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A comparison of single- and multi-parameter wave criteria for accessing wind turbines in strategic maintenance and logistics models for offshore wind farms

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Abstract

Different vessel types for transferring technicians for maintenance and inspection of offshore wind farms are often evaluated and compared by their limiting significant wave height for accessing the wind turbines. The limiting significant wave height is also the parameter that is often used as the access criteria in strategic decision support tools for maintenance and logistics for offshore wind farms. In practice, however, other wave parameters, such as the peak wave period and wave heading, have major influence on the accessibility to a wind turbine for a given vessel. We compare the use of single-parameter and multi-parameter wave criteria for access to wind turbines in two strategic maintenance and logistics models for offshore wind farms: one simulation model and one optimization model. Multi-parameter wave criteria in the form of limiting significant wave heights as functions of peak wave period and wave heading are obtained by numerical analysis of the vessel docking operation. Results for availability, operation and maintenance costs and the optimal vessel fleet size and mix are found using both these multi-parameter wave criteria and using a corresponding single-parameter limiting significant wave height. The comparison indicates that the use of a single limiting significant wave height can give similar results as when using more complex multi-parameter wave criteria. An important precondition is that the single limiting significant wave height is carefully chosen to represent the vessel and the wave conditions.

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1. Introduction

The operation and maintenance (O&M) activities at an offshore wind farm are more challenging than those of their onshore counterpart. The wind turbines are exposed to rough weather conditions that complicate and reduce the

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accessibility of the wind farm for inspection and maintenance visits. Experience indicates that the weather criteria for using a vessel to access the wind turbines, especially restrictions regarding the wave conditions, is a major factor in determining downtime and total O&M cost for an offshore wind farm.

The significant wave height (Hs) is the most common weather parameter for evaluating and comparing the accessibility to wind turbines for different vessel types and access systems. In practice, other wave characteristics also play a major role, mainly wave period and wave heading [1]. Other weather parameters may also be relevant, e.g. current, relative wave headings for wind sea and swell, wind speed and wind direction. Furthermore, when a value is given for the limiting significant wave height (LHs) for a service vessel, it is often unclear what procedure, if any, is used to estimate it. An important question to answer is if such a simplification of the weather criteria for access to the wind turbines can lead to systematically inaccurate assessment of the performance of vessels and access systems.

Strategic decision support tools can be used to analyse strategic questions, such as which vessels will give the overall best performance of a given offshore wind project. There exists a number of strategic maintenance and logistic models for offshore wind farms; a review of such models is given in [2]. The majority of existing models are primarily based on using a single-parameter LHs as the criteria for a vessel to be able to access the wind turbines. Based on the maximum significant wave height during a given time interval, the models determine whether or not a maintenance activity can be executed. When this is repeated for a large number of representative maintenance activities in representative weather conditions, the models can estimate results such as average wind farm availability, O&M cost, and the optimal vessel fleet size and mix. The purpose of this paper is to investigate how the results of strategic maintenance and logistic models are affected when more complex, multi-parameter wave criteria are used instead of only a single-parameter LHs to model accessibility to the wind turbines. In other words, we will compare a *multi-parameter analysis*, using multi-parameter wave criteria (MPWC), with a *single-parameter analysis*, using single-parameter weather criteria (SPWC). Two strategic decision support models are used for this comparison: A discrete-event simulation model for the operational phase of an offshore wind farm, and an optimization model for determining vessel fleet size and mix for maintenance operations at offshore wind farms. Our multi-parameter analysis will include the wave parameters Hs, peak wave period and wave heading, as these are usually the most relevant and there also exist sufficient weather data for these parameters to support the necessary analysis.

The overall methodology used in this paper is as follows. Multi-parameter wave criteria for turbine access for two representative service vessels are obtained by numerical analysis of the vessel docking operation. The method for obtaining such data is described in Section 2.1. These MPWC are then used as input data in decision support tools for O&M activities at offshore wind farms; the simulation model is described in Section 2.2 and the optimization model is described in Section 2.3. These tools are applied to a representative reference case for an offshore wind farm, briefly described in Sec. 2.4. In order to compare the effects of single- and multi-parameter wave criteria, we will need values for LHs to use in the single-parameter analysis. In the absence of any independent, objective method of obtaining such LHs values, we consider a number of possible appropriate measures of LHs for the service vessels in Section 2.5. These estimates are derived from the MPWC for the same vessels by well-defined methods. The results from our comparisons are presented in Section 3 and discussed in Section 4. Finally, we conclude the paper and propose directions for future work in Section 5.

