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NOWIcob – A tool for reducing the maintenance costs of offshore wind farms

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Abstract

It is essential to implement cost-effective operation and maintenance concepts and strategies to achieve a significant reduction of cost of energy from offshore wind farms. A decision support tool (Norwegian offshore wind cost and benefit model – NOWIcob) was developed that simulates the operational phase of an offshore wind farm with all maintenance activities and costs. This tool can be used to understand sensitivities of the operation and maintenance costs due to changes in the maintenance and logistic strategy, and helps to choose an optimized strategy for a specific wind farm.

The model is based on a time-sequential event-based Monte Carlo technique and takes into consideration weather uncertainty and other relevant aspects for the operational phase of an offshore wind farm. Different vessel concepts for accessing the wind farm and time-based, condition-based and corrective maintenance tasks can be simulated. The model delivers results in form of availability, life cycle profit, operation and maintenance cost, produced electricity and other performance criteria.

The main characteristics and the underlying scientific models will be described. In addition, application of the NOWIcob model will be demonstrated for a theoretical case of a far-offshore wind farm using a mothership / daughter ship vessel concept, and benefits of using such a tool will be highlighted.

Keywords: Offshore wind power; Decision support model; Operation and maintenance

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1. Introduction

One of the main factors for increasing the deployment of offshore wind energy is to reduce the cost of energy. Operation and maintenance costs account for around one third of the life cycle cost of an offshore wind farm [1]. Therefore it is essential to implement cost-effective operation and maintenance concepts and strategies to achieve a significant reduction of cost of energy from offshore wind farms. As basis for this objective a decision support tool (Norwegian offshore wind cost and benefit model – NOWIcob) was developed that simulates the operational phase of an offshore wind farm with all maintenance activities and costs. This tool can be used to understand sensitivities of the operation and maintenance costs due to changes in the maintenance and logistic strategy and gives an estimate for the operation and maintenance cost. Such information will help the decision maker to choose cost-optimal solutions for the specific wind farm. Similar models are developed from different organizations, as reviewed in [2]. However, this state of the art review showed that only few models cover the whole life time of an offshore wind farm and none covered all aspects regarded as relevant for the operation and maintenance (O&M) phase. The current version of the NOWIcob model is based on a theoretical framework presented in [3] and a further development of the model described in [4]. This paper will describe the methods and functionalities of the model and will present results from a case study to exemplify its application.

Nomenclature

A_{el}	Electricity-based availability
E_{real}	Produced electricity considering downtime of the wind turbines and electrical infrastructure
E_{theor}	Theoretical possible electricity production with 100% availability
I	Net present income from electricity production
$Loss_{wake}$	Losses in electricity production due to wake effects in the wind farm
$Loss_{el}$	Losses of the produced electricity due to the electrical infrastructure
P_{el}	Electricity price

2. Method

The model is based on a time-sequential Monte Carlo simulation technique where maintenance operations in an offshore wind farm are simulated over the complete life time. This approach was chosen since it has several advantages. The planning and scheduling of tasks that are competing for limited resources, as certainly is the case for offshore wind maintenance tasks, can be simulated by applying a time-sequential simulation. Many of the parameters describing operation and maintenance phase of an offshore wind farm are uncertain and such uncertainty can be taken into account by the Monte Carlo simulation technique. Several input parameters, both controllable options and the uncontrollable external factors, can be changed in the model to assess their impact on performance parameters such as the O&M costs and availability. Controllable options are all strategy choices that the wind farm operator can directly decide on. Uncontrollable external factors include all parameters that are outside the direct influence of the wind farm operator such as the market environment and weather conditions. These factors are usually uncertain. In the model, failure rates are also treated as uncontrollable factors since the model assumes that maintenance actions have no influence on the failure rates. The different aspects of the input are summarised in Figure 1.

