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Cost-benefit evaluation of remote inspection of offshore wind farms by simulating the operation and maintenance phase

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Abstract

This paper presents a cost-benefit evaluation that investigates the potential economic benefits of using remote inspection technology for offshore wind farms. Remote inspection consists of a robot system inside the turbine nacelle that can perform inspections on behalf of an operator located on land. Such a system can reduce the need for expensive and time-consuming access to the turbines. The NOWIcob tool was used to simulate maintenance activities and related logistics during the operational period of an offshore wind farm. Different wind farm cases, with and without remote inspection, were simulated, and the results demonstrate that the use of remote inspection gives robust economic benefits for offshore wind farm projects.

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1. Introduction

Wind has been used as a source of energy since approximately the 7th century [1]. It is a renewable alternative to the fossil fuels, which produce most of our electricity today. To increase the energy produced from wind energy, turbines are being installed offshore, where there are large areas with strong and stable wind. Due to favorable wind conditions, offshore wind turbines are expected to have on average 3000 full load hours per year, compared to between 2000 and 2300 for turbines on land [2]. This results in an expected increase in the capacity factor of a turbine, i.e. the percentage of the theoretical maximum energy output, from about 25% on land to about 40% offshore [3]. Other advantages of offshore wind turbines are that problems with noise are negligible and they are less visible. Whether they can be seen from land depends on the weather conditions, but for turbines more than 20 km from land this will rarely be a concern [4].

The *operation and maintenance* (O&M) of offshore wind turbines is expected to be more expensive than for turbines on land. Several sources estimate that the O&M cost will contribute to between 20% and 25% of the cost of energy offshore [5–8], compared to 10% to 15% onshore. The maintenance strategies that have been successful for

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turbines on land will most likely not be viable offshore, as they typically depend on frequent visits to the turbines. New strategies should be developed, to minimize offshore work [6].

In earlier work, a prototype of an inspection robot that can be used to inspect offshore wind turbines remotely has been developed [9,10]. The use of such a system could reduce the need for working offshore. Based on experiments with this prototype, we found remote inspections to be a viable alternative to manned inspections. In this paper, the focus has been on evaluating whether a remote inspection system would be economically beneficial and result in a more reliable wind farm. To do this, we have used the NOWIcob simulation tool to compare different cases.

2. Remote inspection

Inspections consist of observations, measurements, tests etc. to find the current condition of the turbine, investigate a problem and so on. The intention of the remote inspection concept is to do inspections without accessing the turbine. This both reduces the amount of offshore work and the problems related to accessibility, which both are major concerns for offshore wind farms. Since inspections will be inexpensive to perform, they could also be more frequent and help to get a better control over the wind turbines' condition.

Remotely controlled robots can be used to perform work at locations that are difficult or dangerous for humans to access [11,12]. Such a robot installed inside of the turbine nacelle can perform inspections on behalf of an operator on land. Sensors on the robot, such as cameras, microphones, temperature and vibration sensors can resemble human senses, so the operator can get similar information as if he was in the nacelle. A thermographic camera is considered useful for detection of hot spots from friction or electrical problems.

A prototype of a remote inspection system has been developed and evaluated. It consists of a robot that moves on a rail, which is intended to be installed inside the nacelle of a wind turbine. The robot and an example rail configuration are shown in Fig. 1. Most of the turbine's equipment is located in the nacelle, thus it is natural to have the inspection system there. It is also possible to have a similar system in the hub and tower if necessary.

Movement on rail was chosen because it is a simple and reliable method for moving the robot around the nacelle. A freely moving robot would be more expensive and complex and could easily get stuck, run out of battery power etc. A disadvantage with rails is that the robot only can move where the rail has been installed, thus the rail configuration should allow the robot to observe all necessary parts of the turbine.