2. Methods

2.1. Numerical analysis of docking operation between vessels and wind turbines

There are several types of offshore wind farm service vessel concepts. One type is small vessels for fast and safe personnel transfer to the wind turbines. The typical length of such crew transfer vessels (CTVs) is between 15–30 m and the vessels typically carry up to 12 technicians. A second type is medium-sized supply vessels that have enough sheltered space and deck area to accommodate personnel, equipment, spare parts, workshops, and a gangway. These vessels typically have a length of 70–100 m, can transfer technicians directly to the wind turbines, and can stay offshore for a longer period of time.

Likewise, there exist several different access systems for docking between a vessel and a wind turbine. The simplest type is a fender made of rubber or similar materials. This access system is used mainly by small CTVs. A different type is based on the active motion compensation principle. This type of access systems can be installed on any service vessels as long as the vessels have enough deck space and weight-carrying capacity. In this paper, we will refer to a supply vessel with such a system as a medium-sized vessel with gangway (MVG).

One of the key safety issues involved in the docking operation with fender is the relative motion (slip) between the service vessel and the wind turbine tower at the touch point. Friction force between the vessel-fixed fender and the wind turbine tower keeps the relative motion zero or close to zero. To analyse the docking operation with fender and evaluate the accessibility for a vessel, a new and highly efficient linear frequency-domain approach has been proposed and applied to a small crew transfer vessel [3].

The capability of any active motion-compensated access system is often specified in terms of compensation limits of the 6 degree-of-freedom (DOF) relative motions, velocities, and accelerations. If we assume that the movement of the wind turbine is negligible in the wave-frequency region, then we can assess the accessibility in any particular wave condition by comparing the calculated 6DOF ship motions at the location where the access system is installed with the maximum compensation ranges of that device. This method has been applied to a medium-sized supply vessel [3].

For both vessel types, such analyses can estimate the LHs above which the turbine is not accessible for a given peak wave period and relative wave heading. The details of the methodologies used in the numerical analysis of the docking operation can be found in [3,4].

2.2. Simulation model for analyzing O&M strategies and costs

NOWIcob is a discrete-event simulation model for the operational phase of an offshore wind farm, focusing on maintenance activities and related logistics [5]. Among other possible applications as a research tool, it is intended as a decision support tool for the selection and analysis of the vessel fleet for O&M activities at offshore wind farms. Examples of questions that can be investigated using simulation tools is how the availability of the wind farm, lost income due to downtime and O&M costs depend on e.g. the number and type of crew transfer vessels.

In the model, a given number of years of the operation phase of the wind farm is simulated with an hourly resolution. A Monte Carlo approach is used to capture uncertainties in when wind turbine failures occur and uncertainties in the weather and to quantify the resulting uncertainty in the results. To capture the uncertainty in the weather conditions, a Markov chain weather model is used to generate synthetic weather time series based on a historic weather time series for a chosen location [6–8]. This weather model is operating with weather states defined by the values of multiple weather parameters and is therefore able to accurately reproduce correlations between weather parameters such as wind speed and wave height. A potential limitation of this approach is that it implies discrete weather states, which introduces a resolution in the weather parameters. For this work, the following weather parameters are included in the weather model (resolution in parentheses): Wind speed (1 m/s), wave height (0.1 m), peak wave period (2 s), and wave direction (45 degrees).

2.3. Optimization model for determining vessel fleet size and mix supporting O&M activities

The optimization model determines the optimal vessel fleet size and mix for supporting O&M activities at an offshore wind farm. It uses an algorithm that (explicitly or implicitly) evaluates all possible vessel combinations according to an objective function. This is in contrast to a simulation model that evaluates the performance of one specific fleet. The objective function of this particular model aims at minimizing the total O&M cost of the solution, i.e. the cost of bases, vessels, voyages sailed, downtime cost when turbines are not producing electricity, and any penalty cost that is defined by the user.