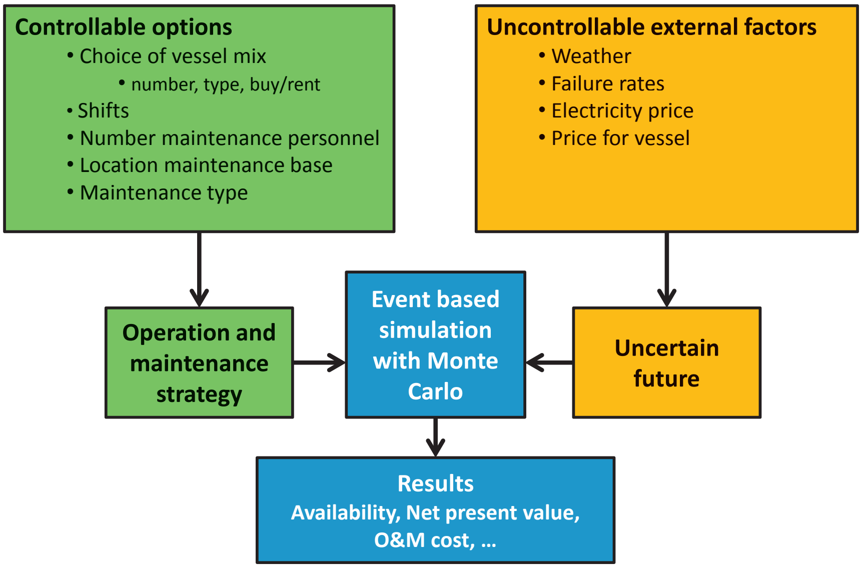

Figure 1: General structure of the model with controllable options and uncontrollable external factors.

Offshore maintenance operations are highly weather dependent, and therefore, weather uncertainty is considered in NOWIcob by performing several simulation runs with different simulated weather time series for each. Consequently, the performance parameters calculated of the model are presented as histograms that represent the probabilities of different outcomes. As illustrated in Figure 2, the model can be divided into four logical parts:

1. Input data
2. Weather simulation
3. Maintenance and logistics
4. Results

First of all, the input data for the specific case are imported and pre-processed. Then, the weather is simulated for each simulation run for the whole lifetime of the wind farm. The core of the model is the maintenance tasks and related logistics that are simulated with an hourly resolution throughout the lifetime. After all simulation runs are performed, the results of all simulation runs are collected and processed.

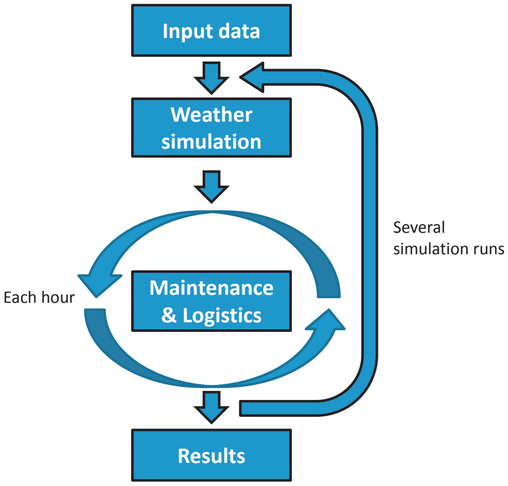

Figure 2: Simplified flow scheme of the model.

2.1. Input data

Several input parameters can be changed to represent different maintenance and logistic strategies. In addition, different scenarios for the vessel cost and expected electricity prices can be specified.

First of all, the wind farm has to be defined by specifying the components that have to be maintained in the operational phase. Main components in the wind farm are divided into three different groups; components for electricity production, electricity transmission, and components that are not related to electricity. In addition, each main component can consist of several subcomponents.

Maintenance tasks can be assigned to each component and three general types of maintenance tasks are used in the model: Time-based, corrective and condition-based maintenance. Time-based maintenance is defined by a fixed time interval. Corrective maintenance has to be conducted after a failure occurs. The points in time when such failures occur are simulated based on a binomial process and annual failure rates. One has the option to specify with yearly resolution how these failure rates change with time, so that one can model time-dependent failure rates due to ageing and other effects. Condition-based maintenance is defined by three factors: detectability, efficiency, and false alarms. Detectability determines the chance that a failure can be discovered before it occurs. Efficiency is a parameter that describes how efficient a condition monitoring system is to give a signal in advance of a possible failure, i.e. the time left until the failure will occur, if such a development to failure was detected. Such condition-based maintenance has the benefit to plan maintenance in advance and to avoid immediate stop of the wind turbine before the maintenance is carried out. False alarms describe the average number of false alarms that occur in a year due to the use of a given sensor or condition monitoring in general. The time when such false alarms occur is also generated with the binomial process.

