

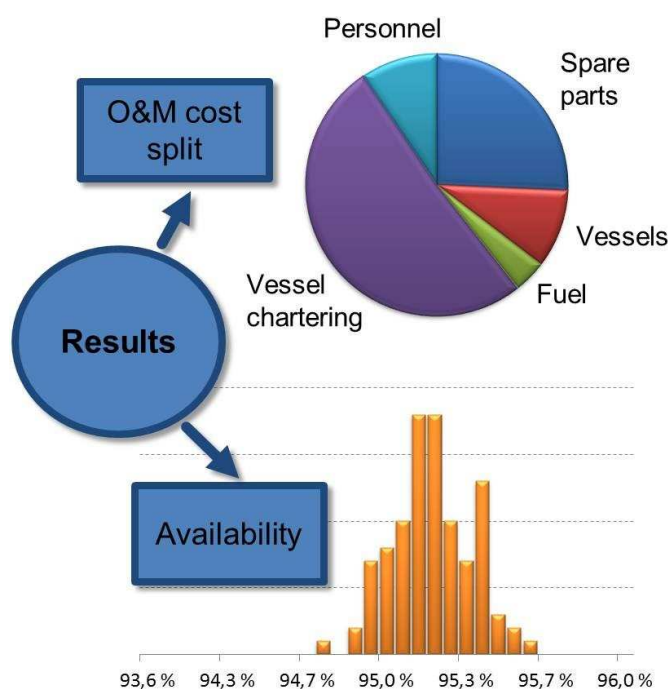
Report

Technical documentation of the NOWIcob tool (D5.1-66)

Model version 3.1

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Model version 3.1

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ABSTRACT

This report describes the current version of the NOWIcob model that has been developed primarily in NOWITECH WP5 and FAROFF. The description is related to the version 3.1 of the model and contains a general introduction to the capabilities of the model and updated descriptions of functionality. NOWIcob is an analysis tool that can be used for decision support for different aspects of offshore wind farm operation and maintenance and logistics strategies. It simulates the maintenance activities and related logistics of an offshore wind farm over a given number of years to estimate key performance parameters such as wind farm availability and operation and maintenance costs. The report also addresses possible application areas of the tool.

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1 Introduction, background and motivation

This report describes the NOWIcob model (Norwegian offshore wind power life cycle cost and benefit model). The model has been developed primarily in NOWITECH¹ WP5 and FAROFF², and, starting 2014, it is also being developed in LEANWIND³. The description is related to version 3.1 of the model and gives a general introduction into the capabilities of the model as well as a description of added functionalities. It is a high-level technical documentation and thus does not aim to describe in details the software architecture, internal data structures or other technical specifications. The report is an update of the previous technical documentation of model (Hofmann and Sperstad, 2014). For more practical user guide, we refer to Hofmann, Sperstad and Kolstad (2014).

NOWIcob is primarily an analysis tool for simulation and optimization of different aspects of an offshore wind farm. It simulates the maintenance activities and related logistics of offshore wind farms over a given number of years to estimate key performance parameters such as wind farm availability and operation and maintenance costs. The NOWIcob model targets two main user groups: researchers and wind farm developers/operators. In the research area, the main application of NOWIcob is the analysis of different operation and maintenance (O&M) strategies, including strategies for logistic support and wind turbine access. Wind farm developers can use NOWIcob for cost-benefit evaluation of different technical solutions for an offshore wind farm project. The model can serve as a decision support tool for decision problems such as, e.g., what crew transfer vessels one should use, where the maintenance bases should be located, or whether the benefits of improvements in condition monitoring would compensate the costs.

The first sections (Section 2 – 5) explain the main structure of the model and which assumptions and functionalities are included in the model. The purpose of these sections is to help the reader to understand the capabilities and limitations of the model so that the reader knows what analyses one can perform with the model. Section 6 describes the activities undertaken to verify and validate the model. Section 7 summarises the history of changes made in the model. Finally, Section 7 summarises the current status of the model and briefly discusses its future development and application. Appendix A gives a detailed overview over the modelling assumptions. Appendix B is a chronological literature list that contains all references related to the development and application of the NOWIcob model.

¹ Centre for Environment-friendly Energy Research (FME) co-funded by the Research Council of Norway, NOWITECH, <http://www.sintef.no/Projectweb/Nowitech/>

² Research project co-funded by the Research Council of Norway, <http://www.sintef.no/home/MARINTEK/Projects/Ocean-Energy/FAROFF---Far-offshore-operation-and-maintenance-vessel-concept-development-and-optimization/>

³ EU 7th framework program project, LEANWIND (Logistic Efficiencies And Naval architecture for Wind Installations), <http://www.sintef.no/Projectweb/LEANWIND/> and <http://www.leanwind.eu/>

2 General model description

The analysis of the operation and maintenance strategy is one of the main objectives for the development of NOWIcob. An operation and maintenance strategy includes all decisions on controllable options in an offshore wind farm project which influence the operation and maintenance cost and the indirect cost of lost revenue due to downtime. These decisions are under direct control of the decision maker. On the other hand, many parameters have an impact on the O&M and downtime costs that cannot be influenced by the decision maker, as for example, future electricity prices and the weather. These external factors are referred to as "uncontrollable uncertainties". The model combines both, the controllable options and the uncontrollable environment, to allow for the analysis of the expected maintenance cost and therewith the cost of energy. In addition, the model can be used to understand sensitivities of the O&M and downtime costs.

