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Risk-Based Operation and Maintenance Planning for Offshore Wind Turbines

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ABSTRACT: Operation and maintenance (O&M) are large contributors to the cost of energy for offshore wind turbines. Optimal planning of O&M should include use of inspections and monitoring results to make decisions that minimize the expected costs through the lifetime of the structures. For offshore structures it is especially important because of the dependence on weather windows for inspections and repairs to be possible. A model has been developed to estimate the expected costs to corrective and condition based maintenance for a wind turbine with a single component. The deterioration of the component is simulated, and the expected costs are found for different strategies. An application example shows that condition based maintenance has the potential of reducing the costs, and a risk based approach can be used to find the optimal strategy for O&M. Further the influence of failure rate and damage parameters are evaluated.

1 INTRODUCTION

Operation and maintenance (O&M) make up around 25-30% of the cost of energy for offshore wind turbines. A major contributor to this amount is the large number of failures that forces the wind turbine to stop producing power until the damage has been repaired (Wiggelinkhuizen, Verbruggen, Braam, Rademakers, Xiang, and Watson 2008). Some failures are severe failures of major components, where the direct costs to spare parts and vessels are large, but also the indirect costs caused by lost production are large because of a large number of days to mobilize a crew with the required spare parts and vessel and additional days to finish the repair. These failures are not expected as the design life of these components often equals the life of the wind turbines, and these failures are rare. Another critical source is a large number of failures of minor components that have significantly smaller design life than the entire wind turbine. The repair itself is often relatively cheap, but associated downtime can make up large costs, especially if repair is delayed by bad weather. Also the failures of minor components can be critical if they result in serial damage to larger components.

1.1 *Condition based maintenance*

In order to reduce the costs to O&M the number of failures can be reduced by using preventive maintenance strategies, where repairs are performed before an actual failure see e.g. (Walford 2006). For condition based maintenance repairs are decided based on the actual condition of the components. This requires understanding of the origin and development of the different failure types, and research is going on it this area see e.g. (Faulstich, Hahn, Jung, Rafik, and Ringhandt 2008) and (Giebhardt 2004). Many components are exposed to deterioration precesses e.g. fatigue, wear, corrosion, and erosion, and eventually this leads to failure. An understanding of the source of damage and development of failure can be combined to an appropriate damage model that can be used to plan repairs in advance.

The damage models will always be encumbered with uncertainties, and condition monitoring measurements can be used to update the models and reduce the uncertainty. Condition monitoring covers both offline inspections and online monitoring, where a large number of techniques are available see e.g (Nilsson and Bertling 2007) and (Wiggelinkhuizen, Verbruggen, Braam, Rademakers, Xiang, and Watson 2008). These methods are also subject to uncertainty, and this should be taken into account. Monitoring methods might also help to determine the events leading up to failure, e.g. acoustic emission sensors can detect a crack before it is visible.

1.2 *Optimal planning of O&M*

Through the life time of a wind turbine there are decisions to make that affects the total costs to O&M. These decisions should be made using risk-based methods such that the expected total costs through the life time are minimized, see the wind turbine framework in (Sørensen 2009) and the theoretical basis in (Raiffa and Schlaifer 1961). Figure 1 shows a decision tree for the life cycle approach to planning of O&M.
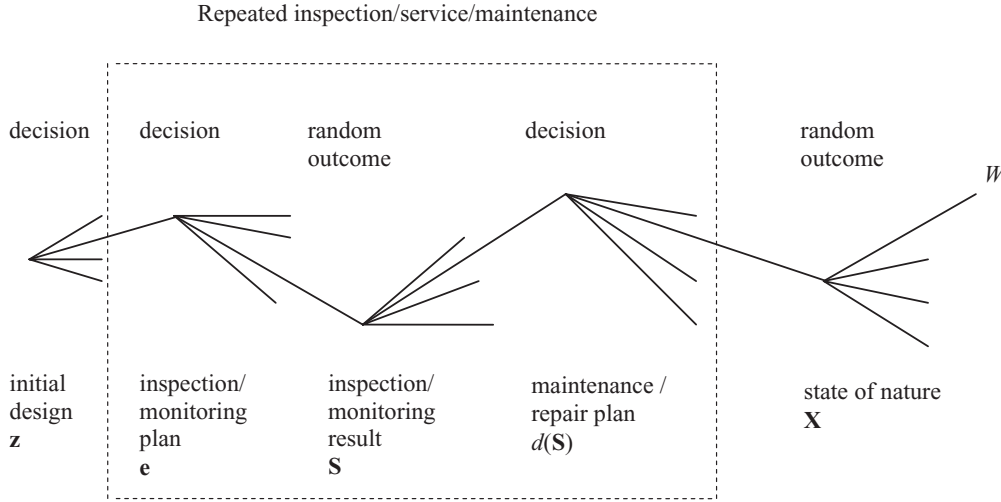