Spare parts, vessels and maintenance personnel are needed for performing a maintenance task. The model considers spare parts and consumables by assigning a lead time and a cost to the maintenance task. Apart from that, it is assumed that they are always available. In defining the logistics strategy, a combination of different types of vessels can be chosen. Vessels can have different abilities, such as access solutions or lifting equipment. In addition, vessels can be specified as normal vessels, motherships or daughter ships. Furthermore, vessels can be operated in several ways. Vessels either have to return in the same shift they sail out or they can stay offshore for given period of time, for example a week, before they have to return to the harbour. It is also possible distinguish between owned vessels that are always available or vessels that have to be ordered with a predefined lead time.

2.2. Weather simulation

The simulation of the weather is based on historical weather time series for the wind farm location. The model needs simulated weather time series for each simulation run to account for uncertainty in the weather. Different methods are available for simulating weather [5]. It was decided to generate weather time series by applying a Markov chain process, since it is assumed that the time series satisfy the Markov property, i.e., it is assumed that the future weather is independent of the weather history, but only dependent on the current weather situation [6].

The historical weather data are used to estimate transition matrices from one weather state to the next weather state. A weather state is here determined by both significant wave height and wind speed values. The resolution of the wind values is rounded to 1 m/s and of the wave values to 0.1 m steps. The transition matrices are generated for each month to capture seasonal variations. Such a transition matrix contains all probabilities for transitions from one state at time X to the next state at time at $X + 1$ for a given month of the year. If one has N states, there will be in total $N \times N$ possible transitions, represented by a $N \times N$ matrix, where matrix element (i, j) is the probability for transition from state i to state j. Based on the transition matrices, weather is randomly generated for each simulation run. The first values for wave height and wind speed are generated from an estimated joint probability distribution for the starting month. After that, the following weather states are generated based on the transition matrices. This approach requires that the historical time series contain fewer distinct states than the total number of data points. Otherwise, this method will only reproduce the historical weather.

The model assumes perfect weather forecast and takes therefore not into consideration that the wind farm might not be accessible if the weather forecast turns out to be incorrect. However, since the model schedules tasks and resources for the current shift, this assumption means that one only assumes perfect weather forecast for the duration of the shift.

2.3. Maintenance & logistics

The time needed for performing a maintenance task depends on several factors. A typical course of action after a maintenance task has to be scheduled is illustrated in Figure 3.

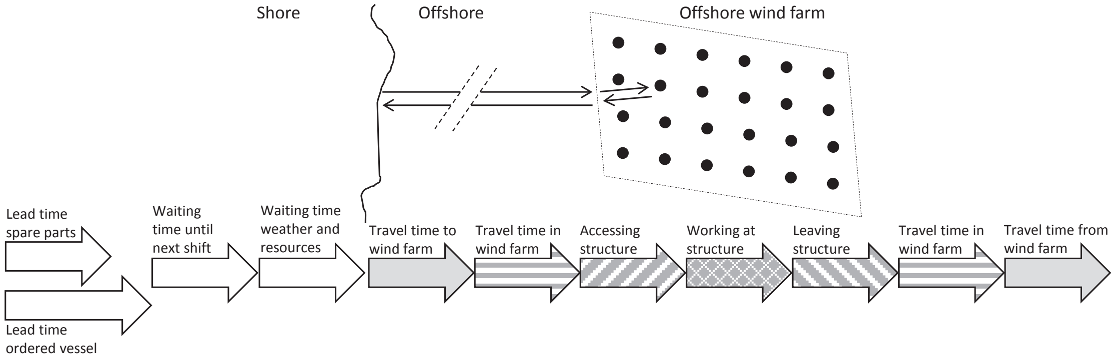

Figure 3: Time used for performing maintenance activities.