The main output from the optimization model is which vessels that should be purchased, which that should be chartered in (and when), and which bases they should use (options for both onshore and offshore bases can be evaluated). To evaluate which vessels and bases are optimal, the optimization model needs to determine the vessels' sailing schedule and which O&M activities they perform on each day of the planning horizon. Whether or not a vessel can leave its base and which O&M activities it is able to perform on a given day, is based on the vessel's limiting weather criteria and the given weather input for that day. That is, given the accessibility to the turbines for a vessel during certain weather conditions, the weather conditions on a given day provide the model with a yes - the vessel can access the turbines, or no - the vessel cannot access the turbines.

A planning horizon of one year is defined, although the model can be adapted for shorter and longer planning horizons. It is a deterministic model, i.e. all uncertain parameters like weather data and generated failures leading to corrective maintenance activities are treated as known. A thorough description of the optimization model and algorithm is given in [9].

2.4. Case description of reference wind farm

The reference case we consider is an offshore wind farm with distance 50 km to an onshore maintenance base. The wind farm consists of 80 x 5 MW wind turbines. These turbines need annual service, and in addition there will be corrective maintenance activities prompted by failures. The range of possible failures is represented by five failure categories ranging from frequent manual resets to more rare and severe breakdowns requiring vessels with lifting capabilities.

For all maintenance activities, it is assumed that service vessels will need to transport technicians to the turbine in question, where the vessels will dock to the turbine to transfer the technicians. The vessel concepts performing this activity that will be considered for the wind farm are the ones described in Sec. 2.1: A small crew transfer vessel (CTV) and a medium-sized vessel with a motion-compensated gangway (MVG). For convenience, we assume here that the boat landing is on the same side for all turbines and that the turbines can only be accessed from this one direction.

One of the failure categories requires intermediate lifting capabilities and thereby the presence of a larger service vessel. It is assumed that the MVG can fill this function if it is part of the vessel fleet; if not, a medium-sized supply vessel will have to be chartered. The most severe failure category, implying heavy-lifting operations, requires chartering a jack-up vessel.

The weather conditions at the location of the reference wind farm are given by a weather time series for a location in the North Sea with moderately harsh wave climate. The time series contain measurements for wind speed, significant wave height, peak wave period and wave heading with hourly resolution over a number of years. The direction of the turbine boat landing is chosen so that the absolute wave heading in the weather data will also be the wave heading relative to the vessel heading.

2.5. Corresponding single-parameter wave criteria to use for comparison

A challenge to our approach that was alluded to in Section 1 is how to choose representative values for LHs for a given vessel to use in the comparison with multi-parameter weather criteria for the same vessel. To our knowledge, there are no established methods to estimate the LHs for access to a wind turbine for a vessel. Still, LHs values are routinely reported, and are apparently often estimated by expert knowledge or more or less rigorous testing procedures. One approach can be to obtain more or less subjective LHs estimates for the same vessels for which we calculated MPWC. Although this paper does demonstrate a novel method of estimating more complex wave criteria that are also likely to be more accurate, it is not our main aim to compare with other estimates for specific vessels. Rather, we wish to investigate whether it has any added value to use wave criteria based on multiple weather parameters *per se* in strategic logistics and maintenance models. If the hypothesis is that MPWC cannot be accurately represented by a SPWC, we should not be able to get the same results as in the multi-parameter analysis for any measure of LHs used in the single-parameter analysis.

We present below a number of possible, well-defined methods for estimating LHs values that are meaningful to use in a single-parameter analysis to compare with the corresponding multi-parameter analysis. We will use the following notation: The LHs as a function of the peak wave period T_p and the relative wave heading β will be denoted by $H_s^*(T_p,\beta)$. Given weather data in form of a time series of H_s, T_p and β values, a joint probability distribution $P(T_p,\beta)$ of peak wave period and wave heading can be estimated, where we will refer to a pair of values (T_p,β) as a *wave state*. We consider five possible LHs measures:

a) Weighted average: The average of $H_s^*(T_p,\beta)$ weighted by the joint probability distribution $P(T_p,\beta)$ for the weather time series:

$$H_s^{(a)} = \sum_{T_p,\beta} H_s^*(T_p,\beta) \times P(T_p,\beta). \tag{1}$$

b) Most probable wave state: The limiting wave height H_s^* for the most probable wave state (T'_p, β') in the weather time series:

