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Testing the robustness of optimal access vessel fleet selection for operation and maintenance of offshore wind farms

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ABSTRACT

Optimising the operation and maintenance (O&M) and logistics strategy of offshore wind farms implies the decision problem of selecting the vessel fleet for O&M. Different strategic decision support tools can be applied to this problem, but much uncertainty remains regarding both input data and modelling assumptions. This paper aims to investigate and ultimately reduce this uncertainty by comparing four simulation tools, one mathematical optimisation tool and one analytic spreadsheet-based tool applied to select the O&M access vessel fleet that minimizes the total O&M cost of a reference wind farm. The comparison shows that the tools generally agree on the optimal vessel fleet, but only partially agree on the relative ranking of the different vessel fleets in terms of total O&M cost. The robustness of the vessel fleet selection to various input data assumptions was tested, and the ranking was found to be particularly sensitive to the vessels' limiting significant wave height for turbine access. This is also the parameter with the greatest discrepancy between the tools, implying that accurate quantification and modelling of this parameter is crucial. The ranking is moderately sensitive to turbine failure rates and vessel day rates but less sensitive to electricity price and vessel transit speed.

1. Introduction

With more than 3200 offshore wind turbines connected to the European grid at the start of 2016 (EWEA, 2016), operation and maintenance (O&M) of these assets is a key challenge to achieve commercially viable projects. The estimated contribution of O&M to the life cycle cost of an offshore wind farm varies significantly, accounting from 15 to 30% (Musial and Ram, 2010; Wiser et al., 2016). Offshore logistics and vessels are major contributors to the O&M costs, estimated to account for almost 45% (GL Garrad Hassan, 2013; Smart et al., 2016), and are decisive factors in ensuring high availability of the wind turbines and hence high electric power production. As offshore wind farms are remote, unmanned and often difficult to access due to weather restrictions, the offshore logistics related to O&M becomes a highly complex task. Since most offshore wind farms have been in operation for only a few years, there is a general lack of O&M industry experience. Developers, original equipment manufacturers (OEM), operators, and financial institutions are looking for tools to guide decision making when deciding on maintenance strategies, vessels, manning, and investments. The problem is exacerbated for non-OEMs, since much of the existing operating experience has been gained during the initial warranty period. This increases the uncertainty for non-OEMs around future operations.

This paper focuses on decision support tools applied to the selection of the O&M vessel fleet, i.e. the crew transfer vessels or other logistics solutions for accessing the wind turbines to conduct maintenance. This is an example of a decision problem in offshore wind O&M that has received much attention both in the research literature and in the industry. For instance, optimising the offshore logistics solution and investigating its robustness to assumptions are often done as a part of due diligence in preparation for the investment decision for offshore wind

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projects. In practice, a number of aspects must be considered in the selection of O&M vessels, such as the technical, hydrodynamic evaluation of the accessibility of the turbines by the vessels (Wu, 2014; Guanche et al., 2016). However, this paper takes a higher-level, strategic perspective and considers the economic evaluation of the vessels as part of the overall logistics system of the wind farm. The research literature reports a number of tools for such economic evaluation that have been applied to the problem of selecting the O&M vessel fleet, including analytic cost tools (Besnard et al., 2013), simulation tools (Dalgic et al., 2014, 2015a, 2015b; Endrerud et al., 2015; Sperstad et al., 2016) and mathematical optimisation tools (Halvorsen-Weare et al., 2013; Gundegjerde et al., 2015). For comprehensive reviews of strategic decision support tools for offshore wind O&M and logistics more generally, see Hofmann (2011) and Shafiee (2015).

As a large number of strategic decision support tools have already been developed, the purpose of this paper is emphatically not to present yet another new or improved tool. The work is rather motivated by the need to reduce the uncertainties that still remain related to both modelling assumptions and input data for such tools. Uncertainties related to input data assumptions have been studied in some of the works cited above using sensitivity analysis. Sensitivity analysis for offshore wind O&M is also treated more generally in Martin et al. (2016). However, the insights from previous sensitivity studies may have restricted generality as they depend on the modelling assumptions implemented in the particular decision support tool considered in each study. Uncertainties related to modelling assumptions intrinsic to the tools were previously addressed in Dinwoodie et al. (2015) by comparing four different simulation tools for calculating O&M costs and wind farm availability. In that study, a reference wind farm case with relevant input data was defined, and baseline results were reported for the different tools. The comparison revealed how different tools can produce significantly different results because of dissimilar modelling assumptions. However, Dinwoodie et al. (2015) considered only simulation tools for O&M, and the study did not consider the application of the tools as decision support tools for optimising the O&M strategy.

