldsymbol{\theta}^*}$ is obtained by conducting an exhaustive search across the subsequent sets of parameter values: $\Delta t \in \{4, 8\}$ [year], $p_{th} \in \{5 \cdot 10^{-4}, 10^{-3}\}$, $n_{I_c} \in \{1, \dots, 22\}$, $\eta = 1$ and $a_R = 1$ [mm].

The expected lifetime cost $\mathbb{E}[C_2|\mathcal{S}_{\boldsymbol{\theta}}]$ is estimated using MCS with 400 samples of the inspection outcome $\mathbf{Z}$, cost model parameters $\mathbf{W}$, and corresponding repairs. The estimated expected lifetime cost $\mathbb{E}[C_2|\mathcal{S}_{\boldsymbol{\theta}}]$ is shown in Figure 11 as a function of $\boldsymbol{\theta}$. All strategies with $n_{I_c} = \{3,4,5,6\}$ result in similar expected lifetime costs. Consequently, the decision-maker has the flexibility to select a strategy based on their specific inspection interval and reliability requirements. Notably, in the current example, the optimal strategy $\mathcal{S}_{\boldsymbol{\theta}^*}$ is characterized by $\boldsymbol{\theta}^* = [\Delta t = 8, p_{th} = 1 \cdot 10^{-3}, n_{I_c} = 6, \eta = 1, a_R = 1]^T$.

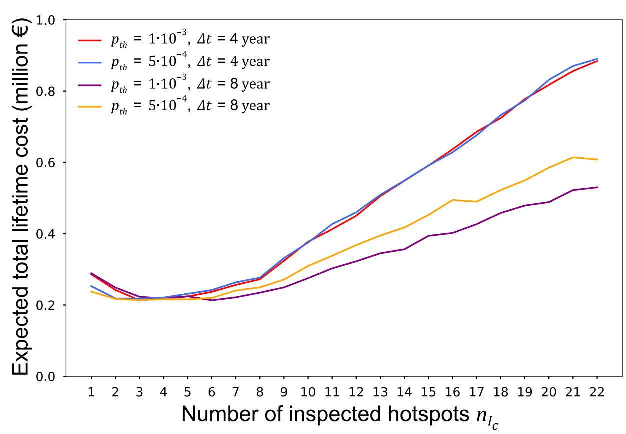

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Figure 11. Expected total lifetime cost $\mathbb{E}[C_2|\mathcal{S}_{\boldsymbol{\theta}}]$ in function of $\boldsymbol{\theta} = [\Delta t, p_{th}, n_I, \eta, a_R]^T$ determined based on the probabilistic I&M cost model

The decomposed expected total lifetime cost $\mathbb{E}[C_2|\mathcal{S}_{\boldsymbol{\theta}}]$ in function of $\boldsymbol{\theta}= [\Delta t = 8, p_{th} = 1 \cdot 10^{-3}, n_{I_c} = 1, \ldots, 22, \eta = 1, a_R = 1]^T$ is given in Figure 12.