Figure 1. Decision tree for optimal planning of operation and maintenance. (Sørensen 2009)

There are three types of decisions which considers in turn the initial design, inspections/-monitoring, and repairs. This correspond to a pre-posterior decision problem, where the state of nature at one point is affected by previous decisions. Some decisions on the initial design, **z**, has influence on the O&M costs, e.g. the reliability level of components and decisions that influence the maintainability of the wind turbine.

The decision that is most important in order to avoid that damages lead to failures, is the decision on how and when to make repairs, given by the decision rule $d(\mathbf{S})$. The premise for this decision is the inspection/monitoring result, **S**, that is dependent on the decisions made regarding inspection/monitoring, **e**. An increased monitoring effort will have a higher cost, but the decision on repairs can be made with less uncertainty about the damage state.

The realizations of the stochastic variables, **X**, including damage development and possible failure, will depend on the decisions made. The optimal strategy for a fixed initial design, z, can be found as the one with minimum expected costs, W^*:

$$W^* = \min_e \min_d E_X E_{S|X} W(\mathbf{e}, \mathbf{S}, d(\mathbf{S}), \mathbf{X}) \tag{1}$$

E denotes expectation with respect to the subscribed variables.

In this paper simulation has been used to evaluate the expected costs for different decisions on maintenance strategies, both corrective maintenance and condition based maintenance with different inspection/repair decisions. The optimal solution has been found as the one with smallest expected costs, and the influence of the damage parameters on the optimal strategy and costs has been investigated.

2 MODEL

In this study the expected costs for different O&M strategies are found for a design lifetime of 20 years. For simplicity only one wind turbine with a single component is considered. This method allows an easy understandable model to be used and clearly illustrates the main decision mechanisms.

The damage development is governed by the weather, and repairs require appropriate weather windows. Further the lost power production depends on the wind speed. Met Ocean weather data from Horns Reef 2 in Denmark has been provided by Danish Hydraulic Institute, and has been bootstrapped on a yearly basis, which gives pseudo random weather. The used weather data consist of hourly mean values of the significant wave height and wind speed.

