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ScienceDirect

Energy Procedia 94 (2016) 261 – 268

Energy Procedia

13th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2016, 20-22 January 2016, Trondheim, Norway

# Investigating key decision problems to optimize the operation and maintenance strategy of offshore wind farms

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**Abstract**

This paper investigates three decision problems with potential to optimize operation and maintenance and logistics strategies for offshore wind farms: the timing of pre-determined jack-up vessel campaigns; selection of crew transfer vessel fleet; and timing of annual services. These problems are compared both in terms of potential cost reduction and the stochastic variability and associated uncertainty of the outcome. Pre-determined jack-up vessel campaigns appear to have a high cost reduction potential but also a higher stochastic variability than the other decision problems. The paper also demonstrates the benefits and difficulties of considering problems together rather than solving them in isolation.



Peer-review under responsibility of SINTEF Energi AS

*Keywords:* operation and maintenance; logistics; offshore wind; optimization; jack-up vessels; crew transfer vessels; decision support

## 1. Introduction

There is still a great need for the offshore wind industry to reduce costs. An objective of the EU FP7 project LEANWIND [1] is to provide cost reductions across the offshore wind farm lifecycle by identifying potential areas for optimization in all relevant processes. The operation and maintenance (O&M) phase of an offshore wind farm is subject to a vast range of decisions and, therefore, opportunities to improve efficiency. Optimizing the O&M strategy involves finding solutions to these decision problems. Based on work completed in LEANWIND, this paper applies a decision support tool to investigate three decision problems with potential to optimize O&M and logistics

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Peer-review under responsibility of SINTEF Energi AS
doi:10.1016/j.egypro.2016.09.234

strategies for offshore wind farms. Decision support tools have been applied to O&M optimization since the early days of the offshore wind industry and [2] provides a recent review of the literature on relevant decision problems. This paper is concerned with strategic decisions, particularly the selection and utilization of vessels, and considers a selection of problems for corrective and preventive maintenance: 1) If chartering jack-up vessels for predetermined heavy maintenance campaigns, what is the optimal composition of annual campaign periods? 2) What is the optimal number and composition of crew transfer vessels (CTVs) to service the wind farm for smaller corrective and preventive maintenance tasks? 3) What is the optimal start month for annual preventive maintenance services? The following paragraphs briefly review the existing literature on these topics and summarize how this paper contributes.

The use of jack-up vessels for heavy maintenance (major replacements) is the biggest contributor to O&M cost [3]. Therefore, it is interesting to investigate how costs can be minimized by optimizing their use. A number of different strategies are considered in the literature including "Fix-on-failure" (FoF), namely short-term on-the-spot charters [3–6]. In the other extreme, long-term charters (for a number of years) or purchasing of jack-up vessels is also considered by a number of sources [3–6]. However, this strategy only appears to be viable for very large wind farms [3]. Waiting until a number of failures have occurred before chartering a vessel is often referred to as a batch repair strategy [4,5]. Short-term annual charters are also considered in [3–6], while the Crown Estate has investigated sharing strategies to optimize the use of jack-up vessels for O&M [7].

For the majority of maintenance tasks, the only vessel needed is a crew transfer vessel (CTV) to allow technicians to access the wind turbines. The problem of selecting the best fleet of crew transfer vessel has already been studied using simulation models [8,9], and a mathematical optimization model has also been developed [10]. A comparison of different models applied to this problem is presented in [11]. Whereas corrective tasks are usually performed throughout the year as required, the majority of preventive maintenance tasks are undertaken in annual service campaigns during spring and summer. The impact of when this campaign is scheduled is in [6,12].

To summarize the objectives and main contributions, this paper a) seeks to identify viable and robust jack-up vessel charter strategies, focusing on predetermined heavy maintenance campaigns, which is a strategy that has so far not been considered in the literature; b) compares the decision problems in terms of cost saving potential and the uncertainties in results, specifically demonstrating higher potential savings but larger stochastic variability for the jack-up vessel decision problem; c) investigates the potential benefit of considering multiple decision problems simultaneously, as solving each problem in isolation and neglecting possible interactions could result in a sub-optimal O&M strategy. In particular, the paper identifies the importance of considering the timing of annual service campaigns with the selection of the CTV fleet. The paper is organized as follows. The general method of approaching the decision problems is described in Sec. 2. Sections 3.1, 3.2 and 3.3 present results for each decision problem, after which they are compared in Sec. 3.4 and combined in Sec. 3.5. Section 4 summarizes the main findings and suggests areas for further investigations.