The model is based on a time-sequential (discrete-event) Monte Carlo simulation technique where maintenance operations in an offshore wind farm are simulated over a number of years of its operational life time with an hourly resolution. Several input parameters, both controllable options and the uncontrollable uncertainties, can be changed to assess their impact on performance parameters, such as the cost of energy (see Figure 1). NOWIcob also includes the possibility to consider future vessel concepts such as mother/daughter vessel combinations or crew transfer vessels that are offshore for several shifts. Offshore maintenance operations are highly weather dependent, and therefore, weather uncertainty is considered in NOWIcob by using a Monte Carlo simulation approach with a weather model generating new, representative weather time series for each simulation run (Monte Carlo iteration). Due to the uncertainties, several simulation runs should be performed for each case. This allows the results delivered by the model to be presented as histograms estimating probability distributions. The results include several performance parameters, such as the availability of the wind farm, the operation and maintenance cost, and the profit of the wind farm project. The model is able to perform simulations over the complete operational life time (i.e., from commissioning to decommissioning) of the wind farm and to calculate the performance parameters as the net present value, e.g., of the profit.

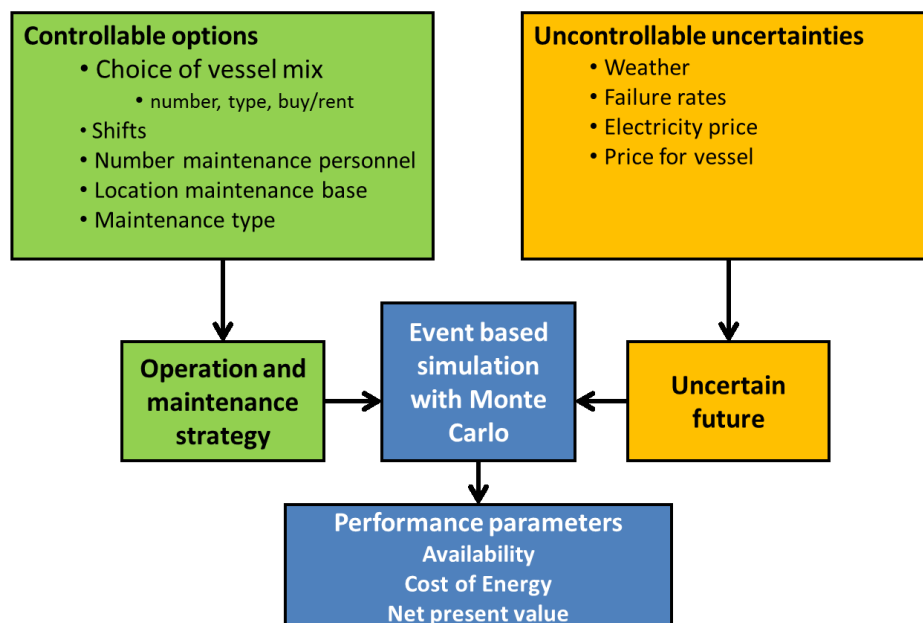


Figure 1 Controllable options and uncontrollable environment.

3 Input-output structure

In general, the process flow of the model can be divided into four logical steps:

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

The model is implemented in MATLAB, but user interfaces for entering input data and for viewing the results are in the form of Excel workbooks.

The simplified flow scheme of the model based on these steps is presented in Figure 2.

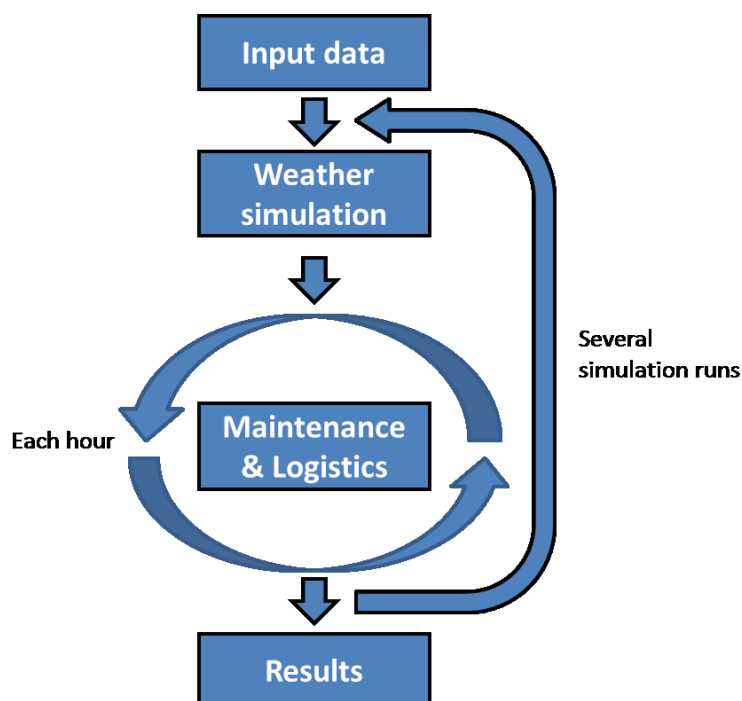


Figure 2 Simplified flow scheme of the model.