The damage size is measured on a relative scale where failure occurs at the value 1. If this value is reached, the component needs a corrective repair in order to restart production of power, as illustrated to the left in figure 2. Condition based maintenance is implemented based on imperfect offline inspections at a fixed interval. The decision rule for repairs is a limit value of the damage size. If a damage larger than this is found at an inspection, a condition based repair is performed, as illustrated to the right in figure 2, where the damage limit is 0.2.
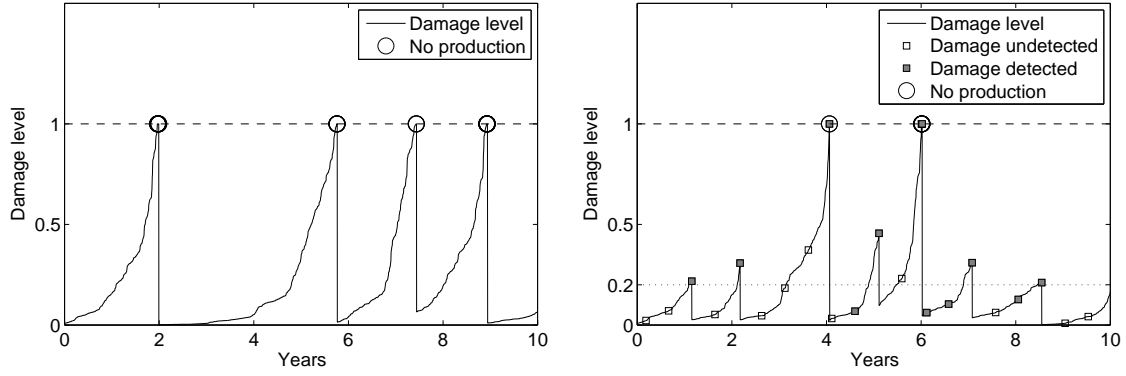

Figure 2. Damage development for corrective (left) and condition based maintenance (right).

2.1 *Damage model*

The component considered in this analysis is assumed to be exposed to deterioration, where an exponential damage model is appropriate. The increase in damage is found using Paris' law for crack growth, see e.g. (Straub 2004). The model is general and can be calibrated to be used in many different applications. The increase in damage is considered to be dependent on both the wind and wave load and the influence of the control system. For simplicity only the mean significant wave height H_s in included directly in the model, as the wind speed and wave height are approximately proportional.

The increase in damage dD/dt is calculated for each 3 hour interval, and is obtained from:

$$\frac{dD}{dt} = C \cdot \Delta K^m \tag{2}$$

C is the damage coefficient, and m is the damage exponent, that gives the shape of the damage curve. ΔK is the damage intensity factor range, and is given by:

$$\Delta K = \Delta s \cdot \sqrt{\pi D} \tag{3}$$

Δs is the cyclic damage range that is considered to the proportional to the mean significant wave height H_s in the three hour period with the proportionality factor x_s. The uncertainty in the damage model is modeled by considering x_s and C as stochastic variables, which each takes a new value after each repair. The initial damage size D_0 is also considered being a stochastic variable.

3

2.2 Inspections

For condition based maintenance inspections are performed at a fixed interval. The inspections are imperfect, so there is a probability that the damage is not detected. The probability of detection (PoD) of damage is higher for larger damages, and is in this analysis modeled by an exponential model:

$$PoD(D) = 1 - \exp\left(\frac{-D}{\lambda}\right) \tag{4}$$

λ is the expected value of detectable damages, and depends on the inspection method. In general a more reliable method has a smaller λ, but is more expensive. Figure 3 shows a PoD-curve, where λ is 0.4.
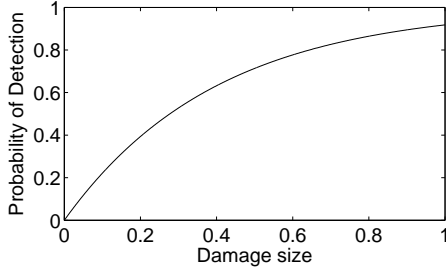

Figure 3. Probability of detection as function of damage size.

2.3 Repairs

Both corrective and condition based repairs are included in the model. A corrective repair is necessary if failure has occurred, and the duration of a repair is modeled stochastic. Repairs can be performed by either boat or helicopter, where a boat is assumed to require a significant wave height smaller than 1.5 m and wind speed smaller than 10 m/s in the repair period (one hour mean values). A helicopter only requires a wind speed smaller than 20 m/s, but is more expensive. Three different transport strategies have been implemented in the model:

- Boat: Always use boat for repairs.

- ASAP: Repair as soon as possible. Boat if possible right away, else helicopter.

- "Risk": The cheapest alternative is always chosen, when lost production is taken into account, calculated based on a perfect weather forecast.