The remote inspection prototype has been evaluated in a series of experiments [9,10], where student volunteers used the prototype to inspect a laboratory that represented industrial equipment. The same inspections were also performed in person, to get a direct comparison between remote and manned inspections. The results from two experiments with 21 and 31 participants demonstrated that remote inspections were almost as successful at detecting errors in the

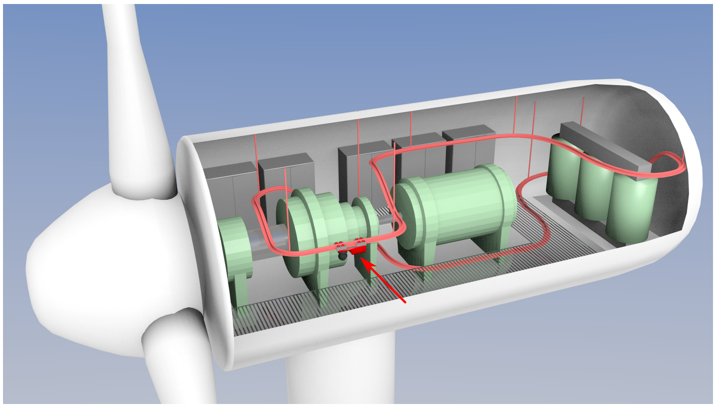

Fig. 1. Concept illustration of a remote inspection robot inside a simplified, generic nacelle. The nacelle consists of main bearing, gearbox, generator, transformer and a couple of cabinets containing electronics. The inspection robot is indicated with an arrow. A suggested rail configuration is also shown.

laboratory as the manned inspections. Most of the difference was likely because many of the participants did not have enough time to complete their remote inspections properly.

Most modern wind turbines, especially offshore turbines, have *condition monitoring systems*. These systems continuously analyze information from a large number of sensors inside the turbine to determine whether it is in acceptable condition or if maintenance is required. Remote inspection is not a replacement for condition monitoring, but is intended to work alongside such systems. Whereas condition monitoring continuously analyze information from sensors to search for patterns that indicate problems, remote inspection allows human eyes, ears and ingenuity to be used without need of transportation to the turbine.

3. Methods

The simulations in this paper have been performed to determine whether there is an economic benefit to remote inspections of offshore wind turbines, using a system similar to the prototype that has been evaluated earlier [9,10].

3.1. NOWIcob

NOWIcob [13] is an event-based simulation model for the operational phase of an offshore wind farm, focusing on maintenance activities and related logistics. Among other possible applications as a decision support and research tool, it is intended as a tool for estimating operation and maintenance costs, including lost income due to downtime, for different maintenance strategies. A Monte Carlo approach is used to capture inherent uncertainties in the number of turbine failures and the weather and to quantify the resulting uncertainty in the results.

A simulation case is defined, among other inputs, by a set of failure categories associated with the wind turbines. A failure rate is specified for each failure category. During simulations, failures occur at random intervals according to these failure rates. Each failure prompts a maintenance task, and the simulation model then assigns vessels and technicians to these tasks when such resources are available and the weather conditions are adequate for carrying out the necessary maintenance activities. One may specify for maintenance tasks whether pre-inspection is necessary, which means that technicians will have to access the wind turbine to investigate the failure before the actual maintenance task can be scheduled. Whether the turbine continues to run as normal after a failure or it has to be stopped until maintenance is performed can be specified for each of the failure categories.

Condition monitoring systems are modelled in NOWIcob in the following, simplified manner. For each failure category, it can be specified whether condition monitoring is able to give an early warning for an incipient failure or not. If so, the probability that a warning is given is specified, together with the number of days before a failure occurs the warning is given. If maintenance is performed during this time window, then an alternative, condition-based maintenance activity is performed instead of the normal activity for the failure category. For each failure category that condition monitoring can detect, a false alarm rate and the type of maintenance activity that will be performed in the case of an erroneous alarm can also be specified.

In this paper, we have chosen to focus on two of the result parameters from the NOWIcob tool. These are the availability of the turbines in the wind farm and the cost of energy. Two types of availability are considered. Time-based availability is the percentage of the time the turbines are operational on average, while electricity-based availability describes how much electricity has been produced compared to how much would have been produced if there were no downtimes.

