Reference Cases for Verification of Operation and Maintenance Simulation Models for Offshore Wind Farms

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ABSTRACT
Due to lack of operating experience in the field of offshore wind energy and large costs associated with maintaining offshore wind farms, there is a need to develop accurate operation and maintenance models for strategic planning purposes. This paper provides an approach for verifying such simulation models and demonstrates it by describing the verification process for four models. A reference offshore wind farm is defined and simulated using these models to provide test cases and benchmark results for verification for wind farm availability and O&M costs. This paper also identifies key modelling assumptions that impact the results. The calculated availabilities for the four models show good agreement apart from cases where maintenance resources are heavily constrained. There are also larger discrepancies between the cost results. All the differences in the results can be explained by different modelling assumptions. Therefore, the models can be regarded as verified based on the presented approach.

1. INTRODUCTION
1.1. Motivation
Offshore wind energy is a new area for operation and maintenance (O&M) research, and the operational legacy of the industry is only just over a decade. Operation and maintenance cost modelling software tools are being developed to support activities in this field. Because of the novelty of offshore wind energy generation and lack of real data, there are limited options for validation and verification of these models. Verification and validation of a simulation model is essential if the model is to say something useful about the system it is meant to represent. We define verification as ensuring that the simulation model is implemented according to the specifications of the conceptual model of the system; validation is defined as ensuring that this conceptual model is in fact a faithful representation of the real system for the purposes of the model [1]. It may prove difficult for researchers to acquire suitable data to perform model validation. For full operational validation [1], necessary historical data would include repair and logistical costs, statistical information on component reliability and performance indicators such as total operations costs or availability. This type of information is possessed by the farm owner/operator, turbine manufacturer or non-existent for new generation wind turbines.

1.2. Background

Several O&M simulation models for offshore wind farms have been developed, of which Hofmann [2] provides a thorough overview. Often, the intended applications of the models differ slightly. For example, one model will focus on assessing heavy-lift vessels, whereas another will be used for maintenance strategy optimisation.

There are no universally specified guidelines for what it means for a simulation model to be verified and validated [3]. One position is that models are never entirely validated because it is not practicable to assess correspondence between the system and the model for its entire domain of applicability [1]. Even if the system is observable and a comparison of model output and system output is possible, one is often interested in predicting system behaviour under circumstances not observed today. This is the case for nascent industries such as offshore wind energy, where novel and untested O&M strategies have to be considered in order to reduce the cost of energy. It can then be argued that the best one can do is to systematically explore the output behaviour of the model to build confidence and increase its credibility [1].

In the absence of data for the system with which one may compare the output data of the model, one may compare those with other models. This may be regarded as validation if one of the other models has already been validated [1]. But even if this is not a case, it is a method of increasing credibility of the different simulation models by bringing together experts and gaining experience on how the models behave. Such an endeavour has been referred to as *intercomparison*. Another term used is *code-to-code-comparison*. One example of code-to-code comparison within offshore wind research is the Offshore Code Comparison Collaboration, Continuation (OC4) [4] which has the aim to verify simulation models for the dynamics of floating turbine substructures.

Such intercomparison efforts may be regarded as verification efforts and not validation, since one is not observing the output of actual systems. But as such, they have been reported to be quite successful in uncovering implementation mistakes and identifying the limits to the applicability of the various models [4]. For offshore wind O&M models, there is, to the best of our knowledge, little work reported in the literature on model comparison and verification and validation, the exceptions being [5] and [6].

1.3. Objective

We specify two main objectives of this collaborative work: the first regards the development of a verification process and the second regards its implementation and the verification of four offshore wind O&M cost models.

The focus of this paper is to demonstrate the verification process by defining a set of reference cases that can be used as a benchmark for other model developers and help to verify their models through intercomparison. Four offshore wind O&M models simulated these cases and the results are provided. If there is a convergence in the results, this makes it more credible that the different model developers have made consistent assumptions and have correctly implemented their models according to these assumptions. If the models produce different results, on the other hand, then investigation of these differences may provide useful insight about which model assumptions are important. Identifying these modelling assumptions is a secondary objective of this work. In addition, through collaborative investigation, improvements in several of the models were identified.

