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On risk-based operation and maintenance of offshore wind turbine components

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A B S T R A C T

Operation and maintenance are significant contributors to the cost of energy for offshore wind turbines. Optimal planning could rationally be based on Bayesian pre-posterior decision theory, and all costs through the lifetime of the structures should be included. This paper contains a study of a generic case where the costs are evaluated for a single wind turbine with a single component. Costs due to inspections, repairs, and lost production are included in the model. The costs are compared for two distinct maintenance strategies, namely with and without inclusion of periodic imperfect inspections. Finally the influence of different important parameters, e.g. failure rate, reliability of inspections, inspection interval, and decision rule for repairs, is evaluated.

1. Introduction

The costs of operation and maintenance (O&M) of offshore wind turbines are significant contributors to the cost of energy—up to 30% of the cost of energy. Optimal planning of O&M should include the use of inspections and monitoring results to make decisions that minimize the expected total costs through the lifetime of the structures. For offshore wind turbines it is especially important because of the dependence on weather windows for inspections and repairs to be possible. The aim of this work is to demonstrate the effect of the use of condition-based maintenance compared to the use of corrective maintenance for a generic case. For simplicity, only a single wind turbine with a single component is included in model, but the relative influence of different parameters are considered to be generic.

1.1. Maintenance activities

In general maintenance activities can be divided into corrective and preventive maintenance. Corrective maintenance is performed if a component has failed, and preventive maintenance is performed to avoid failure. Preventive maintenance can be divided into scheduled and condition-based maintenance. Scheduled maintenance is performed on scheduled times, and could e.g. be lubrication, tightening bolts, and changing filters [1]. Condition-based maintenance is performed on the basis of the actual health of the component, and thus it requires a condition-monitoring system with online monitoring and/or inspections, see e.g. [2,3]. For offshore wind turbines service visits are performed on a scheduled basis, where scheduled maintenance are performed, and at the same time inspections can be performed at a relatively low additional cost.

The use of corrective maintenance is the most simple strategy, but it has several flaws. The failure of one minor component can cause escalated damage to a major component, which gives large repair/replacement costs. Further failures will often happen during a period with large wind loads, and the site will be unaccessible during that period, which will cause lost production, see e.g. [4]. Thus the costs for corrective maintenance are associated with much larger uncertainty than preventive maintenance [2].

2. Optimal planning of inspection and maintenance

Optimal planning of O&M should basically be based on risk-based methods, where pre-posterior decision theory is used to take all available information from past experience, inspections, and monitoring into account. The theoretical basis is described in this section and is based on the wind turbine framework [5] and general theory in [6].

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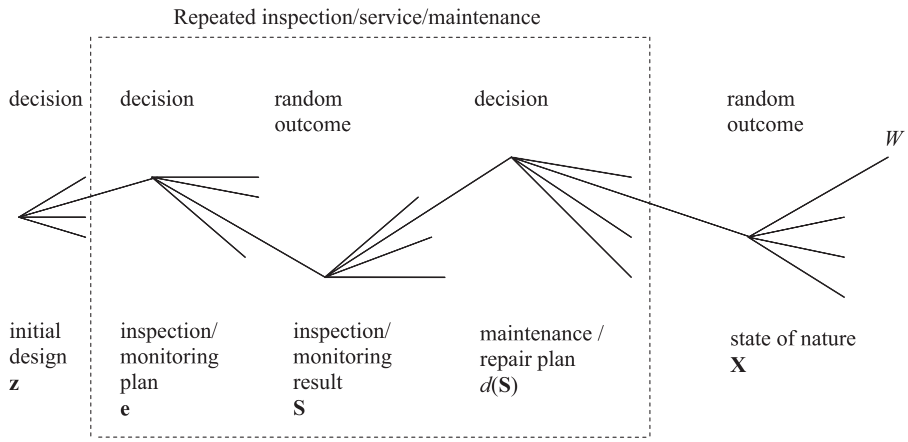

Fig. 1. Decision tree for optimal planning of inspections and maintenance [5].

The problem of making decisions that minimize the expected costs through the lifetime of the wind turbines can be represented using a decision tree as shown in Fig. 1. In this model there are three types of decisions: initial decisions regarding the design, decisions regarding the inspections/monitoring and decisions on maintenance/repair.