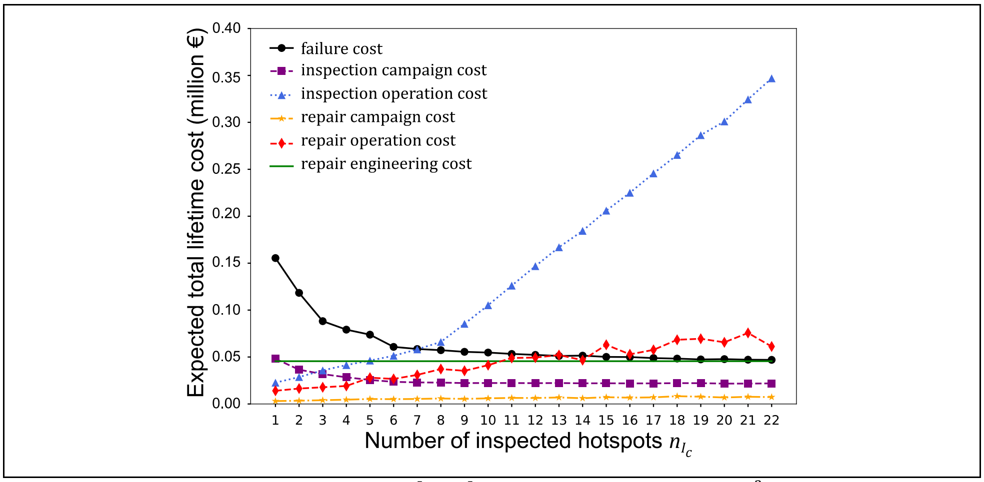

Figure 12. Decomposed expected total lifetime cost $\mathbb{E}[C_2|\mathcal{S}_{\boldsymbol{\theta}}]$ in function of $\Delta t = 8, p_{th} = 1 \cdot 10^{-3}, n_{I_c} = 1, \ldots, 22, \eta = 1, a_R = 1\ mm$

To determine whether one should consider the I&M strategy at all, the difference between the expected lifetime cost $\mathbb{E}[C_0]$ evaluated by the SS-A and the minimum expected lifetime cost $\mathbb{E}[C_2|\mathcal{S}_{\boldsymbol{\theta}^*}]$ quantified with the PIPA-DA is calculated. The relative $\overline{VoI}_{SS-A}^{PIPA-DA}$ is computed as (Farhan et al., 2021):

$$\overline{VoI}_{SS-A}^{PIPA-DA} = \frac{\mathbb{E}[C_0] - \mathbb{E}[C_2|\mathcal{S}_{\boldsymbol{\theta}^*}]}{\mathbb{E}[C_0]} \quad (32)$$

Figure 13 shows the relative $\overline{VoI} = (\mathbb{E}[C_0] - \mathbb{E}[C_2|\mathcal{S}_{\boldsymbol{\theta}}])/\mathbb{E}[C_0]$ together with the expected lifetime cost $\mathbb{E}[C_2|\mathcal{S}_{\boldsymbol{\theta}}]$ and $\mathbb{E}[C_0]$ in function of $\Delta t = 8, p_{th} = 1 \cdot 10^{-3}, n_{I_c} = 1, \ldots, 22, \eta = 1, a_R = 1$.

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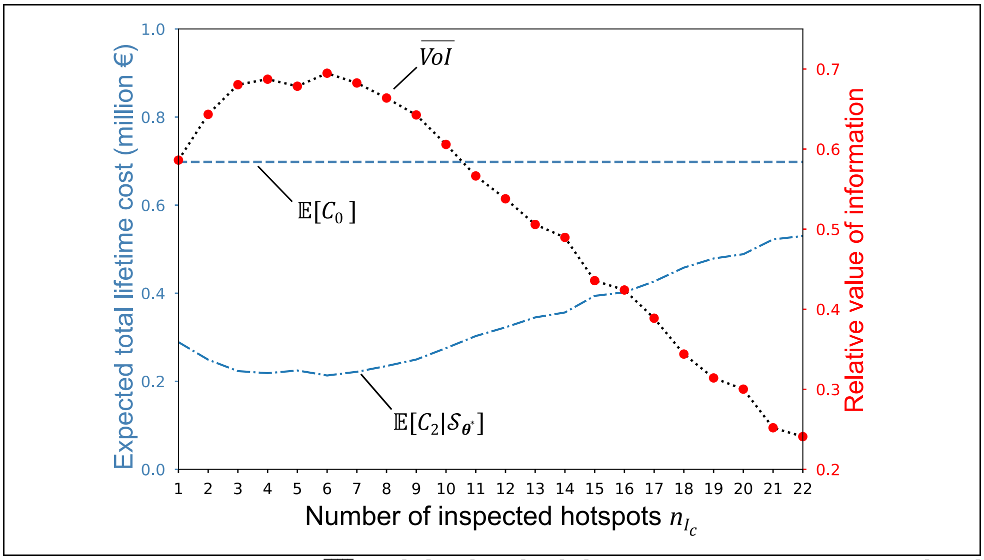

Figure 13. *Relative value of information* $\overline{VoI} = (\mathbb{E}[C_0] - \mathbb{E}[C_2|\mathcal{S}_\theta])/\mathbb{E}[C_0]$ *together with the expected lifetime costs* $\mathbb{E}[C_2|\mathcal{S}_\theta]$ *and* $\mathbb{E}[C_0]$ *in function of* $\Delta t = 8, p_{th} = 1 \cdot 10^{-3}, n_{I_c} = 1, \dots, 22, \eta = 1, a_R = 1$ *mm*