2. METHODOLOGY

2.1. Verification process

In order to compare the models, it was necessary to determine a base case which represents offshore wind farms currently operating in Europe as well as capturing current industry practices for maintenance activities. The base case was influenced by reviewing the configuration of existing wind farms in Europe [7]. This reference case is fully described in Section 2.3, specifying all relevant parameter values. The models tested in this study have additional input parameters, but they have been restricted to a “minimal” case that can be run meaningfully for most mature models of this kind. This allows as close as possible a comparison of the developed models while still being sufficiently complex to be representative of the operational reality. Using the base case, each model was run on a limited set of cases and the key output parameters of availability and direct O&M costs were compared. After this a larger set of cases were run with each model; the results from this are presented in Section 3 and analysed in Section 4.

Due to the complex nature of simulating offshore wind O&M and the wide range of corresponding modelling assumptions, exact replication between models was not expected nor required to consider the models verified against each other. Instead, the results were required to be qualitatively similar and show consistent trends across cases and the differences between results were required to be logically explained. Observed differences between initial model results were used as part of the verification process where as many modelling assumptions as possible were mapped and used to determine if differences were due to differences in logical implantation of the models or due to errors. Where an individual model did not meet these criteria, it was developed until the above criteria were achieved.

The metrics chosen for comparing models were time-based availability and annual direct O&M costs. Availability in this sense is technical availability defined as "*the percentage of time that an individual wind turbine or wind farm is available to generate electricity expressed as a percentage of the theoretical maximum*" [8], calculated using Eq.1 from IEC Standard 61400-26 [9]:

$$Availability = 1 - (Unavailable\ Time)/(Available\ Time + Unavailable\ Time) \qquad (1)$$

This definition of availability is widely used within the wind industry as an indicator of wind farm operational performance. Poor availability indicates either poor wind turbine reliability performance, poor maintenance actions or a combination of both, and any useful O&M model is required to be able to accurately reproduce observed operational values. Annual direct O&M costs are comprised of vessel, technician and repair costs. These are of particular importance for models as they are costs that can be directly influenced in the operational phase and it is therefore also critical that they are accurately captured.

2.2. Description of models considered for verification

A common core methodology has been independently adopted across all models; discrete event, time-sequential modelling in combination with Monte Carlo simulation experiments. A sufficiently large number of Monte Carlo iterations, or simulation runs, dependent on the sample variance of the simulation results, are performed to provide an expected value for key result variables. In addition, the range of individual simulation results provides an indication of precision in the simulation results and expected lifetime performance variability for the given wind farm configuration.

The discrete-event, time-sequential approach creates a time series representing the operational life of a wind farm with simulated failure events and corresponding maintenance tasks. Failures are simulated based on constant failure rates with the simplifying assumption that failures occur independently of each other. When a failure has occurred, turbines remain in a failed state until a successful maintenance task has taken place. Maintenance tasks can be carried out only when suitable vessels are available and the weather allows the wind turbines to be accessed.

A brief summary of the background and key features of the different models are presented below:

2.2.1. NOWIcob

NOWIcob [10, 11] has been developed by SINTEF Energy Research for studying and providing decision support on maintenance and logistics strategies from a developer perspective. An example of the analyses the model is designed for is what type and number of vessels should be used. The model considers the planning and scheduling of maintenance tasks that are competing for limited maintenance resources, taking into account the availability of weather windows. The model simulates with an hourly resolution throughout the lifetime of the wind farm and uses a Markov chain weather model to generate multiple synthetic weather time series from the historical weather data.

2.2.2. University of Stavanger Offshore Wind Simulation Model

The University of Stavanger (UiS) offshore wind simulation model has been developed as a research tool in a project on maintenance organisations and strategies and as a decision tool for offshore wind farm developers in the NORCOWE research centre. The model simulates maintenance planning and execution, as well as marine logistics for the operation and maintenance life cycle phase. A multi-method simulation modelling method was chosen for this model consisting of both the agent-based and the discrete-event paradigms. More information on the model can be found in [12].

2.2.3. ECUME Model

Version 8.2 of the ECUME model has been developed by EDF R&D to be used internally to support the group's activities in the offshore wind industry. The main outputs are mean O&M costs and the annual availability of the wind farm as well as lost production. A Monte Carlo analysis determines the probability distribution of O&M costs. More information on the model can be found in [13].