The cost of energy is the sum of all costs divided by the total electricity produced, which is important for the economics of the wind farm. The cost of energy will depend on the availability, but also on potentially inaccurate assumptions regarding costs, thus it is considered less reliable.

3.2. Simulated wind farm

For the simulations we have defined an offshore wind farm consisting of 100 wind turbines. It does not represent a real, existing wind farm, but has parameters that are representative of modern wind farms. Some of the most important assumptions taken in defining the simulated wind farm will be evaluated below. Each turbine has 3 MW rated power at a cost of € 2 400 per kW [14]. The farm is located 40 km from a harbor, where three *Crew Transfer Vessels* (CTVs), with crews of 12 maintenance personnel each, are stationed. A jack-up is available for larger maintenance tasks and could be chartered for periods of four weeks. For each case, a 20-year life span of the wind farm is simulated 20 times.

Three main categories of failures have been defined, minor, medium and major, as summarized in Table 1. For each of these failure categories, there are a corrective and a condition-based maintenance activity, where the condition-based ones are less extensive. If a failure occurs, the turbine cannot be used until corrective maintenance is performed. All medium or major maintenance activities must be preceded by a pre-inspection that takes three hours as part of the preparation.

Table 1. List of failure categories.

		Corrective maintenance			Condition-based maintenance		
Failure category	**Failure rate**	**Working Duration**	**Pre-inspection**	**Jack-up needed**	**Working Duration**	**Pre-inspection**	**Jack-up needed**
Minor failure	4/year	18 hours	No	No	6 hours	No	No
Medium failure	0.5/year	36 hours	Yes	No	12 hours	Yes	No
Major failure (repair)	0.1/year	72 hours	Yes	Yes	24 hours	Yes	No
Major failure (replacement)	0.1/year	72 hours	Yes	Yes	60 hours	Yes	Yes

The major failures are divided into two subcategories, major repair and major replacement. For major replacement, a jack-up is required for both corrective and condition based maintenance activities. For major repair, a jack-up is only required for corrective maintenance, as it is assumed that condition-based maintenance prevents damage to a large turbine part and the repair can be performed without a jack-up.

3.3. Simulation cases

Three main simulation cases have been defined, and summarized in Table 2. They all share the parameters described in Section 3.2, and the failures described in Table 1.

Table 2. Summary of the simulation cases.

	Simulation cases		
Parameter	**Base**	**Condition monitoring**	**Remote inspection**
Corrective maintenance	Yes	Yes	Yes
Condition-based maintenance	No	Yes	Yes
Pre-inspections	Manned	Manned	Remote
False alarms	None	Manned	Remote

3.3.1. Base case

For the base case only corrective maintenance is performed.

3.3.2. Condition monitoring case

For the condition monitoring case, there is a 70% probability that the condition monitoring system provides a 10-day warning for minor and medium failures and 20 days for major failures. There are also false alarms, which are as common as the failure, i.e. half of the alarms are false. These require a *manual reset* activity that consists of an inspection on site that takes three hours.

The condition monitoring system adds € 160 000 to the cost of each turbine. The cost is a rough estimate, since it will have no effect when comparing the condition monitoring and remote inspection cases. The condition monitoring system also adds a sensor failure that is expected to occur on average once a year. To replace the sensor is a relatively small maintenance task. Since the turbine is not dependent on one individual sensor, the turbine can continue to run normally after this type of failure.

3.3.3. Remote inspection case

The turbines in the remote inspection case are equipped with a remote inspection system in addition to condition monitoring. This allows pre-inspections and false alarm resets to be performed without access to the turbines. It is assumed that remote inspections are as effective as manned, but that they take longer to perform. The time required for remote inspection tasks is therefore twice as long as the time needed for the corresponding remote inspection.