7.3 Predictive information and predictive action decision analysis considering the expected I&M costs

The numerical example considers only a single turbine support structure. In this case, the cost models defined in Eq. (17) and (18) can be expressed as linear functions of the number of inspected and repaired components as follows:

$$C_I = C_{I_C} + n_{I_c} \cdot C_{I_{Op}} \quad \text{with} \quad C_{I_{Op}} = \frac{t_{I_c} \cdot (1 + WD_{CTV}) \cdot C_{CTV/shift}}{t_{shift_{CTV}}} \tag{33}$$

and

$$C_M = C_{M_C} + C_{M_E} + n_{M_c} \cdot C_{M_{Op}} \quad \text{with} \quad C_{M_{Op}} = \frac{t_{M_c} \cdot (1 + WD_{CTV}) \cdot C_{CTV/shift}}{t_{shift_{CTV}}} \tag{34}$$

For the PIPA-DA, the expected inspection costs can thus be formulated such that they only depend on the inspection outcomes $\mathbf{Z} = \mathbf{z}$ and corresponding repairs as determined by the strategy $\mathcal{S}$, i.e.:

$$\mathbb{E}[C_I|\mathcal{S}, \mathbf{z}] = \mathbb{E}_{\mathbf{W}|\mathbf{Z}=\mathbf{z}}[C_I|\mathcal{S}, \mathbf{z}, \mathbf{W}] = \sum_{j=1}^{m} \mathbb{E}_{\mathbf{W}|\mathbf{Z}=\mathbf{z}}[c_{I,j}(\mathcal{S}, \mathbf{z}, \mathbf{W})] \cdot \gamma_j \cdot [1 - \Pr(F_j|\mathcal{S}, \mathbf{z})] \tag{35}$$

with

$$\mathbb{E}_{\mathbf{W}|\mathbf{Z}=\mathbf{z}}[c_{I,j}(\mathcal{S}, \mathbf{z}, \mathbf{W})] = n_{I_C,j}(\mathcal{S}, \mathbf{z}) \cdot \mathbb{E}[C_{I_C}] + n_{I_c,j}(\mathcal{S}, \mathbf{z}) \cdot \mathbb{E}[C_{I_{Op}}] \tag{36}$$

where $n_{I_C,j}(\mathcal{S}, \mathbf{z})$ and $n_{I_c,j}(\mathcal{S}, \mathbf{z})$ are the total numbers of inspection campaigns and component inspections in year j.

Equivalently, the conditional expected maintenance costs can be expressed as:

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$$\mathbb{E}[C_M|\mathcal{S},\mathbf{z}] = \mathbb{E}_{\mathbf{W}|\mathbf{Z}=\mathbf{z}}[C_M|\mathcal{S},\mathbf{z},\mathbf{W}] = \sum_{j=1}^{m} \mathbb{E}_{\mathbf{W}|\mathbf{Z}=\mathbf{z}}[c_{M,j}(\mathcal{S},\mathbf{z},\mathbf{W})] \cdot \gamma_j \cdot [1 - \Pr(F_j|\mathcal{S},\mathbf{z})] \quad (37)$$

with

$$\mathbb{E}_{\mathbf{W}|\mathbf{Z}=\mathbf{z}}[c_{M,j}(\mathcal{S},\mathbf{z},\mathbf{W})] = n_{M_C,j}(\mathcal{S},\mathbf{z}) \cdot \left(\mathbb{E}[C_{M_C}] + \mathbb{E}[C_{M_E}]\right) + n_{M_c,j}(\mathcal{S},\mathbf{z}) \cdot \mathbb{E}[C_{M_{Op}}] \quad (38)$$

where $n_{M_C,j}(\mathcal{S},\mathbf{z})$ and $n_{M_c,j}(\mathcal{S},\mathbf{z})$ are the number of repair campaigns and component repairs in year j. Note the models defined in Eq. (36) and (37) do not explicitly account for the inspection and repair location and inspection and repair methods to simply the notation.