2.2.4. Strathclyde University, Centre for Doctoral Training Offshore Wind OPEX Model

This model has been developed at the Centre for Doctoral Training in Wind Energy Systems to provide a complementary analysis tool to a previously developed probabilistic model [14]. The initial model development focussed on the use of specialist heavy-lift vessels for offshore wind and to inform decision support for operational strategies [15]. It has subsequently been developed to capture the full range of operations associated with offshore wind maintenance. A Multivariate Auto-Regressive climate model is incorporated that determines accessibility and power production of the wind farm. The model uses a maintenance shifts simulation approach across the lifetime of the farm to determine availability and resource usage. Costs are then calculated post simulation.

2.3. Description of reference cases

The wind farm specified for the simulation model comparison consists of 80 Vestas V90 3.0 MW wind turbines, assumed to have a hub height of 90 m. The closest turbine is located 50 km from an onshore maintenance base, representing a typical value for current offshore wind farms. The power curve of the turbines is given in Table 8 in Appendix A.

Because the reference cases are designed as "minimal cases", as explained in Section 2.1, we neglect several aspects of real offshore wind farms that are not essential to this comparison of O&M models. Cable and grid infrastructure, substations, and other parts of the balance of plant were not considered for O&M operations in the wind farm. No specific farm layout is indicated, and wake effects, electrical losses and other losses not due to turbine failures and maintenance are neglected. Some other aspects such as spare parts logistics are also neglected for simplicity in this model comparison.

The weather data used in this study comes from the FINO 1 [16] offshore research platform which is situated approximately 45 km off the coast of Germany within the German development zone for offshore wind farms. It can be considered representative of Central North Sea conditions and lies close to the existing Alpha Ventus wind farm. The data set used for this analysis covers the years 2004–2012. The wind speeds are recorded at 90 m, corresponding to typical offshore wind turbine hub heights, and the significant wave heights are measured using a wave buoy. Due to the harsh climate and length of the data set there were variations in recording interval and periods where gaps exist in the data. The data was therefore pre-processed into hourly resolution and gaps were filled using a cubic spline interpolation. The time duration chosen for the simulated period was 10 years, so this time series was extended or repeated by different means in each of the simulation models.

Three vessel types were considered: 1) Crew Transfer Vessels (CTV), 2) Field Support Vessels (FSV), and 3) Heavy-Lift Vessels (HLV). All three vessel types are restricted by weather criteria. In addition to weather criteria, every vessel type has a limited capacity for technicians, a fixed transit speed, mobilization time, charter cost and charter period; all given in Table 1 in Appendix A.

Failure data were provided by a developer based on their expert knowledge and are representative expectations for the current generation of offshore turbines. Five failure categories were defined based on the categories defined in the RELIAWIND [17] project: i) manual reset, ii) minor repair, iii) medium repair, iv) major repair and v) major replacement. The five failure categories have individual average annual failure rates. The failure data used are given in Table 4 in Appendix A.

A corrective maintenance strategy was used in the study, in combination with annual service on every turbine. The repair process consisted of repairs with predefined average repair times for the five failure categories. The five failure categories require different numbers of technicians and different types of vessels. Repair times and requirements are listed in Table 4 in Appendix A. Maintenance tasks were assumed to be carried out when maintenance resources (vessels and technicians) were available

Table 1. Definition of the different reference cases considered

Case	Case description
Base case	Defined in Chapter 2.3.
More CTVs	The number of CTVs was increased from 3 to 5 and the number of technicians was increased from 20 to 50.
Fewer CTVs	The number of CTVs was reduced from 3 to 1.
More technicians	The number of technicians was increased from 20 to 30.
Fewer technicians	The number of technicians was reduced from 20 to 10.
Failure rates down	All failure rates were 50% of base case failure rates (only corrective maintenance; annual services remain unchanged).
Failure rates up	All failure rates were 200% of base case failure rates (only corrective maintenance; annual services remain unchanged).
No HLVs	Failure rates for failure categories requiring heavy-lift vessels (major repair and major replacement) were set to zero.
No weather limits	Weather limits for operation of all vessels were effectively set to infinity.
Historical weather data	An 8-year time series for the weather data was used instead of synthetic weather time series (for models using such).
Manual resets only, Minor repairs only, Medium repairs only, Major repairs only, Major replacements only	For "Manual resets only", e.g., failure rates for all failure categories except for manual resets were set to zero. Similarly for "Minor repairs only", etc. There were no annual services for any of these cases.
Annual services only	Failure rates for all failure categories were set to zero, making annual services the only form of maintenance.

and the wind farm was accessible based on the specified vessel weather limits. The repair process was carried out cumulatively until the repair time had been reached and the turbine was then returned to an operational state.