Failures or other events triggering a maintenance task can occur at any hour of the year, and the lead and waiting times before a maintenance task can be performed will vary. Additional waiting time can occur for maintenance tasks due to adverse weather and if not enough vessels or maintenance personnel are available. If a maintenance task is finally scheduled for a shift, the model considers the time necessary to travel to the wind farm, within the wind farm, and the time required for accessing the turbine. Depending on the type of the maintenance tasks, the component where the maintenance is performed is stopped at different times. Time-based and condition-based maintenances will only lead to a stop for the time when personnel are working at the component inclusive the access time. On the other hand, corrective tasks will lead to an immediate stop when the failure occurs.

Maintenance personnel are also considered in the model by specifying the number of personnel needed for a maintenance task. Personnel are located at predefined maintenance bases, motherships, or on vessels that stay offshore for more than one shift. Personnel based at a maintenance base can be used by all access vessels that are stationed at that location. Motherships have their own dedicated personnel that can be used by the daughter ships and the mothership itself.

If new maintenance tasks have to be executed, the model checks if personnel, vessels and a weather window are available for the given task. A task can be executed as long as the remaining working time available in the shift for a maintenance task is above a defined threshold. It is possible to work with a maintenance task over several shifts, if it cannot be finished in one shift. Then the personnel has to be transported to the maintenance location each shift. Access vessels can serve several maintenance operations in parallel. Other vessels with special abilities required during the maintenance task can only serve maintenance tasks sequentially. If a vessel serves several maintenance tasks in one shift, the travel in the wind farm is as illustrated in Figure 4.

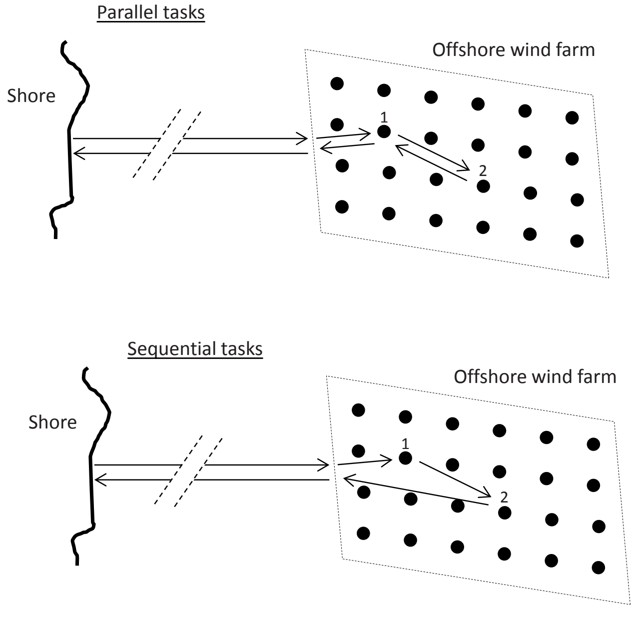

Figure 4: Travel time in wind farm for several tasks.

It is possible that several maintenance tasks are scheduled for a shift and that they are competing for the limited resources. Therefore, the maintenance tasks are sorted according to a prioritisation. All maintenance tasks that are already started have highest priority. Thereafter, the maintenances are sorted by whether an ordered vessel is needed for performing that task and finally by what type of maintenance has to be performed. Corrective maintenance is given the highest priority, then condition-based maintenance, and then time-based maintenance. If several can be used to perform a given maintenance task, the vessels with the lowest cost are used.

2.4. Results

The results delivered by the model include histograms of several performance criteria. The performance criteria calculated by the model are:

- Time-based and production-based availability
- Net present income based on electricity production
- Net present O&M cost
- Net present value of profit

Different definitions of availability exist. Time-based availability and production-based availability are two typical availabilities used for offshore wind energy. The availability based on time is defined here defined as the operative time of the wind turbines divided by the life time of the wind turbines [7]. The production-based availability is calculated based on the real and theoretical possible electricity production. The result delivered by the model is availability based on electricity production for the whole wind farm. This availability does not only consider the downtime of the wind turbines, but also downtime of the electrical infrastructure as the inner cables, substation and export cable.