The expected lifetime cost $\mathbb{E}[C_2|\mathcal{S}_{\boldsymbol{\theta}}]$ is now estimated using the expected values of the I&M costs as a function of as a function of $\boldsymbol{\theta}$. The results are shown in Figure 14. The analysis provides the same optimal strategy $\mathcal{S}_{\boldsymbol{\theta}^*}$ with $\boldsymbol{\theta}^* = [\Delta t = 8, p_{th} = 1 \cdot 10^{-3}, n_{I_c} = 6, \eta = 1, a_R = 1]^T$ as determined in Section 7.2.

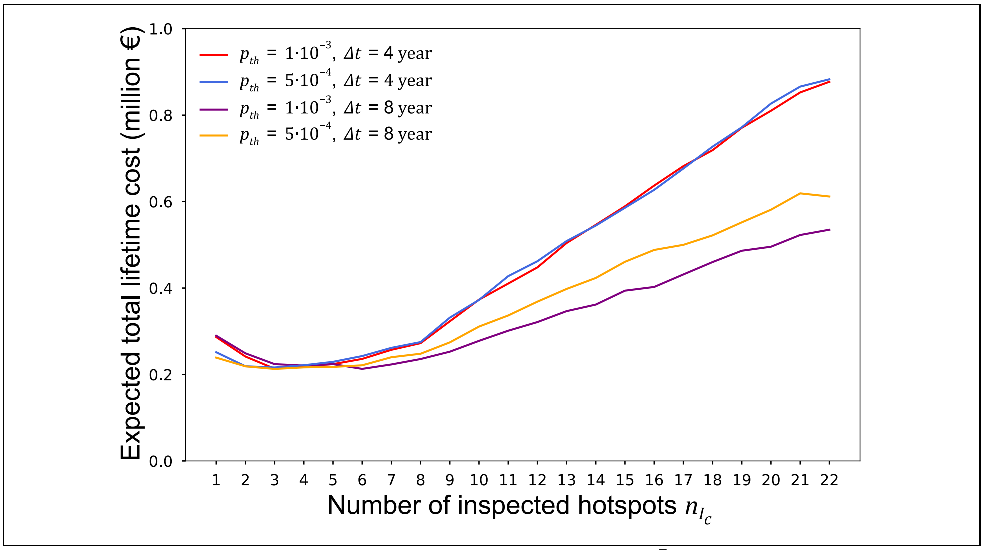

Figure 14. *Expected total lifetime cost $\mathbb{E}[C_2|\mathcal{S}_{\boldsymbol{\theta}}]$ in function of $\boldsymbol{\theta} = [\Delta t, p_{th}, n_I, \eta, a_R]^T$ determined based on the expected values of the I&M costs*

The analysis demonstrates that the I&M costs can be considered deterministically as expected values in the decision and value of information analysis if they are included in the optimization on a linear basis.

Moreover, using the case study as an example, the expected I&M costs can also be normalized based on the expected campaign and may be utilized in similar analyses as a normalized cost model. The expected I&M costs normalized based on the expected campaign cost are summarized in Table 7.

Table 7. *Normalized cost model based on the expected campaign cost*

Cost parameter	Ratio	Normalized value
Campaign cost c_{M_C}, c_{I_C}	$9.11 \cdot 10^3/9.11 \cdot 10^3$	1.00
Failure cost c_F	$2.00 \cdot 10^7/9.11 \cdot 10^3$	2193.77

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Engineering repair cost c_{M_E}	$4.55 \cdot 10^4/9.11 \cdot 10^3$	5.00
Inspection cost below water with EM $c_{I_{Op}}$	$8.87 \cdot 10^3/9.11 \cdot 10^3$	0.97
Inspection cost above water with EM $c_{I_{Op}}$	$3.54 \cdot 10^3/9.11 \cdot 10^3$	0.38
Repair cost below water with welding $c_{M_{Op}}$	$4.58 \cdot 10^4/9.11 \cdot 10^3$	5.02
Repair cost above water with welding $c_{M_{Op}}$	$3.80 \cdot 10^4/9.11 \cdot 10^3$	4.17

Similarly, the expected I&M costs can also be normalized based on the expected failure cost and can be used to compare the with the previous studies utilizing similar concepts. The normalized cost model based on expected failure cost is given in Table 8.