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. A maintenance task is defined as any task (i.e. technical and administrative actions, including supervision actions) carried out by the maintenance organisation intended to retain an item in, or restore it to, a state in which it can perform a required function. See also International Electrotechnical Commission (1990). Here, an item is understood as a turbine or any other component of a turbine or of the wind farm. This includes, e.g., annual turbine services, intra-array cable inspections, repairs or replacements of turbine components and resetting the turbine (manually or remotely). Each shift, the model goes through the list of pending maintenance tasks and schedules as many as the maintenance organisation has time for that shift. After all shifts in a simulation run are simulated, the result parameters are calculated. After all simulation runs are performed, the results of all simulation runs are collected and processed.

4 Input data

This section focuses on the structure and specification of the input data. Data input to the NOWIcob model is organized through two Excel workbooks, where one contains basis data and the other case-specific data. In addition, a text file with historical weather time series is needed. The basis data contain all information that can be reused in several case-specific set ups. Examples for basis data are electricity price scenarios and different types of vessels.

Since the case specific data refer directly to the basis data, a typical approach for preparing the data for the model is first to specify the basis data and thereafter the case specific data. One has also to choose which weather data is used in the model. Figure 3 shows the different input files. A detailed illustration of the relation between basis data and case specific data can be found in Appendix B.

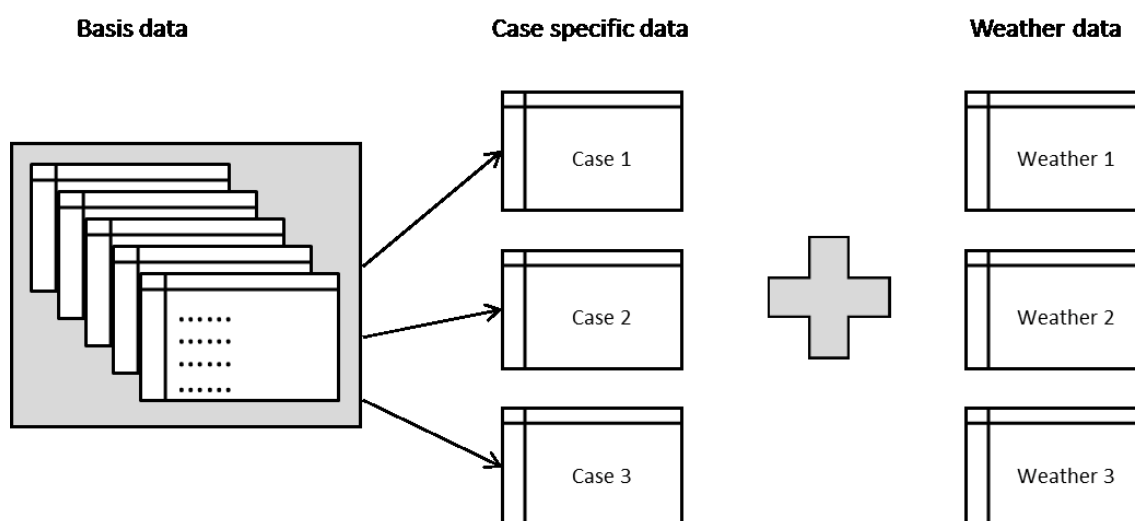


Figure 3 Input files to the model.

4.1 Weather data

The weather data are represented by a data time series with the following parameters in columns separated by tabulators:

1. Wind speed [m/s]
2. Wind direction [0-360]
3. Wave height [m]
4. Wave period [s]
5. Wave direction [0-360]

Weather data are stored in separate text files. Time series for wind speed are needed to calculate power production, and significant wave heights are typically needed as weather limits for vessels and maintenance operations. Which of the other weather parameters that will be required in a simulation depends on how the weather limits are specified for different vessels and maintenance operations.

4.2 Lists of input parameters

The units used are kilometres for distances and knots for travel speeds. The currency is flexible and can be specified freely. If the input parameter is a yes/no question, increased indentation of the following input parameters in the list below indicates that they only are applicable if the answer was yes. Input parameters that merely are descriptive labels have been omitted in these lists. More detailed definitions of the input parameters are given in the user's guide of the model. In the model, turbine types are treated as subset of a broader class of *main component* types; other possible main components are cables or offshore substations. In this list, the terms main component and turbine will be used interchangeably.