$$H_s^{(b)} = H_s^*(T'_p, \beta'). \tag{2}$$

c) Average wave state: The limiting wave height H_s^* evaluated for the average peak wave period $\bar{T}_p$ for the most likely wave heading β'' for the weather time series:

$$H_s^{(c)} = H_s^*(\bar{T}_p, \beta''). \tag{3}$$

d) Corresponding accessibility: The limiting wave height $H_s^{(d)}$ is such that the fraction P_{acc} of wave states in a given weather time series with significant wave height $H_s < H_s^*$ is the same as the average accessibility for the vessel concept for the same weather time series, as calculated based on the multi-parameter wave criteria. In other words, the average accessibility should be the same whether estimated using MPWC or the SPWC given by $H_s^{(d)}$. Mathematically, this corresponds to the definition

$$\int_0^{H_s^{(d)}} \mathrm{d}H_s \; P(H_s) = P_{\mathrm{acc}} = \int_0^{\infty} \mathrm{d}H_s \; P(H_s) \times P_{H_s \leq H_s^*}, \tag{4}$$

where $P_{H_s \leq H_s^*}$ is the fraction of wave states with significant wave height H_s for which the turbines are accessible for the given weather time series.

e) Smallest value: The most restrictive limiting wave height from the multi-parameter wave criteria:

$$H_s^{(e)} = \min_{T_p, \beta} \left\{ H_s^*(T_p, \beta) \right\}. \tag{5}$$

3. Results

3.1. Wave criteria

The numerical analysis methodology described in Section 2.1 was applied to one CTV and one MVG. The LHs H_s^* was calculated for a discrete set of wave states with peak wave period ranging from $T_p = 3$ s to $T_p = 17$ s in steps of 2 s and with relative wave heading β in steps of 45 degrees. The resulting functions $H_s^*(T_p, \beta)$, our multi-parameter weather criteria, are shown graphically in Fig. 1. The LHs values for the MVG for low T_p are unrealistically high, and should be understood as a mathematical result; what it means is that the turbines in practice will be accessible for this vessel for all possible wave heights for low T_p [3]. In Fig. 1, it is therefore assumed that H_s^* is constant as a function of T_p below $T_p = 3$ s.

Table 1 shows the possible values for a single limiting wave height corresponding to the MPWC presented in Fig. 1, as calculated based on the different suggestions in Section 2.5. To obtain the values in Table 1, a value was calculated for each of the functions $H_s^*(T_p, \beta)$ shown in Fig. 1 for each of the 50 weather time series synthetically generated by the weather model described in Sec. 2.2. The average value is reported, and the estimate of the uncertainty of the last digit given in parentheses is the standard error of the average. This quantifies the statistical uncertainty associated with the weather conditions, but does not take into account any possible systematic errors in the calculated weather criteria or associated with the resolution of the weather parameters. One apparent result is that the weighted average LHs estimate $H_s^{(a)}$ has significantly higher values than the other possible SPWC. We will discuss the reason for this and why this naive estimate is not a representative measure of the LHs in Section 4.

3.2. Comparison of single- and multi-parameter wave criteria using a simulation model

We have applied the simulation model described in Section 2.2 to the case described in Section 2.4 using the multi-parameter wave criteria presented in Fig. 1. We consider two possible vessel fleets for the wind farm: i) Three CTVs at all times and chartering a MVG when necessary for lifting, and ii) having a single MVG in the wind farm at all

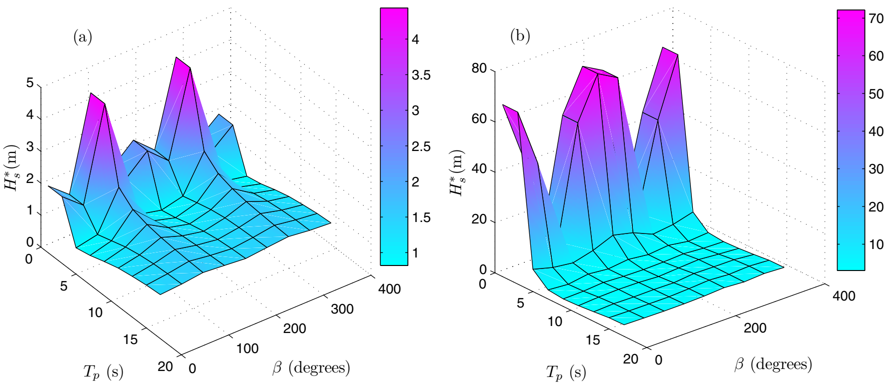

Fig. 1. Multi-parameter weather criteria for (a) the CTV and (b) the MVG.