## 2. Methodology

The NOWIcob O&M simulation model [13,14] developed by SINTEF Energy Research was used to undertake this study. This strategic decision support model is a discrete-event simulation model for the O&M phase of offshore wind farms, which has been developed further and applied as an O&M strategy model within the LEANWIND project. Using a Monte Carlo approach, it captures the stochasticity of weather, times of turbine failure etc. A 10 year simulation period was chosen.

A set of offshore wind farm scenarios has been defined in LEANWIND and provides the reference for this paper. The base case wind farm scenario comprises 125 turbines set at 30 km from shore. The turbine is the LEANWIND 8 MW reference wind turbine [15], and metocean data correspond to the location of West Gabbard [16]. To produce representative metocean conditions at the site, 100 synthetic metocean time series were generated by a multi-parameter Markov chain weather model based on the metocean data. When comparing different strategies, the difference in results between two strategy solutions is calculated for each metocean time series to reduce the variance. The standard error of the differences is used as a measure of uncertainty for the results that are reported, which are averages over results for all the 100 Monte Carlo iterations.

To model the decision problems, a set of promising strategy solutions were defined and ranked according to the *total O&M cost,* which is defined here as the sum of direct O&M costs and lost revenue due to downtime for a given case over the simulation period. Minimizing this objective function is equivalent to maximizing the profit of the wind farm project, making the optimal trade-off between low direct O&M costs and high wind farm availability. Cost reduction in this paper always implicitly refers to reduction of the total O&M cost. An electricity price of 195 €/MWh was chosen based on the maximum guaranteed strike price of 150 £/MWh in the UK Contract for Difference support scheme for 2016/2017 [17]. While this is quite an optimistic assumption, sensitivity studies found that the main conclusions of this paper were not affected by choosing a more conservative revenue per MWh.

The three decision problems are first analysed separately. The same methodology is then applied to co-optimize different problems and investigate their interactions. When treating the problems in isolation, only a subset of relevant maintenance tasks are considered to isolate the impact of the strategy decisions on the model outputs. The full set of maintenance tasks is presented in Table 1 and [18,19] includes further details. For decision problem 1) (jack-up vessel campaigns), only major replacements are included in the analyses, and for 2) and 3) (CTV fleet optimization and annual service campaign timing), all maintenance tasks except for major replacement are included. Coupled decision problems include all maintenance tasks. Corrective maintenance is always prioritised over preventive maintenance (i.e. annual services). It is assumed that all annual services must be completed during the year for the maintenance strategy to be considered acceptable. Other key model inputs and assumptions are presented for each decision problem in Section 3 or in Appendix A.

Table 1. Failure and maintenance data set.

| Maintenance task | Failure rate [per turbine per year] | Active maintenance time [h] | Spare part lead time [days] | Number of technicians required | Vessel required |
|---|---|---|---|---|---|
| Manual resets | 5 | 3 | 0 | 1 | CTV |
| Minor repair | 3 | 7.5 | 0 | 3 | CTV |
| Major repair | 0.3 | 22 | 10 | 5 | CTV |
| Major replacement | 0.11 | 34 | 60 | n/a | Jack-up vessel |
| Annual service | n/a | 70 | 0 | 3 | CTV |

## 3. Results and discussion

### 3.1. Jack-up vessel campaigns

Extending studies in the existing literature, this paper analyses one particular charter strategy: a set of annual heavy maintenance campaigns set to fixed months each year. The key decision variable being considered is the number and duration of time intervals a jack-up vessel is to be chartered. To restrict the number of scenarios examined, each jack-up campaign period is assumed to be of duration 1 month, and a selection of 67 campaign compositions of 2, 3 and 4 months were simulated. Two or three consecutive 1-month periods are considered as a single campaign. See Appendix A for other modelling assumptions.