General data

For each case / wind farm, one must specify the following:

- Life time / simulation length in years
- Weather data file as a time series of different weather parameter (at least wind speed and significant wave height)
- Average distance to travel between turbines for planned maintenance tasks
- Average distance to travel between turbines for unplanned maintenance tasks
- Working hours per shift
- Number of daily shifts
- Fixed cost per maintenance person per year
- Wake loss (percentage of production)
- Electrical loss (percentage of production)
- Discount rate
- Minimum working time; the maintenance task will be postponed if the time window for actual work is smaller than this
- Electricity price for each month in each year of the operation of the wind farm
- Fuel price for vessels

Main components

For each type of main component on the wind farm, one can specify the following:

- Main component (referring to the list *Main component basis data*)
- Number of main components of this type
- Investment cost

Main components basis data

For each main component (turbine type, substation, cable type, etc.) that can be considered for the wind farm, one has to specify the following:

- Is it an electricity-producing component?
 - Rated power
 - Cut-in wind speed
 - Cut-out wind speed
 - Power curve (specified by percentage of rated power production as a function of wind speed; data points given define a piecewise linear curve)

Components per main component

Each main component can contain several subcomponents, but specifying these is optional. If no subcomponents are specified, this list will only contain the main components themselves.

- Main component that the subcomponent belongs to
- Number of subcomponents per main component
- Percentage of its function the main component loses when this component fails

Maintenance actions

Maintenance actions are the set of operations that must be performed to complete a maintenance task. (See *Time-based maintenance tasks* and *Corrective and condition-based maintenance tasks* below.) Each maintenance action consists of at least one main operation step, and in addition, a pre-inspection can be specified. The following input parameters apply:

- Name of the maintenance action
- Working duration
- Personnel access to turbine needed?
 - Logistics time for transferring equipment to the turbine
 - Number of personnel needed for maintenance action
- Pre-inspection needed?
 - Time needed for performing pre-inspection
 - Personnel access to turbine needed?
 - Logistics time for transferring equipment to the turbine
 - Number of personnel needed for pre-inspection
- Ability needed? (Typically a specific vessel capability; see *Vessels basis data* below. Two abilities can be specified.)
 - Ability name
 - Number of extra personnel needed for the ability

Time-based maintenance tasks

Here, maintenance tasks that occur based on a time schedule are specified with the following parameters:

- Main component / subcomponent of main component (referring to list *Components per main component*)
- Number of years between each maintenance task
- Start date (day of the year) for tasks
- Number of main components scheduled to be serviced per shift
- Costs of spare part / consumables
- Lead time to provide spare part / consumables
- Name of the maintenance action that has to be performed for executing the maintenance task
- Does the main component have to be stopped during maintenance?

Corrective and condition-based maintenance tasks

Here, maintenance tasks that occur in response to random failures are specified. In addition, it can be specified if condition monitoring can be used to detect a prospective failure.

- Main component / subcomponent of main component (referring to list *Components per main component*)
- Failure rate (per component per year)
- Failure rate adjustment curve (referring to list *Failure rate adjustment curves*)
- Costs of spare part / consumables
- Lead time to provide spare part / consumables

- Name of maintenance action to perform for corrective tasks
- Does the failure result in the component stopping to function?
- Does the main component have to be stopped during maintenance?
- Possibility of condition-based maintenance?
 - Detectability as percentage of failures that can be discovered in advance
 - Efficiency as days in advance a failure can be discovered
 - Costs of spare part / consumables
 - Lead time to provide spare part / consumables
 - Average number of false alarms per year
 - Is the main component stopped at the instant the fault occurs?
 - Does the main component have to be stopped during maintenance? Name of maintenance action to be performed in cases that turns out to be false alarms

Failure rate adjustment curves

For each (piecewise linear) failure rate adjustment curve, one has to specify data points with the following:

- Year of operation
- Failure rate adjustment factor (actual failure rate in a given year is the stated base failure rate times the adjustment factor)

Locations

The locations table contains all the locations where the vessels are stationed, for example a harbour.

- Distance to the offshore wind farm
- Personnel available per shift
- Seasonal dependence of personnel availability?
 - Start of the season
 - Stop of the season
 - Personnel available per shift off season
- Yearly fixed cost

Vessels

For each vessel type used in the wind farm, one has the following input parameters:

- Vessel type (referring to the list *Vessels basis data*)
- Number of vessels
- Home port where vessel is stationed (referring to list *Locations*)
- Does it have daughter vessels?
 - Vessel type of daughter vessel (referring to the list *Vessels basis data*)
 - Number of daughter vessels
 - Fixed cost per daughter vessel per year
- Is it an ordered vessel?
 - Order lead time (mobilisation time)
 - Charter duration
 - Charter cost inclusive mobilisation cost
- Seasonal dependence of availability
 - Start season
 - Stop season
 - Available at another base off season?
 - Name of the base (referring to list *Locations*)
- Fixed cost per year
- Operation mode of the vessel (one shift, several shifts, always offshore)

- Can stay offshore for several shifts / days?
 - Days it stays offshore over night
 - Days it has to stay onshore after being offshore
 - Personnel available per shift per vessel
 - Cost per year for transporting personnel to vessel

Fixed vessel for maintenance

It is possible to specify if a specific access vessel or helicopter has to be used for a maintenance action.