Table 1. Values for possible single-parameter LHs measures corresponding to the multi-parameter wave criteria.

Measures for the corresponding LHs	LHs (m) for CTV	LHs (m) for MVG
a) Weighted average	1.513(6)	12.3(2)
b) Most probable wave state	1.11(2)	3.24(4)
c) Average wave state	1.030(3)	3.18(1)
d) Corresponding accessibility	1.160(2)	3.26(1)
e) Smallest value	0.82	3.01

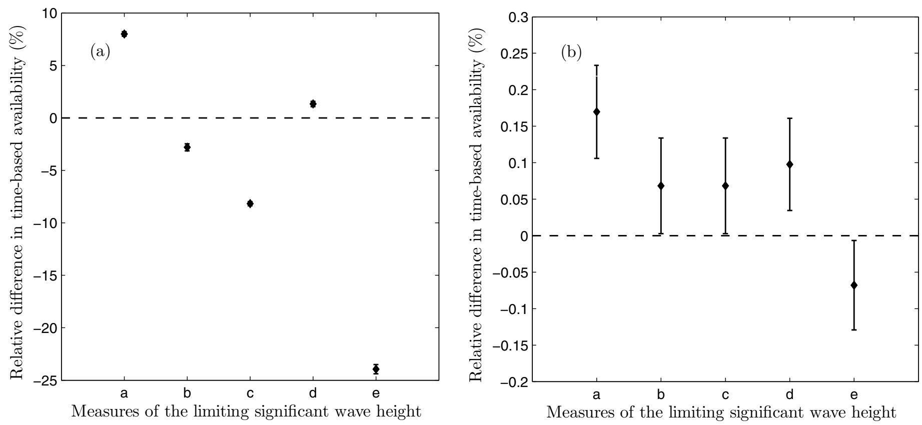

Fig. 2. Comparison of time-based availability between the multi- and the single-parameter analysis in the simulation model for the CTV (a) and the MVG (b).

times, letting it function as the service vessel as well as using it for lifting when necessary. We have also carried out simulations for each case using single-parameter wave criteria corresponding to the five measures of LHs in Table 1. Since the weather model used by the simulation model has a resolution of 0.1 m, we have chosen to round off the LHs estimates used as the single-parameter wave criterion accordingly. For each of these simulations, we have performed 50 independent simulation runs of 8 years of the wind farm operational phase, each simulation run using its own synthetically generated weather time series.

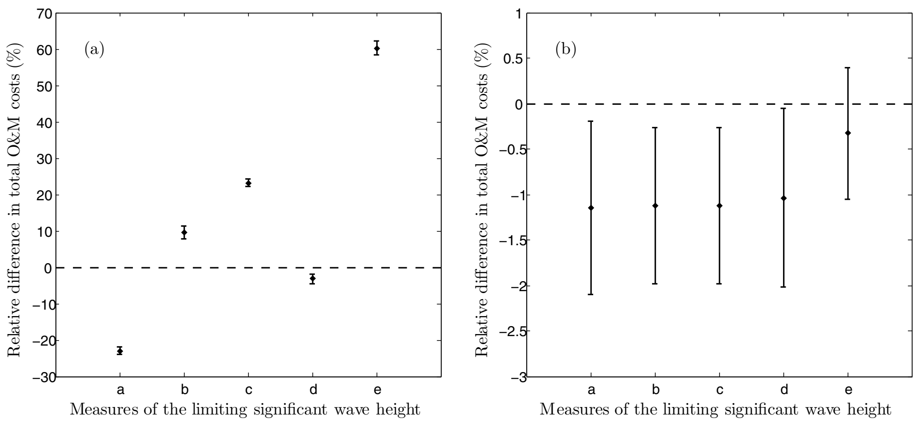

Fig. 3. Comparison of total O&M cost between the multi- and the single-parameter analysis in the simulation model for the CTV (a) and the MVG (b).