Condition based repairs are assumed to be performed at the same time as inspections. They are performed if a damage size larger than a repair limit is found at the inspection.

2.4 Costs

The costs included in the model are costs to inspections, repairs, and lost production. For condition based maintenance there are costs to inspections and to repairs. Both are assumed to be performed by boat and have fixed prices. Corrective repairs imply costs to lost production and repairs. Costs to lost production are calculated using a power curve for a 5 MW wind turbine. The cost of corrective repairs depends of the duration of the repair (repair days) and the transport type, as shown in table 1. All costs, C, are discounted into present values, C_0, using $C_0 = C/(1+r)^T$ where T is the time difference in years and r is the real rate of interest.

Table 1. Cost of repairs.

Repair type	Transport	Costs
Condition based	Boat	C_R
Corrective	Boat	$C_R(C_{B1} + C_{B2} \cdot \text{repair days})$
Corrective	Heli	$C_R(C_{H1} + C_{H2} \cdot \text{repair days})$

3 APPLICATION EXAMPLE

The described model is generic, and other damage, inspection, and repair models can easily be implemented to represent a specific case. In this section the model has been used to find the optimal inspection plan and repair limit for a case where the costs are given table 2 and the damage parameters are given in table 3. The damage parameters are balanced for H_s inserted in meters, and are calibrated to a mean time between failures (MTBF) of 2 years, which is typical for some components (Faulstich, Hahn, Jung, Rafik, and Ringhandt 2008).

Table 2. Specific costs.

Description	Symbol	Value
Power price	b	0.04 euro/kWh
Inspection cost	C_{INSP}	2500 euro
Repair cost	C_R	10000 euro
Boat cost factors	C_{B1} / C_{B2}	1.0 / 0.5
Helicopter cost factors	C_{H1} / C_{H2}	1.5 / 0.75
Real rate of interest	r	5%

Table 3. Means, coefficients of variation, and distribution types for damage parameters.

Symbol	Mean	COV	Distribution
m	2	-	Deterministic
C	10^{-6}	0.2	Lognormal
x_s	11.5	0.1	Lognormal
D_0	0.02	0.02	Exponential
repair days	3 days	0.5	Lognormal

3.1 *Corrective maintenance*

For corrective maintenance the only decision concerns the transport strategy. Figure 4 shows the expected number of repairs and expected costs for the three different transport strategies. When only a boat is used there are large costs to lost production. When ASAP is used these costs are reduced significantly, but the costs to expensive repairs by helicopter are increased. The risk-based option with perfect weather forecast gives the perfect balance between lost production and fast expensive repairs. In reality this option is not realistic as the forecasts will always be uncertain, and the costs to corrective maintenance with best realistic transport strategy will be between the options ASAP and risk-based. In the following the risk-based transport strategy is used for all corrective repairs.
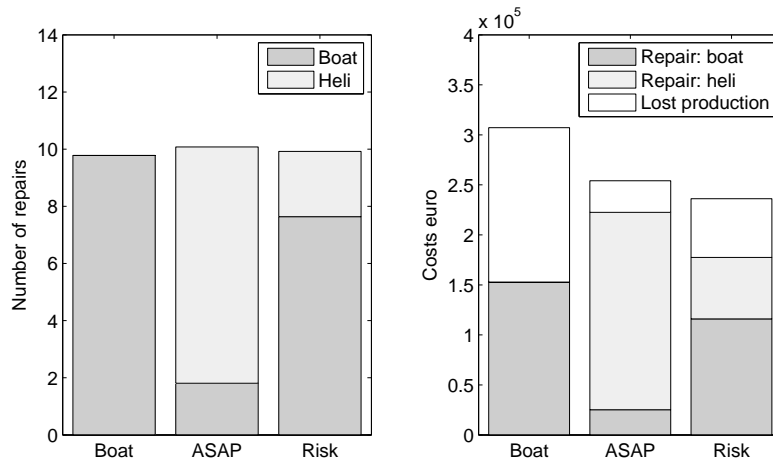

Figure 4. Influence of transport strategy.