- Name of maintenance action
- Name of access vessel

Vessels basis data

For each vessel type that can be considered for the wind farm, one has to specify the following:

- Travel speed
- Fuel consumption when travelling
- Fuel consumption when stationary
- Maximum number of maintenance personnel there is room for on the vessel
- Wave limit above which the vessel has to return to a safe harbour
- Wind limit above which the vessel has to return to a safe harbour
- Does it have the ability to let maintenance personnel access a main component?
 - Approaching time before personnel can access the turbine
 - Time for transferring one person from the vessel to the turbine
 - Access wave limit
 - Access wind limit
 - Access weather limits input file name for complex weather limits if used
- Name of ability 1-3 (Parameters as below for each ability)
 - Wave limit
 - Wind limit
 - Ability weather limits input file name for complex weather limits if used

4.3 Basis data

Basis data contain all information that can be used in several set ups for different cases. All data are stored as tables in an Excel file. Data tables are defined for the following topics:

- Currencies
- Electricity price scenarios
- Electricity prices
- Main components
- Power curves
- Power curve data
- Abilities
- Vessels
- Failure rate adjustments
- Failure rate adjustment data

4.4 Case-specific data

The case specific data can be changed for each case set up. They include typical decisions that together represent a strategy for the operation and maintenance phase, including logistics. All data are stored in several tables in an Excel file. The different tables cover the following topics:

- General data
- Main components case
- Components per main component
- Maintenance actions case
- Pre-inspection needed
- Abilities needed
- Maintenance – time-based
- Maintenance/failures – corrective/condition-based
- Locations
- Vessels case
- Availability and cost of vessels
- Operation of vessels

5 Methods, model functionalities and model assumptions

The functionalities and main assumptions of the model are summarised in the following overview. The functionalities of the model and the underlying assumptions are described in the following subsections, and a more detailed overview of the model assumptions can be found in Appendix A.

Wind farm design	<ul style="list-style-type: none"> • Divided into main components and subcomponents • Flexible definition of the number of main components and subcomponents • Two general groups of main components (electricity production or no production) • A single, homogenous wind farm is assumed
Weather simulation	<ul style="list-style-type: none"> • Weather data are time series of wind speed, wave height; other optional parameters as wave period wave direction and wind direction • Weather data parameter value resolution is (by default) 0.1 m for wave heights and 1 m/s for wind speed • Both historic and synthetic weather time series can be used; synthetic weather time series are created by a Markov process • Seasonality of weather characteristics are taken into account on a monthly basis • Time resolution of the simulated weather time series is 1 hour • Perfect weather forecast for the entire shift is assumed
Failure simulation	<ul style="list-style-type: none"> • Maintenance is defined per main component and/or subcomponent • Three types of maintenance are considered: time-based, corrective and condition-based maintenance • Time based: defined by start date in the year, duration between the tasks and how many new operations that may be initiated in parallel per shift • Corrective: defined by yearly failure rate, exponentially distributed time to next failure, where the failure rate can change from year to year • Condition based: defined by three factors <ul style="list-style-type: none"> ○ Detectability: probability to discover a failure before it occurs ○ Efficiency: time until the failure occurs ○ False alarms: number of false alarms per year • The intensity of time-based (preventive) maintenance does not affect failure rates • Assumed to be no common-mode failures or other correlations between failures for different turbines, components, etc. • Assumed to be no correlations between environmental loads and the rate (or the times) of failures
Maintenance logistics	<ul style="list-style-type: none"> • A defined maintenance action is assigned to each maintenance task • One maintenance action can consist of a pre-inspection and the main maintenance operation • For each of this two the following properties can be defined: <ul style="list-style-type: none"> ○ If access to a structure is needed ○ The time needed for performing the work ○ Number of maintenance personnel needed • Optional extra abilities needed can be specified for the main maintenance task and the personnel needed for these abilities • Lead time obtaining spare parts can be defined per maintenance • Access vessels can serve several maintenance tasks in parallel

- One task may require several vessels (with several different vessel abilities), and the model dynamically assigns vessels to maintenance tasks

Vessels

- The following properties define a vessel:
 - Travel speed
 - Maintenance personnel capacity at vessel
 - Offshore stay weather limits (wind speed and wave height)
 - Ability to access a structure with weather limits (wind speed and wave height, optional complex weather limits)
 - Other abilities and the weather limits for using them
 - Number of daughter vessels if vessel is a mother ship
- The vessels can be operated in different ways
 - One shift (comes back to harbour after each shift)
 - Several shifts (stays offshore for several shifts)
 - Always offshore
- Vessels can be chartered (defined order/mobilisation time and a given charter period)
- Vessels are stationed at freely definable locations
- Different availability of vessels can be specified for two seasons (main season and off season)