The remote inspection system has an estimated cost of €80 000, which comes in addition to the cost of the condition monitoring system. It is expected that the system is reliable, and that failures occur on average once every five years. When a failure occurs, it is assumed that the faulty robot is replaced with a new. The time needed to do this is short, but there is a relatively high spare part cost. Similar to sensor failures in the case of remote inspection, the turbine can continue to operate normally if the remote inspection system fails.

There are also other potential benefits to remote inspections, e.g. reduction of failures due to inexpensive, frequent inspections. Since these effects are uncertain and difficult to quantify they have not been included in the simulations.

3.4. Sensitivity to the number of CTVs

Three CTVs were used in the main simulation cases. The size of the vessel fleet and number of maintenance personnel is important for the operation of the wind farm as it determines how many maintenance activities it will be possible to perform. To be sure, that the results were not specific to a vessel fleet with three CTVs, the condition monitoring and remote inspection cases were simulated with two and four CTVs.

3.5. Pessimistic case variants

When defining the standard remote inspection case, in 3.3.3, some assumptions were made regarding how the remote inspection system works, its cost etc. To evaluate how sensitive the results are to changes in some of these assumptions, we have performed four additional simulations. Each of these has changed one parameter to an estimate that is pessimistic for the remote inspection case. These pessimistic cases are:

- *High cost*: The investment cost of the remote inspection system is five times higher.
- *Frequent robot failures*: The failures in the remote inspection system occur five times as often.
- *Consequence*: The turbine is stopped when remote inspection failures occur.
- *Lower failure rates*: All failure rates of the wind turbines are reduced by a factor of three. Since only one third of the workload will remain, one CTV is used instead of three.

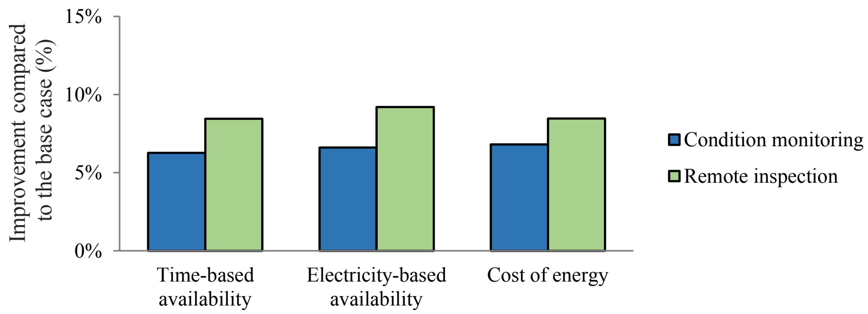

Fig. 2. The improvements in availability and cost of energy compared to the base case.

4. Results

4.1. Condition monitoring vs remote inspections

As the intention is to learn the relative performance of the cases, the results are presented as the improvement compared to the base case. By using relative values, we minimize the effect of any bias in the base case parameter values.

Figure 2 describes how much the condition monitoring and remote inspection cases improved the availability and cost of energy compared to the base case. For the cost of energy, a positive value in the figure relates to a *decreased* cost of energy. Figure 3 shows how the electricity-based availability and cost of energy is compared to base case for different numbers of CTVs.

4.2. Pessimistic case variants

The results of the pessimistic remote inspection cases are shown in figure 4. In this figure, the improvements compared to the condition monitoring case are shown, with negative values indicating an inferior result for the pessimistic case.

For the *lower failure rates* case, the figure shows the difference between condition monitoring and remote inspection, both simulated with the same reduction in failure rates.