In this paper, four simulation tools, one mathematical optimisation tool and one analytic spreadsheet-based tool have been tested on the reference case from Dinwoodie et al. (2015) to compare how they rank a predefined set of vessel fleets. The objectives of this work is to answer the following research questions: a) How robust is the ranking of vessel fleets to the kind of decision support tool that is used? Even if different decision support tools disagree on the absolute performance measures of different vessel fleets for offshore wind O&M, do they still agree on the relative ranking of the vessel fleets? b) How robust is the ranking of the vessel fleets given by each tool to the assumptions made for different key input parameters?

Although previous work has compared different offshore wind O&M decision support tools qualitatively (Hofmann, 2011), this is the first time the robustness of offshore wind O&M decision support has been investigated quantitatively, using more than one tool. Furthermore, it is the first study to consider sensitivities in the ranking of different vessel fleets. Addressing these research questions through a comparison of different tools can identify the direction for further model validation and development work, reducing the uncertainty associated with decision support for offshore wind O&M and logistics. Furthermore, model comparison and sensitivity studies can identify which uncertainties in the input data are most important to consider and may also provide other recommendations for using advanced tools to support offshore wind O&M and logistics decisions.

The rest of the paper is organized as follows. Section 2 explains the proposed methodology for O&M vessel fleet optimisation and sensitivity analysis. The reference wind farm, vessel alternatives and decision support tools used are also introduced in this section. Section 3 presents the results for the vessel fleet ranking and sensitivity analysis. The results are discussed in Section 4, after which the paper is concluded in Section 5 by summarizing key findings and suggesting implications for the use of strategic decision support tools for selecting the O&M vessel fleet.

2. Methodology

This section describes the proposed methodology for O&M vessel fleet optimisation and sensitivity analysis. The focus is on the selection of the *access vessel* fleet, i.e. the fleet of crew transfer vessels (CTV) and/or other vessel concepts for transferring and allowing technicians access to the turbines. The section first defines the optimisation problem and then introduces the decision support tools used for evaluating different vessel fleets. This is followed by a description of the base case specifications for the reference wind farm and the different vessel types and the vessel fleet alternatives that are considered. Finally, the methodology and cases for the sensitivity analysis are described.

2.1. Vessel fleet ranking

In this section an optimisation problem for the selection of a vessel fleet for O&M of an offshore wind farm is formulated. A solution space of possible vessel fleet alternatives is defined, and for all alternatives in the solution space, the performance of the vessel fleets are evaluated and ranked according to the value of the objective function *f*. The optimal vessel fleet is the one with the lowest value of *f*. For this optimisation problem, a simple objective function, referred to as the *total O&M cost*, is defined to capture the trade-off between O&M costs and wind farm availability:

$$f = \text{Total O\&M cost}$$
$$= \text{Direct O\&M cost} + \text{Lost revenue due to downtime} \quad (1)$$

Lost revenue due to downtime, or lost production or downtime costs, is the difference between theoretical revenue for the ideal case of no wind turbine downtime and actual revenue. This can be expressed mathematically as follows:

$$\text{Lost revenue due to downtime} = P_{\text{el}} \sum_{t=1}^{N_{\text{hours}}} \sum_{j=1}^{N_{\text{turbines}}} E_{\text{theor},j,t} \times \left(1 - A_{j,t}\right) \quad (2)$$

Here, P_{el} is the electricity price, i.e. the revenue generated per MWh, measured in £. The analysis considers a period of N_{years} with a number of hours $N_{\text{hours}} = N_{\text{years}} \times 365 \times 24$. $E_{\text{theor},j,t}$ is the electricity production in units MWh of turbine *j* in hour *t*, given the wind speed and turbine power curve and given that the turbine is available to generate electric power. The availability $A_{j,t}$ of wind turbine *j* in hour *t* is 0 during downtime and 1 when the turbine is available to generate electric power.

Direct O&M cost is here composed by the following cost components:

$$\text{Direct O\&M cost} = \text{Vessel cost} + \text{Personnel cost} + \text{Total repair cost} \quad (3)$$

In reality, there are also a number of other direct O&M cost components that are not included in this equation (GL Garrad Hassan, 2013; Smart et al., 2016), but this simplification is made to focus on the key cost elements that may vary between different O&M vessel fleets. Cost elements that do not vary between different vessel fleets are constant terms in the optimisation problem and do not impact the optimal vessel fleet selection.

The vessel cost is the sum of day rates (i.e. charter costs per day) for all vessels in the O&M vessel fleet:

$$\text{Vessel cost} = N_{\text{years}} \times 365 \times \sum_{v} (\text{Day rate})_v \quad (4)$$

The personnel cost is the sum of annual salaries for all N_{tech} maintenance technicians working in the wind farm:

$$\text{Personnel cost} = N_{\text{years}} \times N_{\text{tech}} \times \text{Annual technician salary} \quad (5)$$