Personnel

- Personnel at one location can be used by all vessels based at that location
- Vessels that are offshore for several shifts have their own dedicated personnel
- Mother ships have their own dedicated personnel that can be used by the daughter ships and the mother ship itself
- Maintenance personnel can only execute one maintenance task per shift
- Different availability of personnel per base can be specified for two seasons (main season and off season)

Power production and income generation

- Electricity production is calculated based on the availability of each main component, the actual wind speed and the power curve of the producing main components
- Wake effects are considered with a constant factor
- Electrical losses in the electrical infrastructure are considered with a constant factor
- Downtime of electrical infrastructure is taken into account with a single factor
- Electricity price is defined by a price scenario with monthly resolution

Results

- Electricity-based availability
- Electricity production
- Net present income
- Net present value of lost income due to downtime
- Net present O&M cost and cost split
- Net present value of profit
- And other details, such as utilization of resources and break-down of unavailability
- Functionality for setting up and performing automated sensitivity analysis

5.1 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 (Monbet et al., 2007). 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 of the current weather situation. Hagen et al. (2013) showed that weather time series generated with Markov chain processes have the same statistical properties, as for example persistence of weather windows, as the historical weather time series.

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 a maximum of five weather parameters: wind speed, wind direction, significant wave height, wave period, and wave direction. The resolution of the wind values is by default rounded to 1 m/s and of the wave height values to 0.1 m steps, but these values can be specified by the user. The number of degrees used for the resolution of wind direction and wave heading needs to be a divisor of 360. 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 $X + 1$ for a given month of the year. If one has N states, there will be in total $N \times N$ possible transitions, represented as 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 with an hourly resolution. The first values 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.

There are two ways of using weather limits together with this multi-parameter weather model (cf. also the user guide): 1) One can either use "simple weather limits", which means that only wind speed limits and wave height limits are taken into account. 2) Alternatively, one can use as input a "matrix of limiting wave heights", which means that for specified vessel abilities, the simple, single-valued wave height limit will be replaced by a matrix specifying how the wave height limit depends on the wave period and the wave heading. (Any explicit dependence on wind direction is not implemented as of model version 3.1.) More specifically, the wave heading in the "matrix of limiting wave heights" is the wave heading relative to a specified reference direction in the wind farm. This direction will typically be the direction of the boat landing of the turbines, and we will henceforth refer to it as the boat landing direction. The boat landing direction can be specified by the user, but it is assumed to be the same for all turbines and for all abilities for all vessel types. What direction the boat landing direction corresponds to in the real world is defined by the coordinate system of the wave headings of the historical weather time series used as input. When using a boat landing direction different from zero, the wave headings in the weather limit input files will be translated to the coordinate system of the weather states by shifting them by the angle given for the boat landing direction. If this shift or rotation angle is not a multiple of the resolution for the wave heading, meaning that the wave headings in the "matrix of limiting wave heights" are not found in the (discrete) wave headings of the weather states, linear interpolation is used to find the wave limit for each wave heading in the weather states.

The approach of this Markov chain weather model requires that the historical time series contain fewer different states than data points. Otherwise, this method will only reproduce the historical weather. Application of the weather model is also limited by the computer that is used, especially by the amount of memory installed. The number of weather states N increases with the number of weather parameters that are taken into account and increases with the resolution chosen for these weather parameters. The memory usage of the transition matrices, in turn, increases rapidly with N . In our experience, it is not possible for a

computer with 8 GB of installed memory to use the weather model to generate synthetic weather time series as N exceeds approximately 10 000.

As of version 3 of the model, one may also choose to only use the historical weather time series. This option is particularly relevant if one has time series of the accessibility of a vessel to the wind turbines for the given historical weather time series. Such accessibility time series can be used as input for the weather limitations for access instead of using a single limiting significant wave height. The option of historical weather time series can also be relevant to use if one wants to use weather parameters with a resolution giving more weather states than the weather model is able to handle for the computer one is using.

The model assumes perfect weather forecast and takes therefore not into consideration that the wind farm is not accessible since the weather forecast was not correct. However, since the model schedules tasks and resources for the present shift, this assumption means that one has a perfect weather forecast for the length of the shift.

5.2 Resources

Different types of resources are needed for performing a maintenance task. The model considers three types of resources:

- Spare parts and consumables
- Vessels and other equipment
- Maintenance personnel

5.2.1 Spare parts and consumables

Spare parts and consumables are considered in the model by definition of a lead time and cost. Apart from that, it is assumed that they are always available.

5.2.2 Vessels and other equipment

Each maintenance task can have the need for one or several abilities as for example lifting of a heavy component. All vessels that have this ability are possible resources for such a maintenance task. In addition, the availability of vessels is dependent on the type of the vessels. Vessels can be a "normal" vessel, a mother vessel or a daughter vessel. Furthermore, the vessels can be operated differently. Vessels may have to sail out and come back in the same shift or they can stay offshore for several days before they come back. Vessels can be "owned" vessels or "chartered" vessels, where all vessels available in the maintenance base on a long-term charter (one or several years) are regarded as "owned" by the wind farm operator. The possibility of chartering vessels externally on a shorter-term charter is considered by specifying an order time. After that time, the vessel is available from the maintenance base as the owned vessels for a predefined charter duration.