Table 8. *Normalized cost model based on expected failure cost*

Cost parameter	**Ratio**	**Normalized value**
Failure cost c_F	$2.00 \cdot 10^7/2.00 \cdot 10^7$	1.0
Campaign cost c_{M_C}, c_{I_C}	$9.11 \cdot 10^3/2.00 \cdot 10^7$	$4.55 \cdot 10^{-4}$
Engineering repair cost c_{M_E}	$4.55 \cdot 10^4/2.00 \cdot 10^7$	$2.28 \cdot 10^{-3}$
Inspection cost below water with EM $c_{I_{Op}}$	$8.87 \cdot 10^3/2.00 \cdot 10^7$	$4.43 \cdot 10^{-4}$
Inspection cost above water with EM $c_{I_{Op}}$	$3.54 \cdot 10^3/2.00 \cdot 10^7$	$1.77 \cdot 10^{-4}$
Repair cost below water with welding $c_{M_{Op}}$	$4.58 \cdot 10^4/2.00 \cdot 10^7$	$2.29 \cdot 10^{-3}$
Repair cost above water with welding $c_{M_{Op}}$	$3.80 \cdot 10^4/2.00 \cdot 10^7$	$1.90 \cdot 10^{-3}$

8 Summary and concluding remarks

This paper formulates and applies a probabilistic cost model to support the operational management of offshore wind farms, which includes I&M of the turbine support structures. It forms a decision-theoretical basis for the optimization of I&M regimes, with an emphasis on integrating the probabilistic cost model into the decision analysis. Different types of I&M of the turbine support structure are discussed, along with the parameters that influence the overall I&M cost. Subsequently, global sensitivity analyses are performed based on the proposed probabilistic cost model to quantify the influence of uncertain parameters on the overall costs. The proposed probabilistic cost model is then applied in a numerical example in which the I&M regime is optimized for a frame with steel members which resembles a jacket support structure of an offshore wind turbine. An SS-A, PIPA-DA and VoI analysis is performed in the numerical example. The SS-A is performed to determine the lifetime risk when no information is collected, and no maintenance actions are performed throughout the structure's lifetime. The PIPA-DA is performed to optimize I&M strategies defined by parameterized decision rules that dictate the actions to be taken during each year of the structure's lifetime based on the available information. First, the analysis is performed based on the probabilistic model of the I&M costs. Second, the PIPA-DA is also performed with expected values of the I&M costs. This is possible since they are included in the model on a linear basis. Both analyses yield the same optimal

I&M strategy. Finally, to determine the cost-effectiveness of the identified optimal I&M strategy, a VoI analysis is carried out considering the probabilistic I&M cost model.

Based on our work, the following conclusions can be drawn:

1. The proposed probabilistic cost model can be utilized to quantify I&M costs at wind farm, structural system, and component level, which can be updated with the new information obtained during the operation of wind farms.
2. The sensitivity analyses performed based on the probabilistic cost model concluded that: at component level, the campaign cost and engineering cost have a higher influence on the overall I&M cost, while the vessel operational cost has the highest impact on the overall I&M costs at structural system and wind farm level.
3. The outlined generic framework can be utilized to optimize the I&M regimes for turbine support structures specifically considering the uncertainties in the I&M costs in the decision-making.
4. The decision analysis in the numerical example identifies an optimal I&M strategy for a steel frame subject to fatigue based on the probabilistic cost model. An optimal inspection interval of $\Delta t = 8$ yr. resulted from PIPA-DA and VoI analysis. Furthermore, if the annual system failure probability exceeds a threshold of $p_{th} = 1 \cdot 10^{-3}$ yr^{-1}, an additional inspection campaign is launched. In each campaign, six prioritized hotspots are inspected, and a repair campaign is launched if fatigue cracks are indicated and measured to be deeper than $a_R = 1$ mm.
5. With the help of the numerical example, it is shown that the I&M costs can be considered deterministically by using expected values in the decision and value of information analysis if they are included in the optimization on a linear basis.
6. The expected I&M costs at the structural system level depend solely on the number of campaigns and components involved in the I&M operations as wells as on the expected campaign, engineering, and operational cost, which therefore can be normalized and used in decision and VoI analyses to optimize the I&M regime of support structures at the structural system level.

In the future, we will research similar concepts to derive deterministic (normalized) cost models for I&M planning at wind farm level.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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