Table 2. Overview of ranking of jack-up vessel campaign compositions.

| **Campaign composition** | **Spring** | | | **Summer** | | | **Autumn** | | | **Winter** | | | **Total O&M cost** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MarJulOct | Mar | | | | Jul | | | Oct | | | | | €674,598,170 |
| MarJunSepDec | Mar | | | Jun | | | Sep | | | Dec | | | €679,158,833 |
| JanAprJulOct | | Apr | | | Jul | | | Oct | | | Jan | | €680,302,966 |
| MarSep | Mar | | | | | | Sep | | | | | | €693,908,980 |
| AprSepOct | | Apr | | | | | Sep | Oct | | | | | €700,734,549 |
| MarAugSep | Mar | | | | | Aug | Sep | | | | | | €706,168,023 |
| AprJunAugOct | | Apr | | Jun | | Aug | | Oct | | | | | €722,050,760 |
| AugSepOct | | | | | | Aug | Sep | Oct | | | | | €788,316,261 |

Table 2 illustrates results for a selection of 8 campaign compositions, chosen to best illustrate trends and including the best and worst solutions found. This selection will be used throughout the paper. Compositions are ranked according to the lowest total O&M cost i.e. the best trade-off between high availability and low direct O&M cost. Even when excluding the worst composition, the difference between the lowest (best solution) and highest (worst solution) total O&M cost is about 50M€, illustrating that planning campaigns could significantly minimize costs of an offshore wind farm. The statistical uncertainty is in the order of 3M€. Therefore, when comparing compositions it should be remembered that the difference between closely ranked solutions might not be statistically significant.

From this study, it appears that compositions with 3 to 4 months are most competitive. A key discernible trend is that it is generally advantageous to have campaign periods evenly distributed across the year. Testing the impact of modelling assumptions, smaller or larger mobilisation costs affect the competitiveness of solutions with 4 campaign periods but gives only small changes in the overall ranking. Although it was found that the top two compositions remain strongest, assuming higher day rates or lower revenue per MWh, in the order of 25%, favours solutions with 2 campaign periods. Comparable increases in the failure rate for major replacements make solutions with four campaign periods more competitive. These patterns are expected and increase confidence in the trends of results, but also indicate the potential impact of modelling assumptions. Considering alternative wind farm scenarios, a strategy with 2 campaigns was generally more advantageous for a farm with fewer turbines (80) or lower-rated turbines (125x5MW), offsetting the cost of campaigns with the reduced production and revenue potential. This highlights that the best solution will depend significantly on the project scenario. It may also be assumed that different metocean conditions could also impact results e.g. harsher conditions could exclude compositions with winter months.

Although this paper focuses on pre-determined jack-up charter periods, to assess the competitiveness of this strategy, a comparison was also carried out with a FoF strategy [18]. Here, the mean mobilisation time for jack-up vessels was assumed to be 2 months. Results indicate a cost saving potential for the best pre-determined campaign strategies of the order of 100M€ compared to a FoF strategy for 125x8MW turbines. The competitiveness of pre-determined strategies over conventional FoF strategies is particularly strengthened if long-term charter agreements offer the wind farm operator lower jack-up vessel day rates.

### *3.2. Crew transfer vessel fleet selection*

Two types of vessels were considered for the problem of selecting the CTV fleet. The most expensive vessel with the best capabilities is referred to as Advanced CTV (ACTV), and is distinguished by a higher travel speed and higher wave height limit for technician transfer. The more basic vessel is referred to as Standard CTV (SCTV). Their specifications are described in Appendix A. These vessels are considered to illustrate the trade-off between low day rates and better capabilities. In this case, the decision variables are the number of vessels for each of the vessel types. 12 possible fleet solutions of between 2 and 4 CTVs were considered.

The optimal solution is 1 SCTV + 2 ACTV and results generally indicate a clear advantage to using the ACTV. Considering only the 6 most promising vessel fleet compositions, the potential cost savings are of the order of 20M€. The uncertainty in the potential cost saving is of the order of 1M€, which is markedly lower than for the jack-up vessel campaign problem (3M€).

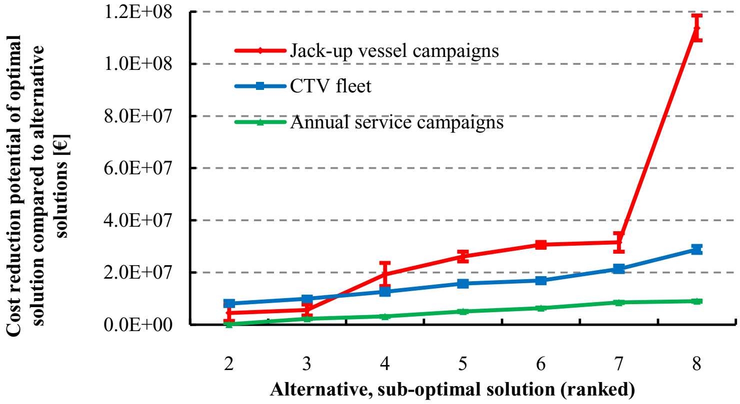
### *3.3. Annual service campaign timing*

For the annual service campaign problem, the decision variable is the starting month of the campaign. From the first day of this month, all turbines are scheduled to be serviced when sufficient resources are available. Although start dates currently used in the industry may range from around March to around May, we have considered starting as early as January and as late as October for illustrative purposes.