The availability of vessels can be specified on a seasonal level. This can be done by specifying a main season where the vessel is available and an off season where the vessel is not available or only available from another base.

5.2.3 Personnel

Maintenance personnel are considered in the model by specifying the number of personnel needed for a maintenance task. Personnel are located at the maintenance base, a mother ship or on vessels that stay offshore for more than one shift. Personnel based at the maintenance base can be used by all access vessels that are stationed at that location. Mother ships have their own dedicated personnel that can be used by the daughter ships and the mother ship itself. One assumption for the maintenance personnel is that each person can only execute one single maintenance task per shift. The availability of personnel can be specified differently for two seasons; main season and off season.

5.3 Maintenance and logistics

The model functionalities regarding the execution of different maintenance tasks and the related logistics are described in the following subsections.

5.3.1 Maintenance tasks and failure model

Three different types of maintenance tasks are used in the model:

- Time-based
- Corrective
- Condition-based

Time-based maintenance has to be conducted after a fixed time interval at a given date of the year. Corrective maintenance has to be conducted after a failure has occurred. The time to a failure from the last time a failure of the same category occurred on the same turbine is calculated based on a homogeneous Poisson process (see, e.g., Rausand and Høyland, 2004) and annual failure rates. That means that the time until the next failure is uncertain, but on average a given number of failures will occur in a year. The failure rates can be set to be time-dependent with a yearly resolution (i.e., adjusted on a yearly basis), so that one can model failure rates developing over time due to ageing or other effects. In this way a combination of time-dependent failure rate adjustments, e.g. a bathtub curve, can be modelled.

Condition-based maintenance is defined in the model by three factors: *detectability*, *efficiency*, and *false alarms*. Detectability determines the probability that a prospective failure is discovered before it occurs. Efficiency is a parameter that describes how efficient a condition monitoring system is in giving a signal in advance of a possible failure, i.e., the time left until the failure actually occurs, if a development to failure has been detected by the condition monitoring system. Efficiency is specified as a fixed number so that the time available for performing the condition-based maintenance task is always the same. However, the time of the year when such a failure is discovered is uncertain and calculated with the same methods as for corrective maintenance. False alarms describe the number of false alarms that occur in a year due to the use of a given sensor or condition monitoring system. The time of the year when such false alarms occur is uncertain and also generated with the Poisson process.

The model assumes continuous condition monitoring and makes no assumption of manual inspections needed to detect developing failures. Perfect coverage of the components or failure modes represented by the condition-based maintenance tasks is also assumed, meaning that the corresponding failures always have a chance of being detected in advance. The modelling of a constant time from detection of a potential failure to the actual failure will occur corresponds to a deterministic PF interval (Rausand and Høyland, 2004).

5.3.2 Prioritisation of maintenance tasks and vessels

It is possible that several maintenance tasks are scheduled for a shift and that they are competing for the limited maintenance resources of the wind farm. Therefore, the maintenance tasks are sorted according to priority. There are three criteria after which the maintenance tasks are prioritised. By default the model gives priority to maintenance tasks after the following order:

1. Type of maintenance task:
 - i. Corrective maintenance is given the highest priority,
 - ii. then condition-based maintenance,
 - iii. and then time-based maintenance.
2. Whether the maintenance task already has started:
 - i. Maintenance tasks that are already started have higher priority,
 - ii. whereas maintenance tasks where no work is done yet will have to wait.
3. Whether an ordered vessel is needed for performing that task:
 - i. If the maintenance task requires ordering of a vessel (jack-up vessels, e.g.), they are typically regarded as more important,
 - ii. whereas maintenance tasks where no ordered vessel is needed is given lower priority.

It is possible to specify a different prioritisation order in the case-specific data; see Hoffmann, Sperstad and Kolstad (2014) for details. For maintenance tasks where everything else is equal, the priority is given by the order in which the maintenance tasks are listed in the input spreadsheet.

(Note that there may in principle be cases where the above prioritisation is not optimal with respect to O&M and downtime costs, as for instance if jack-up vessels needed for a condition-based maintenance task will have to wait because it has to be used together with crew transfer vessels that are occupied with other, corrective maintenance tasks. Also note that in version 3 of the tool, the order of prioritisation criteria was different, with the type of maintenance task being modelled as the least and not the most important.)

It is also possible that several different access vessels and vessels with a special ability could be used to perform a given maintenance task. In such a case, the vessels are used that have most time available for that task and then the vessels with the lowest variable cost (fuel consumption).

5.3.3 Logistics during the execution of a maintenance task

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 can only serve maintenance tasks one after each other. If a vessel serves several maintenance tasks in one shift, the travel in the wind farm is considered as illustrated in Figure 4.