$$A_{el} = E_{real} / E_{theor} \qquad (1)$$

The net present income is the discounted income from the electricity production. The electricity production is based on the simulated weather time series for wind speed and the power curves of the wind turbines. When calculating the electricity production, the model considers losses from wake effects in the wind farm and electrical losses in the electrical infrastructure with a simple factor. Electricity prices are defined in different price scenarios where the electricity price for the whole lifetime is specified on a monthly basis. The income is calculated per year and then discounted with the specified discount rate to obtain the net present income.

$$I = (E_{real} \times Loss_{wake} \times Loss_{el}) \times P_{el} \qquad (2)$$

The model calculates cost for the operation and maintenance phase and includes the following costs:

- Spare part and consumable costs (fixed cost per maintenance task)
- Vessel costs (yearly fixed costs and variable costs when used)
- Personnel costs (yearly fixed costs)
- Costs for using a location such as a harbour, platform etc. (yearly fixed costs)
- Costs for transporting personnel to locations as mothership, offshore platforms etc. (yearly fixed costs)

Vessel costs are specified by a yearly fixed cost component and a variable cost component that is dependent on the utilization of the vessel. The net present value of profit is a performance criterion for the profitability of the wind farm. It is calculated with equation (3) below. The investment costs are specified per main component and are input to the model. Investment costs are only used for the calculation of the net present value of profit and have no other influence on the results of the model.

$$\text{Net present value of profit} = \text{Net present income} - \text{Net present O\&M cost} - \text{Investment cost} \qquad (3)$$

3. Application

A theoretical case of an offshore wind farm was analysed with the model to exemplify different applications. The offshore wind farm consists of 50 turbines and is located 150 km offshore in the North Sea. Weather data are obtained from a weather station located at an offshore oil platform. It was decided to present mainly results of the availability, since the estimates for vessel costs are quite uncertain. However, other results as the net present value of the profit can be presented in the same way. Figure 5 compares the availability results when using a mothership and the case of an offshore accommodation platform. The solution with a mothership has a higher availability since the mothership can be used for lifting operations, whereas for the other alternative, a jack-up vessel has to be ordered, and this is associated with a given lead time (here assumed to be 30 days). For each of the cases, the histogram is based on 100 statistically independent simulation runs.

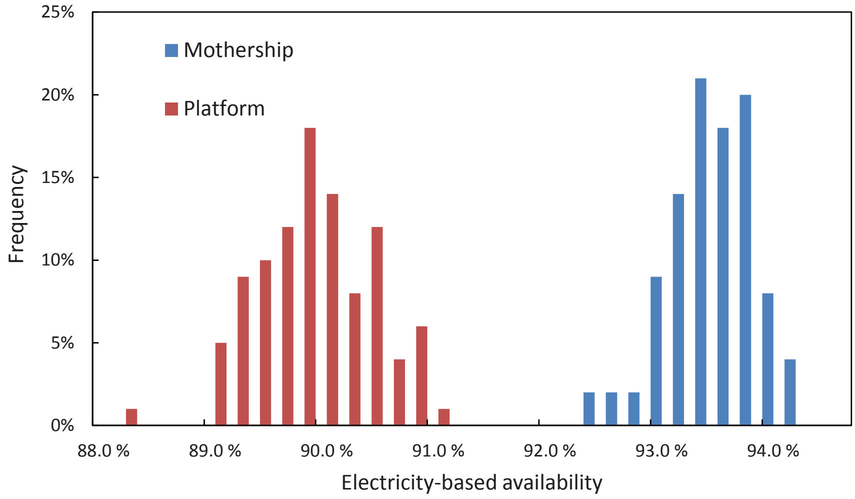

Figure 5: Histograms of the availability when using a mothership versus an offshore platform.

Figure 6 illustrates the results when using a different number of access vessels in the case of a mothership / daughter ship concept. A larger number of access vessels consistently leads to higher availabilities. Naturally, more resources and efforts spent on maintenance also lead to higher O&M costs, and an interesting question is where the optimum of availability versus O&M cost is reached. Since we are still in the process of acquiring reliable cost data, we have chosen to only present results for the availability in the present paper. Future work will focus on results for O&M costs and profit to be able to determine the most cost-effective maintenance and logistic strategies.