Energy-based availability exhibits a clear variation as a function of the start month, having a maximum value around late spring. This is reasonable since downtime hours in winter or autumn correspond to higher lost production than downtime in spring and summer. When solving this decision problem assuming the best vessel fleet found in the above study (1 SCTV + 2 ACTV), the optimal start month was May. The difference between starting in May and starting in March, both fairly reasonable solutions, corresponds to a revenue loss of approximately €3M. With a statistical uncertainty of less than €200,000, while statistically significant, it is lower than typical differences between solutions for the other decision problems considered.

### 3.4. Comparison of impact and uncertainty of decision problems

All decision problems offer statistically significant cost reduction potential, but the magnitude and uncertainty varies. This could impact which problem the decision maker chooses to optimize. To summarize results from Sections 3.1, 3.2 and 3.3, Fig. 1 compares the difference in total O&M cost between the optimal (ranked 1) and alternative (ranked ≥ 2) solutions for each problem. This illustrates the potential for reducing costs and/or increasing revenue by choosing the optimal solution. The 8 solutions with the lowest total O&M cost are considered for each decision problem and are indicated on the right hand side of the figure. Note that some of the solutions included are unacceptable because not all annual services were completed (e.g. the CTV fleet "2 ACTV").




| | | | |
|---|---|---|---|
| 1 | MarJulOct | 1 SCTV + 2 ACTV | May |
| 2 | MarJunSepDec | 2 SCTV + 2 ACTV | Apr |
| 3 | JanAprJulOct | 3 ACTV | Jun |
| 4 | MarSep | 2 SCTV + 1 ACTV | Mar |
| 5 | AprSepOct | 2 ACTV | Feb |
| 6 | MarAugSep | 1 SCTV + 3 ACTV | Jul |
| 7 | AprJunAugOct | 3 SCTV + 1 ACTV | Jan |
| 8 | AugSepOct | 1 SCTV + 1 ACTV | Aug |

*Fig. 1. Comparison of cost saving potential and its uncertainty for the three decision problems.*

Fig. 1 illustrates how the jack-up campaigns have a higher potential for cost reduction but also a higher variability in the results compared to the other problems. This is because the stochastic variability of the results due to major replacements is much larger than the variability due to other failure categories; major replacements happen more rarely, but each of them has a larger impact on the total O&M cost. Ultimately, the decision maker would expect high variation between years for a given scenario and therefore, can be less certain that the expected "optimal" strategy will turn out to be the best choice. In contrast, annual service optimization offers relatively smaller cost savings but lower uncertainty.

### 3.5. Coupling decision problems

#### 3.5.1. Jack-up vessel campaigns coupled with CTV fleet selection

The paper now investigates if the optimal solutions remain so when problems are examined together. Fig. 2 (a) shows how the total O&M cost develops for different jack-up vessel campaign compositions when changing the CTV fleet and (b) shows how the total O&M cost develops for different CTV fleets when changing the jack-up campaign composition. Only a representative subset of solutions is included in the figure. The error bars illustrate the order of magnitude in the statistical uncertainty in the difference between two solutions (±€5–6M).

According to Fig. 2, no solution performs significantly better than the "1 SCTV + 2 ACTV" fleet and "MarJulOct" campaign composition obtained from solving each decision problem in isolation. In some cases, the ranking of solutions changes from the decoupled case in Figure 1, but the overall trend is the same. Therefore, even though not every possible solution has been investigated, there are no indications that studying problems separately results in a sub-optimal solution that is likely to be impacted when interactions with other problems are considered.

However, it is useful to compare the statistical uncertainties for the CTV fleet selection in Fig. 2b with the uncertainties in the decoupled case in Fig. 1. In the decoupled case, the uncertainty for CTV selection was of the order of €1M, but in the coupled case, the uncertainty is of the order of €5M. The reason for the increased stochastic variability is the large variability due to major replacements, as explained in Sec. 3.4. Including major replacements and jack-up-vessels introduces "noise" in the simulation results that makes it harder to discern differences between different CTV fleets with sufficient statistical significance. This makes it computationally much more challenging to solve the decision problem. As a consequence of higher variance, there is also a higher probability of getting a different optimal solution due to chance. This is a key difficulty of solving two problems such as those considered here together rather than in isolation.