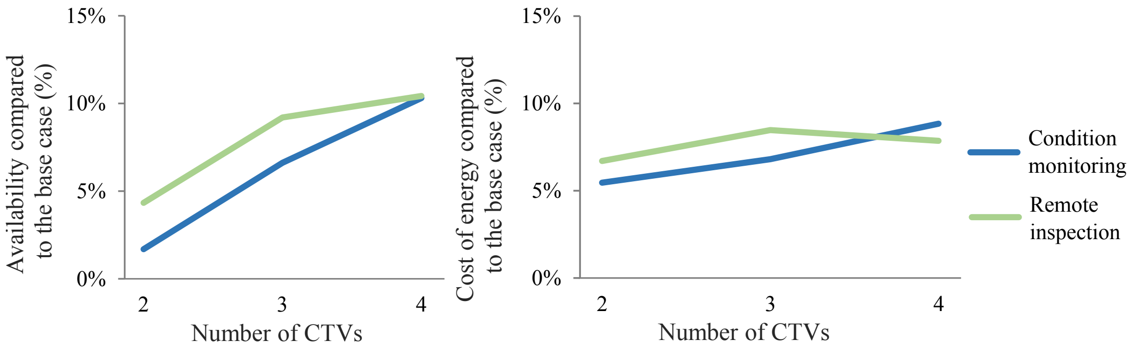

Fig. 3. The improvements in electricity-based availability and cost of energy compared to the base case for different numbers of CTVs.

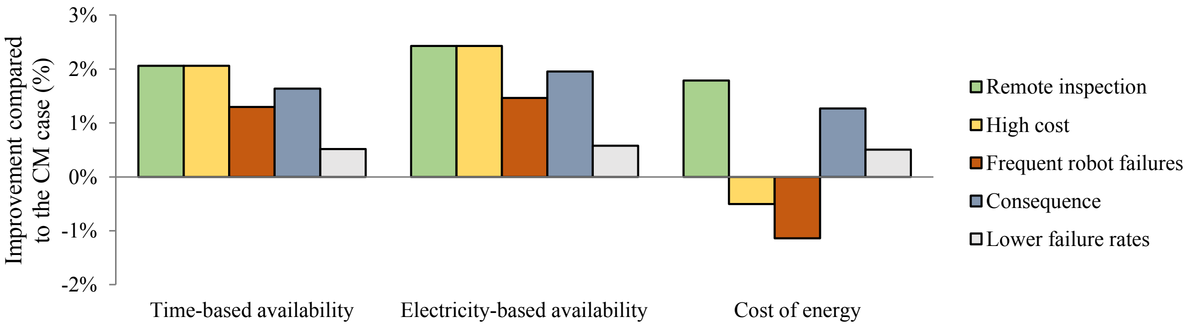

Fig. 4. The effect of the different pessimistic variants to the remote inspection case shown as improvements compared to the condition monitoring case.

5. Discussion

5.1. Condition monitoring vs remote inspection

Both the condition monitoring and remote inspection cases had significant improvement from the base case. It is also clear that the improvements are larger for remote inspection than condition monitoring. The increased availability is likely due to some maintenance activities being performed remotely, thus the maintenance personnel can react faster to the remaining maintenance activities that require access to the turbines. The on-site maintenance activities that are avoided are the minor tasks of pre-inspections and checking false alarms. These tasks require a small amount of work, but are relatively frequent, thus one could argue that it is especially wasteful to do these offshore. The reduced cost of energy is mostly due to less downtime, which will increase the total amount of electricity produced.

The ability to do remote inspections during periods of harsh weather, when the turbines' energy production is at the highest, is a likely reason for the difference between the remote inspection and condition monitoring cases being larger for electricity-based than time-based availability.

5.2. Number of CTVs

The results from the remote inspection cases are better than for condition monitoring for two and three CTVs, while a small benefit is achieved for the condition monitoring case for four CTVs. For the remote inspection cases, the lowest cost of energy was achieved with three CTVs, and additional CTVs would cost more than the benefit they provide.

The condition monitoring case needs four CTVs to get similar results as remote inspection gets with three CTVs. This reduction in the need for vessels and maintenance personnel indicates that fewer maintenance operations are needed to achieve similar availability. It also makes the remote inspection case more robust against the actual cost of vessels and personnel being higher than what have been assumed in these simulations.