3. RESULTS

In this chapter, we present a selection of the simulation results for the reference cases. The main trends for the time-based availability are illustrated in Figure 1, and Figure 2 summarizes the results for the direct O&M costs. The figures show values for both the base case and all the other reference cases; more detailed results for the base case are given in Table 10 in Appendix B. For clarity, and because it is not an aim for this paper, results from the individual models are not shown in the figures. The same trends and qualitative sensitivities were shared by all models, although quantitative effects evidently vary. It was relatively consistent across the reference cases which models gave the highest and the lowest values. Values for each model are given as average values for a number of independent simulation runs over the 10-year simulation time. The number of simulation runs typically ranged from around 50 to 1000. For all cost numbers, the values given are annual values calculated as the average cost value over the 10-year period.

The statistical uncertainties in the results as quantified by the estimated standard error of the sample mean were of the order of 0.2 % for the base case time-based availabilities (see Table 10 in Appendix B for details). This means that we regard the differences between the time-based availability in the base case of the order of 1–3 % to be statistically significant. The uncertainties for the rest of the cases were mostly the same order of magnitude as for the base case, although the uncertainty was substantially larger for cases with lower availability. The uncertainty for the direct O&M costs were of the order of £0.5 m–£2 m for the base case and the other reference cases where heavy-lift vessels are needed; where they were not, the uncertainty in the direct O&M cost were orders of magnitude smaller.

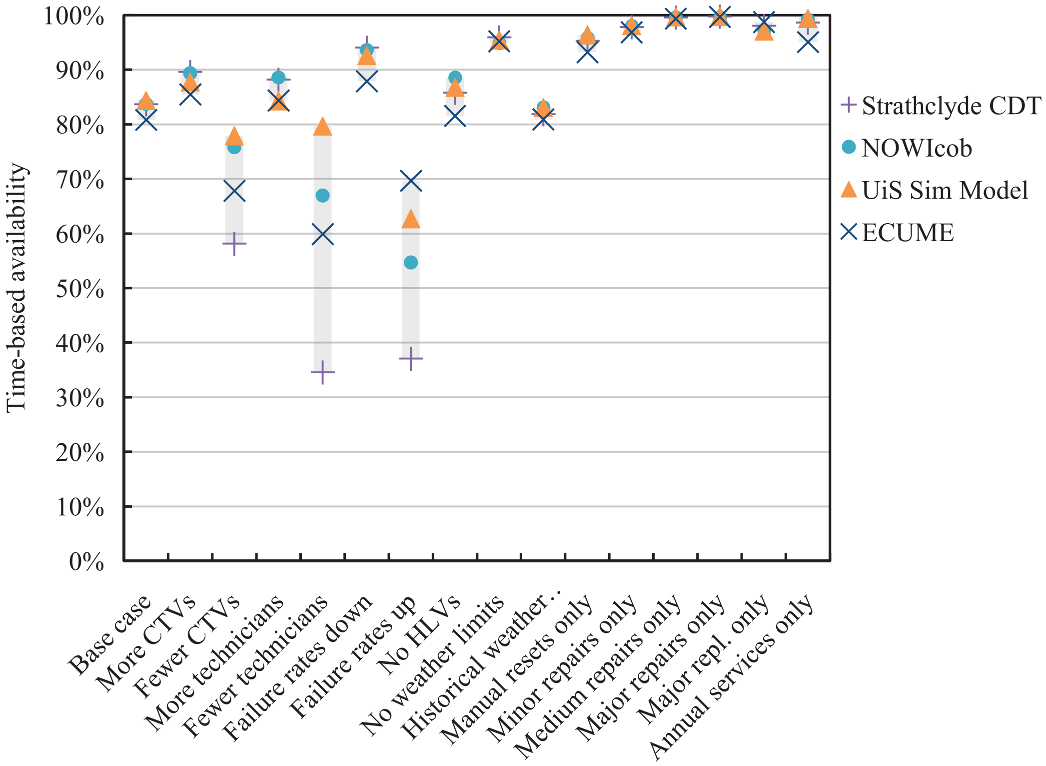

Figure 1. Average value for the time-based availability for the models for the reference cases