In Fig. 2 and Fig. 3, we present a comparison of the results of the multi-parameter and the single-parameter analyses. Fig. 2 shows the results for the time-based availability of the wind farm, while Fig. 3 shows the results for the total O&M cost, which includes lost income due to downtime as well as the direct O&M cost. For both figures, we have calculated, for each of the five measures of LHs in Table 1, the difference between the results using SPWC and MPWC relative to the results using MPWC. The error estimates are the standard error of the average over all simulation runs of this relative difference. For the CTV, as shown in Fig. 2(a) and Fig. 3(a), this statistical error is much smaller than the error due to the finite resolution of LHs in the model, which is of the order of 1–3 %. For the MVG, on the other hand, as shown in Fig. 2(b) and Fig. 3(b), the resolution-induced error is of the same order of magnitude as the statistical error. Taking both these errors into account, we see that for several of the LHs measures, the single-parameter analysis gives results that do not differ significantly from results of the multi-parameter analysis: For the CTV we get similar results for $H_s^{(b)}$ and $H_s^{(d)}$, and for the MVG we get similar results for all LHs measures except from $H_s^{(a)}$. This is the case for both the availability and the total O&M cost.

To complement this comparison, we illustrate in Fig. 4 how the time-based availability depends on the value used for LHs in the single-parameter analysis. The dashed lines between the data points for the discrete values of LHs allowed in the model are guides to the eye, and result values for intermediate values of LHs can be estimated by linear interpolation. This figure also illustrates the error due to the discretisation of Hs, mentioned above. For the matter of comparison, we may also ask: What value of the single-parameter LHs corresponds to the availability or O&M cost obtained using multi-parameter wave criteria? The answer of these questions is quite consistent for the two result parameters, and the equivalent single-parameter LHs value is estimated to be 1.17(1) m for the CTV and 3.0(2) m for the MVG, with the numbers in parentheses indicating the uncertainty in the last digit.

3.3. Comparison of single- and multi-parameter wave criteria using an optimization model

We have applied the optimization model described in Section 2.3 to the case described in Section 2.4 using the multi-parameter wave criteria presented in Fig. 1. In addition, we have tested the same case with each of the single-parameter wave criteria described in Table 1. Since the optimization model optimizes the fleet for a given year, we decided to run each case for five different years (1988-1992) using historical weather data. Unlike the simulation model, where the fleet of vessels is fixed, the optimization model is allowed to decide the number of CTVs and MVGs that are to be purchased or chartered during the planning horizon.

Fig. 5 shows the deviation in percent between the total O&M cost when solving the optimization model using MPWC and each of the SPWC listed in Table 1. The results indicate that $H_s^{(a)}$ and $H_s^{(d)}$ seem to give solutions that significantly under-estimate the O&M costs, with $H_s^{(a)}$ giving 4 % to 8 % lower O&M costs, while for $H_s^{(d)}$ the O&M

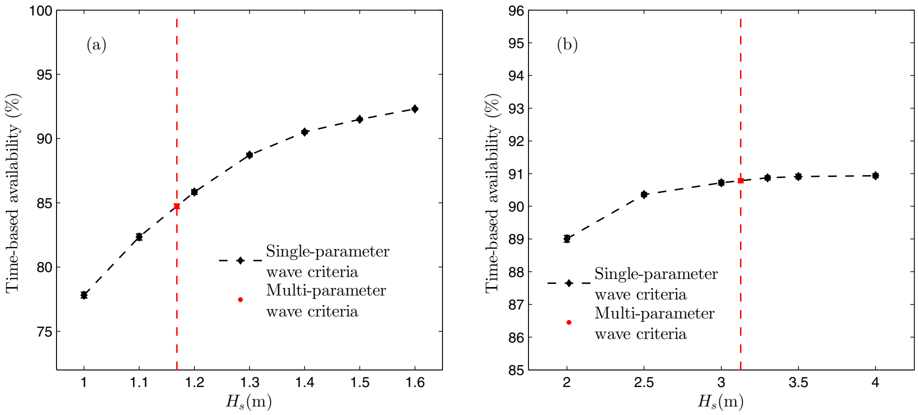

Fig. 4. Time-based availability as a function of limiting significant wave height from a single-parameter analysis with the simulation model, compared with the result for the multi-parameter analysis, for the CTV (a) and the MVG (b).