5.3. Pessimistic case variants

The *high cost* case did not have any effect on the availability, and for the *frequent robot failures* case the availability was only slightly reduced. This indicates that the increased availability due to remote inspections is a robust effect. Both cases had higher cost of energy than the condition monitoring case, but this was with highly exaggerated values. Since either the failure rate or cost has to be approximately five times higher than estimated for remote inspection to produce more expensive electricity, then the advantage of remote inspection is still considered robust. Since the *frequent robot failures* case had the largest effect on the cost of energy, the reliability of the remote inspection system should be given a high priority.

There is normally no reason for shutting down the turbine when there is a failure in the remote inspection system. However, even if this is necessary, the results from the *consequence* case show that this only have a moderate effect on the benefit of remote inspection.

Remote inspection remained beneficial, compared to condition monitoring, for fewer failures and correspondingly fewer CTVs. However, the benefit is smaller than when there are more failures, as fewer failures will cause fewer potential situations were remote inspection can be used.

5.4. Reliability of the results

Every analysis is dependent on the suitability and correctness of the tools that are used. When the analysis involves computer models, this translates into the question of how thoroughly these models are verified and validated. During the last year, NOWIcob has gone through a relatively extensive verification process to ensure that the implementation of the model is consistent with its underlying assumptions [15]. The question of validation seeks to answer whether these assumptions are reasonable for a model of offshore wind farm maintenance activities. For NOWIcob, there are simplifications particularly in the modelling of condition monitoring, as described in 3.1. However, for the purpose of a first cost-benefit analysis of remote inspection in offshore wind turbines, we believe our modelling approach captures the main features of actual systems as they are used in offshore wind farms today.

The failure data that have been used in the simulations are considered relatively realistic, but they have not been verified. Since the estimations for the failures and some other simulation parameters are shared between all the simulation cases, any inaccuracies in the estimations will be the same for all the cases. This means that the exact values of the failure rates will have a similar effect on both the condition monitoring and remote inspection cases. This is demonstrated by the remote inspection still being beneficial for significantly lower failure rates, although the benefit was less pronounced. We consider a reduction in failure rates to be the modification of the failure data that a priori is most likely to reduce the benefit of remote inspection. Condition monitoring and remote inspection has also been evaluated with other wind farm cases that have previously been used with the NOWIcob tool, with similar results. These additional simulations are not presented in this article.

Another question is whether the assumptions made when setting up the simulation cases used in these simulations are reasonable. This has been tested by simulating cases with exaggerated pessimistic parameters, to study how this affects the results.

The advantages of remote inspection over the condition monitoring case are a reduction in manned operations, while the disadvantages are the additional investment cost and failures in the remote inspection system. For the remote inspections to be beneficial, the advantages must be higher than the disadvantages, thus the relationship between the regular failures and the failures in the remote inspection system is important. For the original simulations, the remote inspection failure rate was approximately 4% of the sum of the other failure rates, while it was approximately 21% for the pessimistic case with more remote inspection failures. A benefit for cost of energy is expected for values lower than 10%-15%. However, for all these cases the availability of the wind farm is higher with remote inspection.

One potential problem with the definition of the failures is that the condition-based maintenance activities are too easy and inexpensive to perform compared to the corresponding corrective maintenance. The assumption that the need for a jack-up could be avoided in some cases by doing condition-based maintenance is also questionable. These issues could have given an artificially high advantage for the cases that had condition monitoring systems. However, this will have a minimal effect on the difference between the condition monitoring and remote inspection cases, as both have condition monitoring. Since the main comparison in this paper is between these two cases, this is not considered a problem for the results and conclusions in this paper.

6. Conclusions

The results from the simulations presented in this paper demonstrate that an offshore wind farm, with a remote inspection system combined with condition monitoring, has improved availability and cost of energy compared to condition monitoring alone. The simulation results from different variants of the remote inspection case show that this effect is robust to large variations in the input parameters.

Acknowledgements

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