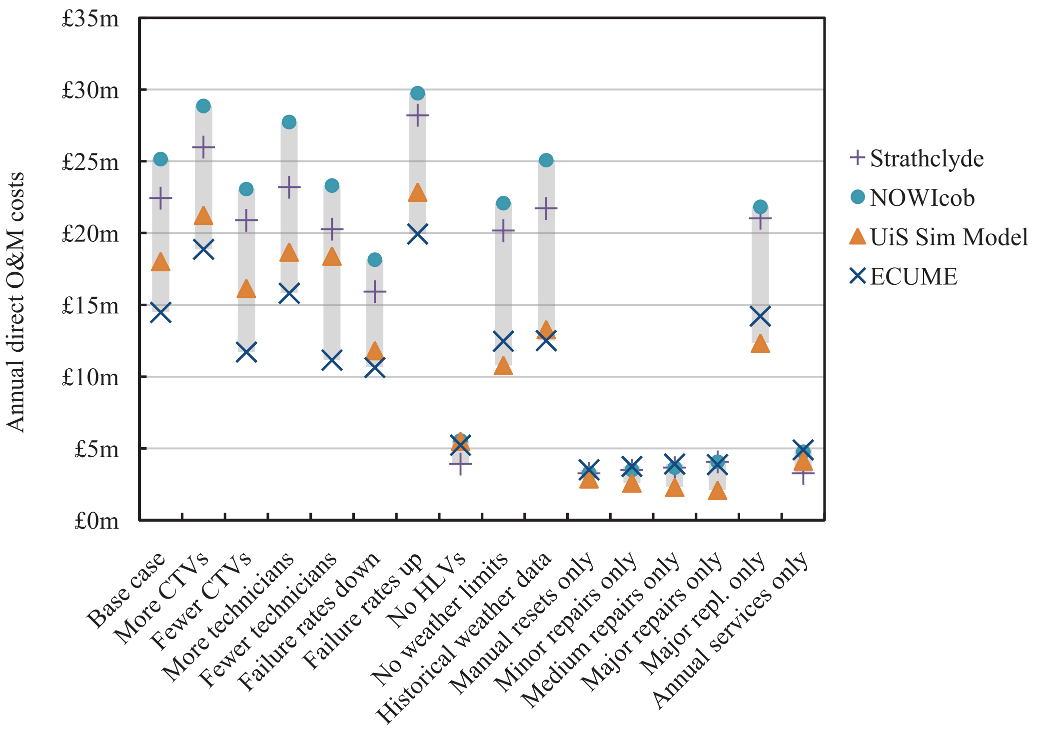

Figure 2. Average values for the average annual direct O&M costs for the models for the reference cases

4. DISCUSSION

The discussion is divided in two parts: first a discussion regarding the verification approach followed by a discussion regarding the results in Section 3 and important model assumptions.

4.1. Discussion regarding verification approach

The first step in the verification approach was to map all input parameters of each individual model and define a base case and several additional variations of this case to benchmark models against each other. After running all the cases, several differences between the models' outputs were identified. Two very basic, but easily forgotten, issues were terminology and definition of key parameters, in order for all to interpret input and output in the same way and use comparable values. Therefore, after the first iteration of model runs, common terminology and parameter definitions were stated (the terminology and definitions used in this paper). After the second iteration, the models' outputs seemed to converge to a greater extent. Consequently, it is recommended for others who wish to use this approach and benchmark against the results presented in this paper to adapt and adhere to the terminology and parameter definitions in this paper.

The second step in the methodology was to run all cases and benchmark models against each other and, through a discussion between model developers, identify the reasons for why a model's output show a large difference from the other models. The most suitable structuring of discussions was to systematically go through all the predefined cases and compare outputs for all parameters. The discussion resulted in a suggestion that the modeller tried out before the next meeting, where model outputs of the next iteration were presented. The number of iterations needed to verify the models varied for the individual models, and it took between 4 and 8 iterations before the models were accepted as verified. For some of the extreme cases, especially where resources were constrained, it was difficult to determine which results could be regarded as most accurate due to the wide range of output values. Nevertheless, the discussions around these special outcomes uncovered many important assumptions with regards to how logistics and resource utilisation are modelled.

A large number of cases were defined, thus requiring a relatively long time frame to complete all simulations. However, all cases contributed insights on different parts of the models, and it is recommended to use all cases for a more complete verification. On the other hand, if any cases should be prioritised, it should be the extreme load cases in addition to the base case, i.e. "Fewer CTVs", "Fewer technicians", "Higher failure rate", "Major replacements only", and "No HLVs".