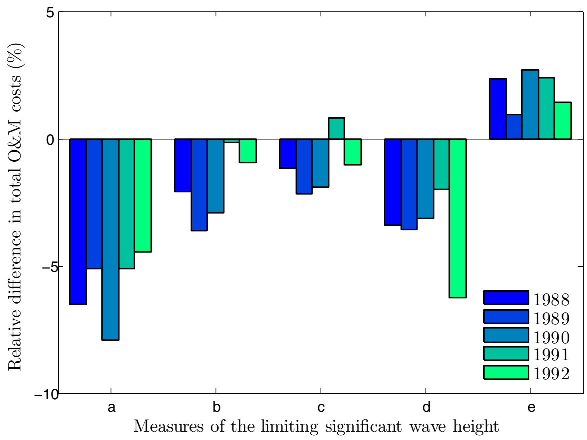

Fig. 5. Comparison of total O&M cost between the multi- and the single-parameter analysis for the optimization model.

costs are 2 % to 6 % lower. As expected, $H_s^{(e)}$ gives an over-estimate of the O&M costs. However, using the most conservative value from the multi-parameter analysis gives a relatively small deviation (≈ 2 %). Both $H_s^{(b)}$ and $H_s^{(c)}$ give small deviations from the multi-parameter analysis, and $H_s^{(c)}$ is the only SPWC which is not consistent in giving either lower or higher cost estimates than using MPWC.

In 17 out of the 25 test cases, the single-parameter analysis gives a smaller vessel fleet than the multi-parameter solution for the same year. The number of MVGs is consistent for all test cases, but the number of CTVs that is purchased is reduced from two in the multi-parameter analysis to one in 16 of the single-parameter test cases and zero in the remaining test case. This indicates that using a single-parameter weather criteria may in some cases lead to an under-estimate on the number of vessels needed to perform O&M activities at a wind farm. Interestingly, it is only the single-parameter $H_s^{(e)}$ that gives the same fleet of vessels as the multi-parameter analysis for all five years.

To investigate the potential error made by purchasing a smaller fleet, we have solved the optimization model using multi-parameter wave criteria with the fleet fixed to zero or one CTV, respectively. The results show that with zero CTVs the O&M cost increases from 3.8 % to 4.8 %, while with one CTV it increases from 0.3 % to 2.3 %. The relatively small difference in O&M cost stems from the fact that the MVG is able to do all the O&M activities that the CTVs perform, only at a slightly higher cost. Thus, the consequence of under-estimating the vessel fleet is small in these test cases.

4. Discussion

In the absence of any single-parameter wave criteria obtained by some independent, well-defined method, we have compared the multi-parameter analysis with single-parameter analyses using five possible suggestions for LHs values representing the MPWC. The methods for estimating a single-parameter LHs were introduced for a fair and thorough comparison of the single- and multi-parameter analysis. Some of the SPWC are obtained using information from not only the MPWC, but also from the actual weather conditions at the offshore wind farm site. This means that these LHs are likely to be representative measures for the accessibility to the wind turbines, compared with other, independently determined LHs measures. In other words, it is reasonable to expect that the single-parameter analysis using these LHs estimates may give relatively similar results compared with the multi-parameter analysis.

For the simulation model, this seems to be the case for several of the single-parameter LHs measures. For some of them, the results would be even closer to those for multi-parameter wave criteria if evaluated by interpolation, using curves as the one illustrated in Fig. 4. The results for the LHs measure $H_s^{(a)}$ gives overly optimistic results for the availability and the total O&M cost. The reason why it is inappropriate to use a simple weighted average of the LHs values over the different values of T_p and β can be seen in Fig. 1(b): Although the calculated LHs for low values of T_p is much higher than any wave height the vessel will ever experience, this has little effect on the actual accessibility to the wind turbines as long as LHs for much more probable values of T_p is much smaller. On the other hand, the most conservative SPWC choice, $H_s^{(e)}$, the smallest possible LHs, gives too pessimistic results in the simulation model, particularly for the CTV. For the MVG, the accessibility is very high and therefore almost independent on the value of LHs in the relevant parameter regime. This makes the sensitivity to the value used for the single-parameter wave criteria much smaller for the MVG than the CTV.