The initial design decisions, z, are included in the model, because the design will influence the realizations of the damage, and thereby the inspection, maintenance and repair costs. In principle there are an infinite number of possible decisions, but this has to be narrowed down to a number of specific designs, in order to make an analysis. Relevant parameters at the initial design stage could be whether to install a permanent crane in the nacelle, and the design life of different fatigue, corrosion, and wear exposed components. Application of risk-based decision models requires that the condition of the wind turbine components/systems can be described by damage models.

The central decision in the analysis is the decision on when and how to maintain and perform repair. Lack of repair before component failure might lead to loss of production and extra costs due to escalated damage. If, on the other hand, a repair is performed before it is necessary, the total number of repairs during the lifetime will be larger than necessary. If a perfect damage model was available it would be straightforward to make the optimal decision; to repair just in time. However, this is not the case because the damage model is associated with uncertainties, and the state of nature, $\mathbf{X}$, of the components are unknown, e.g. stochastic variables describing fatigue development with time.

The prior probability model of the state of nature is denoted P_X. In order to obtain further information on the state of nature, and thereby decrease these uncertainties, experiments, e, can be made, at some cost. For an offshore wind turbine these "experiments" can be divided into online condition-monitoring and manual inspections, see e.g. [7]. Depending on the component of interest different methods are available, and in general these methods will be imperfect in the sense, that the outcome of the investigation, $\mathbf{S}$, can be coupled with the state of nature, $\mathbf{X}$, but with some uncertainty that can be quantified through the conditional probability $P_{S|X}$.

With the new information gained from the monitoring/inspections, Bayesian updating can then be used to determine the posterior probability $P_{X|S}$ for the state of nature. On the basis of this updated probability a decision, a, regarding maintenance/repair must be made. This decision cannot be made before the result from the inspection/monitoring is made, but instead a decision rule, $d(\mathbf{S})$, can be determined/chosen at the design stage as a function of the outcome of the inspection/monitoring, $\mathbf{S}$. This rule states what decision to make, for all possible outcomes of the inspection/monitoring.

The basis for the calculations also includes the utility corresponding to each branch of the tree, in this case quantified in monetary value. The job to find the decisions that maximize the expected utility, that is the expected total gain minus the expected costs, can be done in two different ways, normal or extensive form. In the extensive form analysis the starting point is in the final branches of the tree at the right in Fig. 1. For each branch after the final decision the expected utility is calculated, and for each possible outcome of the experiment, the maximum expected utility is found. The same is done for all branches after the decision on which experiment to make, and the maximum value of the expected utilities gives the optimal choice of inspection/monitoring. In the normal form analysis every possible decision rule for a given experiment is explicitly considered, and for each experiment an optimal decision rule is found. The maximum expected utilities for each available experiment for normal and extensive form, respectively, are given by

$$u^*(e) = \max_d E_X E_{S|X} u(e,\mathbf{S},d(\mathbf{S}),\mathbf{X}) \quad (1)$$

$$u^*(e) = E_S \max_a E_{X|S} u(e,\mathbf{S},a,\mathbf{X}) \quad (2)$$

u^* is maximum utility and E denotes expectation with respect to the subscripted variables. Because $E_X E_{S|X}$ is the expectation over $\mathbf{X} \times \mathbf{S}$ it equals $E_S E_{X|S}$, and it can be shown that the two expressions give same utility for each experiment e. The optimal decision e^* is the one maximizing $u^*(e)$ i.e. $\max_e u^*(e)$.

In principle either analysis forms can be used. In this analysis the expectation is evaluated using simulation, and thus the normal form gives the most direct approach, as $E_X E_{S|X} = E_{XS}$ is the expectation with respect to $\mathbf{X}$ and $\mathbf{S}$, and can be evaluated in one step. In the extensive form the simulations should be divided into two steps in order to maximize with respect to the decision rule before the state of nature is found.

Based on the normal form analysis the optimization problem is to maximize the total gain minus the costs, W, and it can be formulated as

$$\max_{z,e,d} W = B - C_I - C_{IN} - C_{REP} - C_F \quad (3)$$

where B is the expected benefits, C_I is the initial costs, C_{IN} is the inspection and service costs, C_{REP} is the expected repair and maintenance costs and C_F is the expected failure costs, and all values are functions of the design parameters, $\mathbf{z}$, inspections parameters, $\mathbf{e}$, and decision rules for repairs, d.