4.2. Discussion regarding model results

As one can see from the model results from the base case in Figure 1, the generic wind farm generated low availabilities in all models, around 82%, which is a low number for offshore wind farm in the North Sea. The low availability can be explained by the relatively harsh weather data, with an average significant wave height of 1.48 m and accessibility for CTVs 61.6 % of the hours in the weather time series. Another weather-related issue is that all four models work with weather data differently, from using historical time-series to generating synthetic time-series through different methods. This can be one of the reasons for the differences in output among the models. In fact, the variation between models is seen to be significantly smaller for the "Historical weather data" case than for the base case.

By comparison of the model results in Figure 1 and Figure 2, it is apparent that although there are small differences in time-based availability for some cases, direct O&M costs differ quite significantly for all cases except the "No HLVs" case and cases with only single failure categories. Initially, this could indicate that there was a fault in the model logic, that costs were being calculated differently, or both. After debugging and individual testing, it was identified that HLV charter length was modelled differently and was the main reason for large differences in direct O&M costs. The difference was that two of the models used a minimum HLV charter length of one month whenever a HLV was chartered, while the other two only chartered a HLV for the minimum required period. The result of case "No HLVs" also supports this conclusion, as it is easy to see in Figure 2 that the difference between the four models and the mean is close to zero for this case. In addition, the model results confirm what Faulstich et al. [18] highlights, namely that major replacements needing HLVs accounts for the majority of direct O&M costs but only make a moderate impact on availability. On the other hand, small failures only needing CTVs accounts for a small part of direct O&M costs, but have a large impact on availability.

As it can be seen in Figure 1, three cases stand out with large differences in availability among the four models; “Fewer CTVs”, “Failure rates up” and “Fewer technicians”. These can be explained by three important model assumptions related to logistics: 1) Number of parallel maintenance tasks possible; 2) modelling of failures; 3) assigning maintenance tasks to vessels offshore.

First, possibility for and number of parallel maintenance tasks accounted for much of the differences in the time-based availability results of the “Fewer CTVs” case. The Strathclyde model, which has the possibility for three parallel tasks, represents the lowest result in Figure 1. The NOWIcob model, on the other hand, in principle has the possibility for a number of parallel tasks only limited by the number of technicians on the vessels, and it represents the highest result in Figure 1. It is easy to understand that maintenance activities in a model with less limitation on the number of parallel tasks will be more efficient if there is a maintenance task backlog. Whether or not parallel tasks are realistic for a real wind farm depends on several factors such as safety regulations and maintenance strategy. However, it is a crucial assumption to be aware of when developing and using O&M simulation models.

Second, in the “Failure rates up” case, the large differences can be explained by different assumptions in how failures are assigned when a turbine has failed. The Strathclyde model generates failures on a wind turbine without considering if the turbine has failed or not, and the actual average annual failure rate in a simulation will therefore be very close to the average annual failure rate which is input to the model. On the other hand, the UiS offshore wind simulation model only generates a failure for a wind turbine if it is operating, hence, the actual average annual failure rate in the simulation will be lower than the average annual failure rate, which is input to the model. Consequently, the two models are not equally sensitive to a rising failure rate and result in the two outer extremities for this case in Figure 1.

Third, in the “Fewer technicians” case the assumption that maintenance tasks can be assigned during a working shift to vessels that are already offshore is important. In the UiS model a maintenance task can be assigned to a vessel during a working shift while it is offshore. Furthermore, because several small maintenance tasks (which have a large impact on availability) can be performed in series during a shift, this assumption results in a weaker sensitivity to a decreased number of technicians and higher availability for this case.

5. CONCLUSIONS AND FURTHER WORK

This paper presented an approach and reference cases for verifying and partly validating O&M simulation models for offshore wind farms. The conclusions are divided in two parts: conclusions regarding the verification method presented and conclusions regarding the verification of the models considered in this paper.

A main conclusion regarding the verification approach presented is that hypothetical reference cases can be used to verify O&M simulation models. The main advantage of using a comparison approach with reference cases is that it demands thorough quality checks and debugging in the models. It has to be analysed whether differences in results are due to different assumptions and modelling techniques or actual errors in models. This process also leads to further understanding of important assumptions within the different models and of the uncertainty around the model results due to different modelling approaches. It therefore also helps to validate the models to a given extent.