For the optimization model, the relative performance of each of the SPWC is closely linked to the LHs of the CTV. The lower this value is the higher proportion of the O&M activities are performed by the MVG, which has high LHs values, but also higher operating costs than the CTV. Consequently, the O&M costs increase when the LHs of the CTV decreases, though not to the same degree as for the simulation model. The tests also show that for all SPWC criteria except $H_s^{(e)}$ the O&M costs are under-estimated. What is a bigger concern with the SPWC analysis is that it, in most of the tested instances, under-estimates the number of CTVs needed to minimize the total O&M cost of the wind farm. Only for $H_s^{(e)}$, the most conservative LHs measure, does the SPWC analysis give the same number of CTVs as the MPWC analysis. Even though the resulting error in the O&M cost for these small test instances are less than 5 %, this could be a major issue for a larger and more realistic case where many vessel types are considered. In the worst case, the wind farm operator may severely under-dimension his fleet of ships, if basing his calculations only on the LHs value of the ships.

The SPWC measure $H_s^{(d)}$ was defined to correspond to the exact same accessibility of the wind turbines as the MPWC. We may therefore ask what we can expect to gain by going from single- to multi-parameter wave criteria as long as the average accessibilities are the same? What we do not capture by a single LHs is the exact dynamics of the wave states. In other words, we cannot take into account what peak wave periods and what wave headings follow each other and how quickly, and thereby we may have lost accurate information on the length and distribution of weather windows where the turbines are accessible. Although the average accessibility will be the same when using this measure of a single LHs, we will then assume that vessels have access to the wind turbines for some wave states where they do not actually have access, and vice versa. The effect of this approximation seems to be small for the simulation model but somewhat larger for the optimization model.

There are a number of simplifications and assumptions in our approach that are worthwhile discussing. As alluded in the introduction, this work can also be extended to consider other weather parameters such as the decomposition of the sea state in wind waves and swell. This has been neglected in this work, but may result in lower accessibilities [3,4] and consequently larger expected discrepancy between results based on multi-parameter and single-parameter wave criteria. Also, the multi-parameter wave criteria and the weather states in the simulation model were defined for discrete values of T_p and β, and it is possible that some inaccuracies are introduced by the finite resolution. However, as long as we use the same discretisation in the analysis of the single-parameter as for the multi-parameter wave criteria, such inaccuracies should not affect the comparison.

5. Conclusion and further work

In this paper, we have demonstrated how multi-parameter wave criteria obtained from numerical analyses can be used for a more detailed modelling of access to offshore wind turbines in two strategic maintenance and logistics models for offshore wind farms. Similar multi-parameter wave criteria can also be obtained from other methods such as sea trials or tank testing. The multi-parameter analysis was compared with a simplified single-parameter analysis, using only a limiting significant wave height (LHs), a simplification commonly made in the offshore wind industry. The comparison showed that the two approaches may give relatively similar outcomes for strategic decision support models. However, this depends greatly on how well the corresponding single LHs value is estimated. Getting similar results requires that this value is carefully selected. If information on the dependence of the accessibility on peak wave period and wave heading or information on wave conditions is not incorporated into the value used for the LHs, it is likely that the results from the two approaches will vary to a greater extent. Even in a single-parameter analysis, where only a single LHs value is used for a vessel, computing multi-parameter weather criteria may therefore be very useful.

This work opens up a number of possibilities for future research and applications. It is possible to take into account additional weather parameter, e.g. current, independent wind sea and swell components, wind direction, etc. In principle, multi-parameter analysis can also be extended to transit or other vessel operations at offshore wind farms. Another possible application is a cost-benefit analysis of the number and orientation of boat landings for a given wind farm scenario. Taking into account the dependence of the access criteria on relative wave heading, the effect of, e.g., going from one to two boat landings per turbine may be analysed. In cases where it is most convenient to use just a single LHs value for characterising a service vessel, the approach we present in this paper can be a first step towards a method for calculating a good estimate for this LHs value based on a multi-parameter wave criteria analysis. Extending the analysis in this paper to more than two vessels and to weather data from several locations, it is possible to assess if equivalent single-parameter LHs values calculated for a vessel for one offshore wind farm location are also applicable for other offshore wind farm sites.

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