3.2 Condition based maintenance

When condition based maintenance is used there will still be a need for corrective repairs, if the condition based maintenance does not succeed in avoiding all failures, but the total costs to corrective repairs will be smaller. The optimal strategy is the one with smallest total costs. In this case study different inspection intervals and repair limits are considered, and table 4 shows the total expected costs for selected strategies. The minimum is found at an inspection interval of 6 months and a repair limit at 0.1.

Table 4. Total expected costs in 1000 euro.

		Repair limit		
		0.0	0.1	0.2
Inspection	3	251	235	230
interval	6	199	192	195
months	9	196	195	199

Figure 5 shows the expected costs for different inspection intervals and repair limits, when the other is hold constant at the optimal value. In general a larger inspection interval and a larger repair limit decreases the costs to condition based repairs and increases the costs to corrective repairs. The curve for different inspection intervals is rather flat, and in reality other considerations will affect the choice between 6 and 12 month, e.g. the need for service visits.
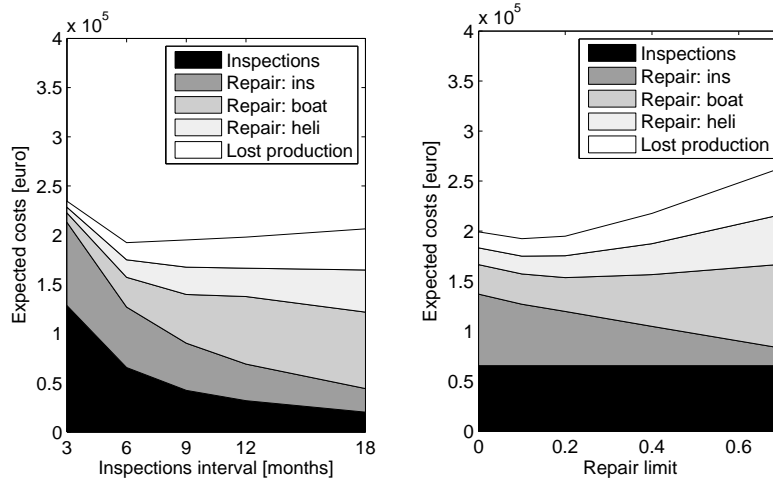

Figure 5. Expected costs for different inspection intervals and repair limits.

3.3 Damage exponent

In the previous example the damage exponent was set to $m = 2.0$. A higher value of the damage exponent will correspond to a damage that more suddenly increases from a low to a high value, and is therefore harder to detect using condition based maintenance. For a damage exponent $m = 2.6$ and the mean value of x_s calibrated to make the MTBF remain two years, the optimal strategy has been found to be an inspection interval of 12 months and repair limit at 0. This repair limit implies that a detected damage should always be repaired.

The diagram to the left in figure 6 shows the expected costs for different inspection intervals. Comparison with figure 5 shows that a smaller inspection interval does not reduce the costs to of corrective repairs as much for a higher damage exponent, and thus the optimal inspection interval is larger. The diagram to the right in figure 6 shows the expected costs when only corrective repairs are used, and when also condition based repairs are used for two different damage exponents. The costs to corrective maintenance are not affected by the damage exponent when MTBF is hold constant, but condition based maintenance is less effective in reducing total costs for a larger damage exponent.
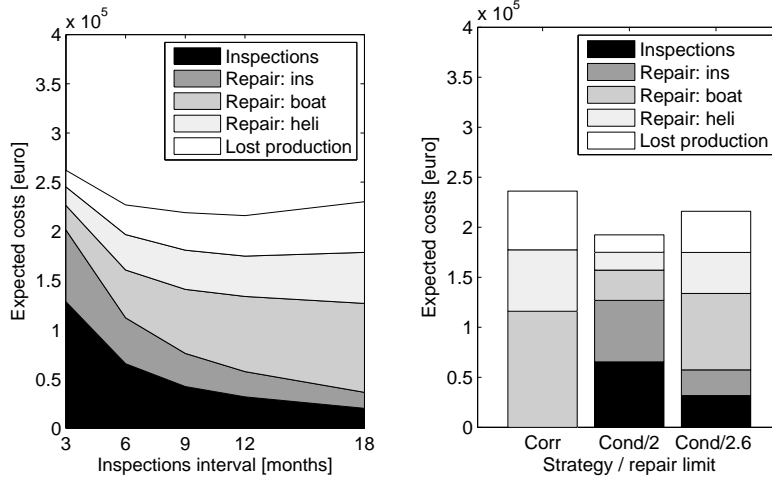
Figure 6. Expected costs for a damage exponent m=2.6 to the left, and for different strategies to the right.