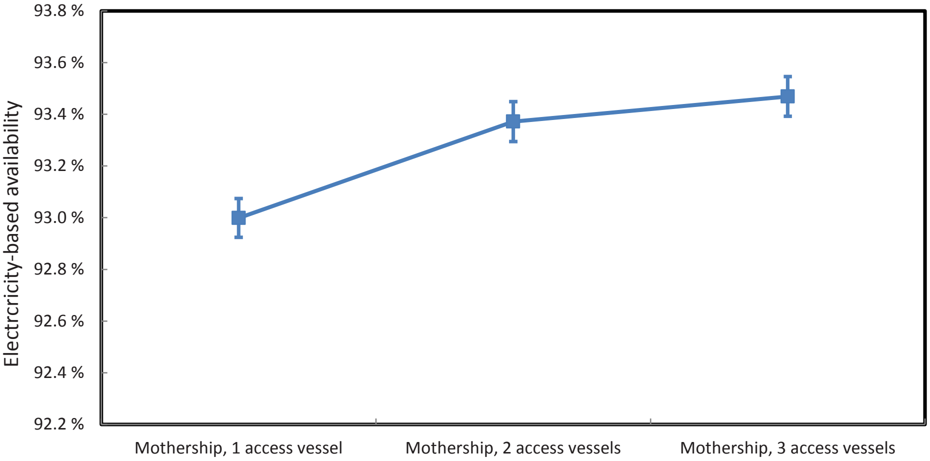

Figure 6: Dependency of availability on the number of access vessels used. The error bars represent the standard error of the results.

Another analysis that can be performed with the model is the effect of different shift and working hour alternatives. As presented in Figure 7, a shift solution with 2 shifts of 10 hours each is the solution among the considered alternatives that will secure the highest availability of the wind farm.

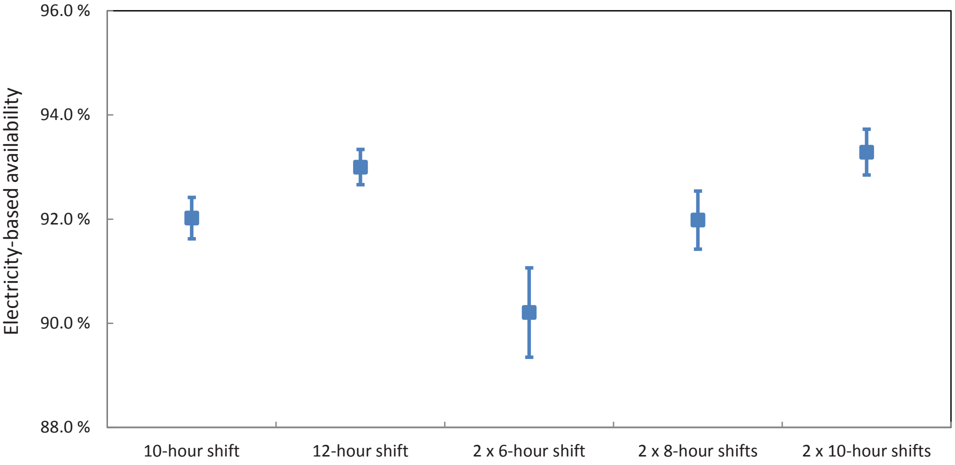

Figure 7: Availability for a number of different shift alternatives. The error bars represent the estimated standard deviation of the probability distribution for the availability.

4. Conclusion

The NOWIcob model for simulating the operational phase of an offshore wind farm has been developed with the aims of helping to reduce the cost of energy for offshore wind. Here, the main features of the NOWIcob model have been described. It has also been demonstrated how the model can produce results with accompanying uncertainties for performance parameters such as availability by appropriately taking into account the randomness of external factors such as weather. Consequences of different decisions related to the maintenance and logistic strategy can be analysed, and the most effective solution can be chosen. This has been illustrated by a test case demonstrating some of the capabilities of the model. The development of NOWIcob will continue to include more relevant aspects of offshore maintenance and logistics in the model. In particular, future work will focus on extending the weather model to additional weather parameters to more accurately capture the process of accessing offshore wind turbines. In addition, it is planned to perform case studies with more realistic cost data to show how the model can be used to determine cost-effective maintenance and logistic strategies.

Acknowledgements

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