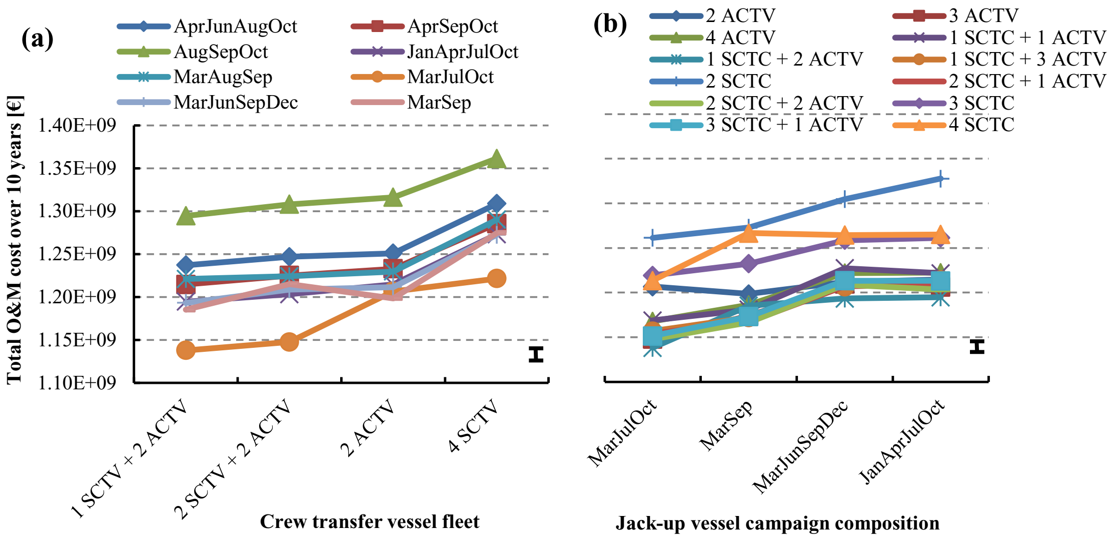



*Fig. 2. Total O&M cost for the coupled problem of jack-up vessel campaigns and CTV fleet selection.*

### *3.5.2. Timing of annual service campaigns coupled with CTV fleet selection*

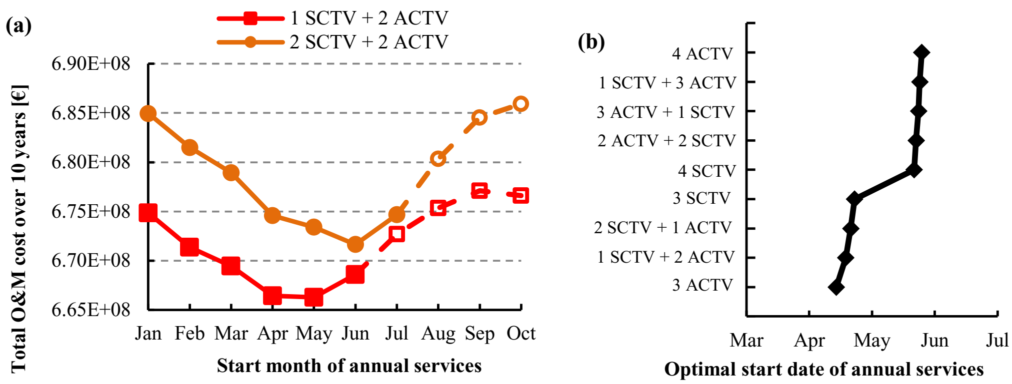



*Fig. 3 Total O&M cost as a function of the start month of annual services (a) and the date with the average lowest total O&M cost (b).*

Fig. 3a illustrates the coupled decision problem of timing the annual service campaigns and selecting the CTV fleet for the two CTV fleets that performed best in the decoupled case. The total O&M cost develops with the start month of annual services as explained in Sec 3.3, and the potential cost reduction depends slightly on what vessel fleet one considers. However, the optimal CTV fleet does not depend on the start month of annual services. When starting late in the year, all annual services cannot be completed; this is indicated by unfilled markers and dashed lines. Uncertainty estimates are smaller than the plot markers. Fig. 3b further examines how the optimal start date for annual services, obtained by averaging over the optimal start month for all simulations, depends on the vessel fleet by. It can be seen that having a larger vessel fleet allows one to start later in the year to reduce downtime costs. This illustrates the potential benefit of coupling different decision problems and considering them simultaneously.