3.4 *Influence of failure rate*

If the the mean value of x_s is calibrated to a MTBF of 4 years instead of 2, and the damage exponent is $m = 2.0$, the optimal strategy has been found to be an inspection interval of 12 month and a repair limit at 0.1. The diagram to the left in figure 7 shows the expected costs for different inspection intervals. The optimal inspection interval is larger compared to the case with MTBF of 2 years because a smaller interval will give too large costs to inspections compared to the decrease in corrective repairs.

The diagram to the right in figure 7 shows the expected costs normalized with respect to the total costs for corrective maintenance for a MTBF at 2 and 4 years respectively. Condition based maintenance is equally good at reducing the total costs to O&M for both MTBF, if the optimal strategy is chosen in each case.
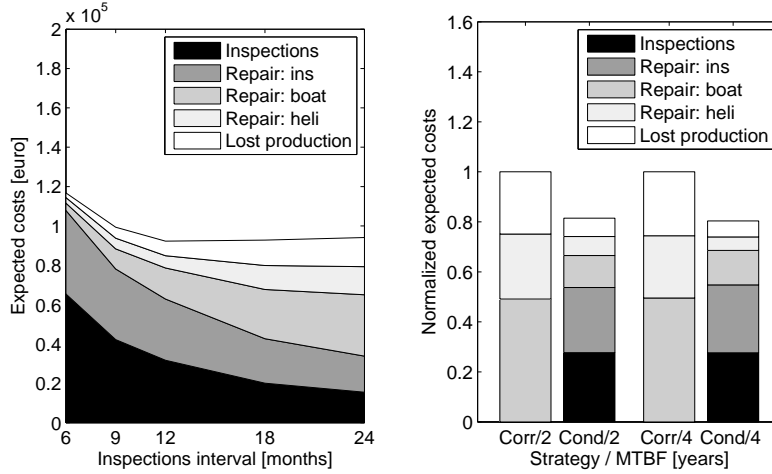

Figure 7. Expected costs for MTBF=4 years to the left, and expected costs normalized to the costs for corrective maintenance for each MTBF to the right.

4 DISCUSSION

The generic model presented in this paper can in principle be modified to reflect any situation, if knowledge is available about an appropriate damage and inspection model for the specific case. The method allows the evaluation of expected costs for a discrete set of different strategies. In the shown example the strategies only considered inspection interval and repair limit, but other parameters could be included as well, e.g. different inspection procedures with different reliability levels and costs, and other types of decision rules for repairs.

The present model only considers a single wind turbine with one component, but in reality a

wind turbine has many components with different MTBF. Here it could be relevant to find a joint optimal strategy, where the same inspection interval is used, but the repair limit could differ for different components. For two components with MTBF of 2 and 4 years respectively the joint optimal strategy seems to have an inspection interval of around 12 months, because the cost curve is most steep on the lower side of the optimal point, see figure 5 and 7.

A high value of the damage exponent significantly reduces the gain from condition based maintenance, which means that the method is most effective for curves with more constant slope.

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