Several models were tested using the proposed verification approach and it can be concluded that all models can be regarded as verified for the functionalities covered by the scope in the reference cases. However, the models cannot be regarded as fully validated. A full conceptual model validation [1] would require a more extensive and critical analysis to understand what assumptions would represent real-world offshore wind farm O&M to a sufficient degree. However, the discussion between the model developers and users identified the major assumptions and increased the credibility of the modelling approaches.

Due to different modelling approaches and assumptions, the simulation results showed major differences in the cases where maintenance resources are highly restricted. Even though these cases are less relevant for the analysis of a real wind farm, they give valuable insight into model assumptions. Based on these results, it can be concluded that the following model assumptions may have a large effect on the simulation results, and the modeller should therefore pay high attention to these when deciding on a modelling approach:

– Possibility to perform parallel maintenance tasks in a shift
– Approach of modelling failures
– Possibility to assign maintenance tasks to vessels when offshore
– Approach on modelling of charter options for heavy-lift vessels

Further work should focus on setting up additional reference cases that test model functionalities neglected in this initial verification process. Some examples are the inclusion of helicopters, mother vessels, more detailed heavy-lift vessel chartering strategies and condition monitoring. In addition, a more thorough understanding of the impact of different assumptions and modelling approaches is needed, so that one can decide on what aspects to focus on when modelling and what aspects have to be closest to reality. If the objective had been to achieve more accurate estimates of availability and O&M cost, as opposed to comparing such parameters between different models as in the present paper, more effort must be put in data validation, inclusion of balance of plant maintenance operations, other O&M cost components, etc. The presented work focuses on the verification of simulation models. In the future, the proposed reference cases should be extended to allow for inclusion of optimization models by setting up cases where the optimal vessel fleet has to be found from several available vessel types.

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APPENDIX A: INPUT DATA FOR BASE CASE

Table 2. Explanation of input parameters

INPUT PARAMETER	Definition
Cut-in wind speed	The wind speed (m/s) at which a wind turbine starts producing electricity.
Cut-out wind speed	The wind speed (m/s) above which a wind turbine stops producing electricity.
Day rate	Price per day (£/day) for hiring of a vessel. Includes fuel costs and all other operational costs.
Distance maintenance base to wind farm	The shortest linear distance from the onshore maintenance base to the closest wind turbine in the farm.
Failure rate	The average number of failures per turbine per year.
Governing weather criteria	The weather parameter that limits access or operations at a wind turbine, either significant wave height (m) or wind speed (m/s).
Maximum offshore time	Maximum amount of time a vessel is permitted to stay offshore continuously before returning to the maintenance base.
Mobilisation cost	The cost associated with planning and preparing a marine operation before the vessel arrives at the wind farm.
Mobilisation time	The lead time associated with planning and preparing a marine operation before the vessel is ready to depart from the maintenance base.
Number of daily shifts	The average number of working shifts during each 24 hour period.
Number of turbines	The number of wind turbines in the wind farm.
Number of vessels	A fixed number of vessels for the simulation experiment.
Number of technicians available	A fixed number of technicians available on the maintenance base all working shifts for the simulation experiment.
Technician cost	Salary cost per year per technician (that is assumed to be available in the wind farm for all working shifts).
Price of electricity	A constant price per megawatt hour (£/MWh) of electricity.
Repair cost	A fixed cost per repair task. Includes spare parts and consumables, but not vessel costs, technician costs, downtime costs, etc.
Repair time	A fixed duration of a repair task after technicians have arrived to the turbine. Time for technicians to move from a vessel to a turbine assumed to be zero.
Required technicians	The number of technicians needed to execute a maintenance task on the turbine.
Simulation resolution	The time unit (second, minute, hour, day, etc.) representing one time tick in the model.
Simulation runs	The number of simulation runs or Monte Carlo iterations per Monte Carlo experiment.
Simulation time	The length of a simulation in model time (number of years simulated).
Speed of vessel	The average speed in knots of a vessel moving at sea.
Vessel type	The vessel type required to execute a maintenance task.
Weather criteria	The highest allowed magnitude of the governing weather criteria.
Wind and wave weather data	The weather database used.
Wind turbine power curve	The power characteristics of a wind turbine as a function of wind speed.
Working shift	The number of working hours in a working shift.