## 4. Conclusions and further work

Comparing strategy solutions for different decision problems of corrective and preventive maintenance of offshore wind farms, this paper substantiates the assumption that optimizing the jack-up charter strategy offers substantial economic potential. Results indicate that pre-chartering jack-up vessels for a set of campaign periods could be a competitive strategy. Also, strategies with a number of campaign periods spread evenly over the year were generally ranked highly. While the optimal solution appears fairly robust, it should be remembered that results are highly dependent on the scenario.

Results differ greatly between decision problems in terms of the stochastic variability and associated uncertainty. The selection of a jack-up vessel campaign compositions is associated with much larger variability than selection of the CTV fleet or the timing of annual service campaigns. This is because failures requiring heavy maintenance are much rarer but have much higher impact than failures requiring only CTVs. This implies a lower certainty for a wind farm operator that the expected best solution actually turns out to be the most profitable for that particular wind farm over the years it is operational, and hence a higher risk. In contrast, although the potential impact of optimizing the timing of annual service campaigns is much smaller, the certainty of actually realizing this potential is also larger.

This paper demonstrates that there is potential for improvements by considering coupled O&M strategy decision problems. For instance, having a larger CTV fleet allows the concentration of annual services to the summer months, which have less wind production and downtime costs. On the other hand, our results do not indicate that interactions between the problems of CTV fleet selection and jack-up vessel campaign period optimization are so strong that these two problems need to be solved together. Also, due to the increased stochastic variability introduced by heavy maintenance, co-optimizing multiple coupled decision problems involving jack-up vessels is more challenging.

This work suggests that pre-determined jack-up vessel campaigns may be a competitive strategy and should be further explored. To improve this strategy, campaign periods of different lengths could also be considered. This would greatly increase the solution space, making it necessary to use optimization models to explore all possibilities. It should also be compared with other more advanced strategies for vessel chartering including condition-based maintenance. Furthermore, the uncertainties and risks associated with strategic decision support highlight the need to optimize O&M and logistics on shorter time scales. More operational and tactical decision support would allow decision makers to mitigate risks and take into consideration conditions that are unpredictable on a strategic level.

## Acknowledgements

The research leading to these results has received funding from the European Union Seventh Framework Programme under the agreement SCP2-GA-2013-614020 (LEANWIND). The contributions of I. B. Sperstad and M. Kolstad are co-funded under the research centre NOWITECH.

## Appendix A. Input data

This appendix describes some modelling assumptions underlying this study. Many assumptions forming the basis for this paper can also be found in Appendix C of [19], or are based on technical experience and discussions with industry within the LEANWIND project. Key input parameters for the vessels considered are specified in Table 3. The wave height limits for the CTVs apply to technicians transfers to turbines. Major replacement operations for jack-up vessels are divided in three operational phases: jacking up (6 hours), lifting (10 hours), and jacking down (4 hours). The wave height limit of the jack-up vessel applies to the jack-up and jack-down phases only, whereas the wind speed limit only applies to the lifting/repair phase. A sensitivity study found that more optimistic wind speed limit for lifting, more optimistic wave height limits for jacking or more conservative time duration of lifting operation only marginally impact the ranking of the jack-up vessel campaign compositions. Jack-up vessels are assumed to operate 24 hours a day while at site; technicians access the turbine via a gangway from the jack-up vessel, obviating the need for CTVs. However, CTVs are needed for pre-inspections, and an 8-hour pre-inspection is assumed for major repairs and major replacements. The cost of each month-long jack-up vessel campaign period is assumed to equal 30 day rates and a mobilisation cost equalling six day rates is considered per campaign (irrespective of the duration of the campaign). Also, it is assumed that 13.5% of the theoretical wind power production is lost due to wake effects, electrical losses and losses due to downtime of the electrical infrastructure.

Table 3 Vessel data.

| Vessel | Vessel speed [knots] | Technician space | Day rate [€] | Mobilisation cost [€] | Wave height limit [m] | Wind speed limit [m/s] |
|---|---|---|---|---|---|---|
| Standard Crew Transfer Vessel (SCTV) | 22 | 12 | 3400 | n/a | 1.5 | n/a |
| Advanced Crew Transfer Vessel (ACTV) | 35 | 12 | 6200 | n/a | 2.0 | n/a |
| Jack-up vessel | 12 | n/a | 140 000 | 840 000 | 1.8 | 11 |

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