Table 3. Vessel input matrix with input for the three vessel categories

VESSEL INPUT	Crew transfer vessel	Field support vessel	Heavy-Lift vessel
Number of vessels	3	1	1
Governing weather criteria	Wave	Wave	Wave/Wind
Weather criteria	1.5 m	1.5 m	2.0 m / 10.0 m/s
Mobilisation time	0 weeks	3 weeks	2 months
Mobilisation cost	£ 0	£ 0	£ 500 000
Speed of vessel	20 knots	12 knots	11 knots
Technician capacity	12	60	100
Day rate	£1750/day	£9500/day	£150 000/day
Maximum offshore time	1 shift	4 weeks	No limit
Comment	Hired on a long-time charter so that the vessel always is available at the maintenance base.	Hired. Charter period 1 month. Has external crane.	Hired. Charter period 1 month. Wave height for jack-up operation, wind speed for crane

Table 4. Input matrix for all five failure categories and for annual service

FAILURE INPUT	Manual reset	Minor repair	Medium repair	Major repair	Major replacement	Annual service
Repair time	3 hours	7.5 hours	22 hours	26 hours	52 hours	60 hours
Required technicians	2	2	3	4	5	3
Vessel type	CTV	CTV	CTV	FSV	HLV	CTV
Failure rate	7.5	3.0	0.275	0.04	0.08	1
Repair cost [19]	0	£ 1000	£ 18 500	£ 73 500	£ 334 500	£ 18 500

Table 5. Simulation experiment description

MODEL DESCRIPTION	Value	Comments
Simulation time	10 years	
Simulation resolution	1 hour	Weather data time resolution is 1 hour.
Simulation runs	Flexible	Dependent on the model.

Table 6. Description of the generic wind farm

WIND FARM DESCRIPTION	Value	Comments
Number of turbines	80	
Distance maintenance base to wind farm	50 km	
Wind and wave weather data	FINO [16]	Significant wave height and wind speed data, pre-processed into hourly resolution and gaps filled using a cubic spline interpolation.

Table 7. Technician input data

TECHNICIAN INPUTS	Value	Comments
Technician cost	80 000 £/year	Per available technician.
Number of technicians available	20	
Working shift	12 hours	A working shift starts at 07:00 and ends at 19:00.
Number of daily shifts	1	

Table 8. Input data to calculate production and revenue

REVENUE INPUTS	Value
Price of electricity	90 £/MWh
Wind turbine power curve	Based on V90 power curve from [20]
Cut-in and cut-out speeds	3 m/s, 25 m/s

Table 9. Outputs metrics used for comparison of models with definitions

OUTPUT RESULTS FOR COMPARISON	Definition
Availability - time based	*"The percentage of time that an individual wind turbine or wind farm is available to generate electricity expressed as a percentage of the theoretical maximum"* [8].
Availability - energy based	Actual energy produced by wind farm divided by potential energy production for the farm in ideal case with zero downtime, both during the same time period.
Annual loss of production divided by simulation time.	Loss of production in MWh multiplied by the electricity price
Annual direct O&M cost simulation time.	Sum of vessel, repair and technician costs divided by
Annual vessel cost divided by simulation time.	Sum of chartered vessel days multiplied by vessel day rate
Annual repair cost simulation time.	Sum of repair costs for all maintenance tasks divided by
Annual technician cost	Annual technician cost multiplied by number of technicians available.
Standard error	Measure of the precision of the average values stated as results for availability and direct O&M costs, given by, $\sigma/\sqrt{n}$, where is the estimated standard deviation for the results from n individual simulation runs.

APPENDIX B: DETAILED RESULTS

Table 10. Results for the base case for the different models

	Strathclyde CDT	NOWIcob	UiS Sim Model	ECUME value	Average
Availability - time based	83.70 %	83.74 %	84.40 %	80.82 %	83.16 %
Availability - energy based	82.11 %	82.86 %	84.00 %	81.70 %	82.67 %
Annual loss of production	£17.28 m	£16.63 m	£15.48 m	£18.64 m	£17.01 m
Annual direct O&M cost	£22.44 m	£25.17 m	£17.93 m	£14.48 m	£20.00 m
Annual vessel cost	£17.84 m	£19.18 m	£12.24 m	£9.30 m	£14.64 m
Annual repair cost	£3.00 m	£4.39 m	£4.08 m	£3.58 m	£3.76 m
Annual technician cost	£1.60 m	£1.60 m	£1.60 m	£1.60 m	£1.60 m
Standard error - time-based availability	0.22 %	0.14 %	0.12 %	n/a	0.16 %
Standard error - annual direct O&M cost	n/a	£1.34 m	£2.05 m	n/a	£1.70 m