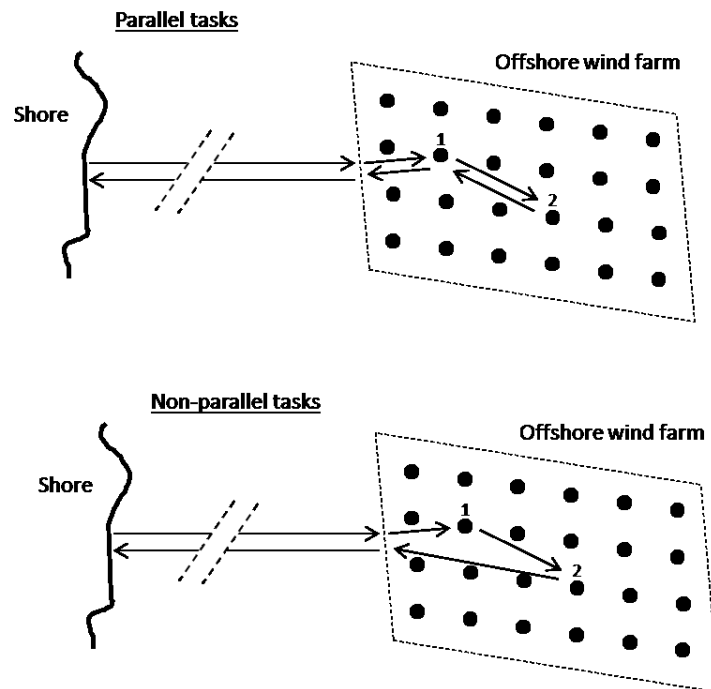


Figure 4 Travel time in wind farm for several tasks.

The model does not consider an optimized travel route and is based on the simplification that an access vessel will pick up the personnel of the first task last. This simplification is needed to allow for a maximum size of the time windows when the access vessel is available. Figure 5 gives an example of how the model schedules a vessel that has to perform two maintenance tasks in one shift. The first example represents an access vessel, and therefore, the maintenance tasks can be executed parallel. In the second example, the maintenance tasks have to be performed one after each other since lifting of a heavy component is involved.

As one can see for the parallel tasks, the vessel has to travel out to the wind farm, travel in the wind farm to the right location of the first maintenance and will transfer the personnel onto the wind turbine. These personnel will be picked up again at the latest possible moment. In our example, this will be right before the weather window ends. Otherwise, it would be at the end of a shift. The access vessel can so travel to the second maintenance task, while the personnel are working on the first turbine. Also these personnel are picked up at the latest moment in the weather window. The scheduling is different if the maintenance tasks cannot be performed parallel. In that case, the personnel are picked up right away after the work is finished and first then will the transport to the next maintenance task be done.

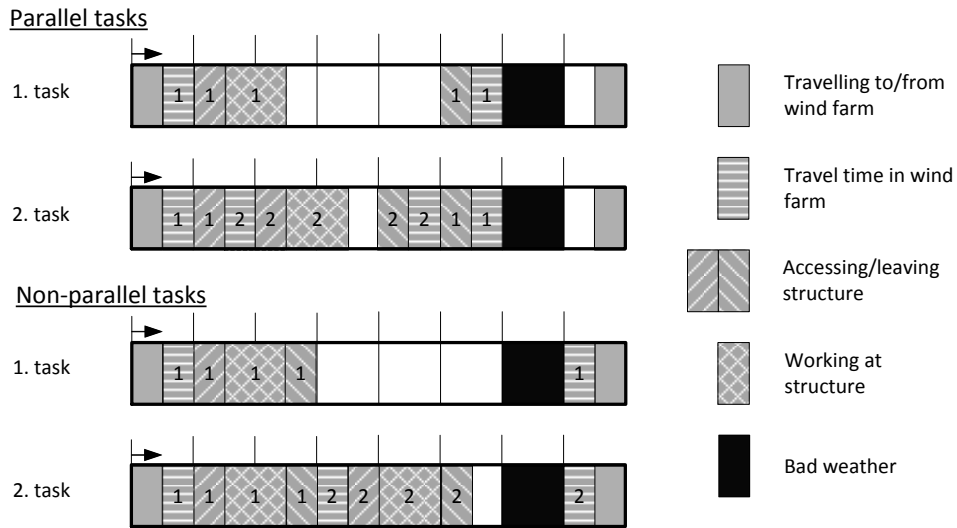


Figure 5 Example of scheduling of two maintenance tasks in one shift.

In addition to the described functionalities of the model, it is also possible to specify several operation steps (subtasks) per maintenance task. Each subtask will then be dealt with as it would be a single maintenance task. That means that each subtask has to be executed in a new shift. If a vessel or spare parts have to be ordered for the subtask, this will be first done when the previous subtask is finished and not at the start of the complete maintenance task. As of model version 3, the user interface limits the number of possible subtasks to 2: One main operation step and one optional pre-inspection operation step.

5.3.4 Availability of the wind farm

The time needed for performing a maintenance task depends on several factors. A typical course of action once the need for a maintenance task is identified is illustrated in Figure 6.

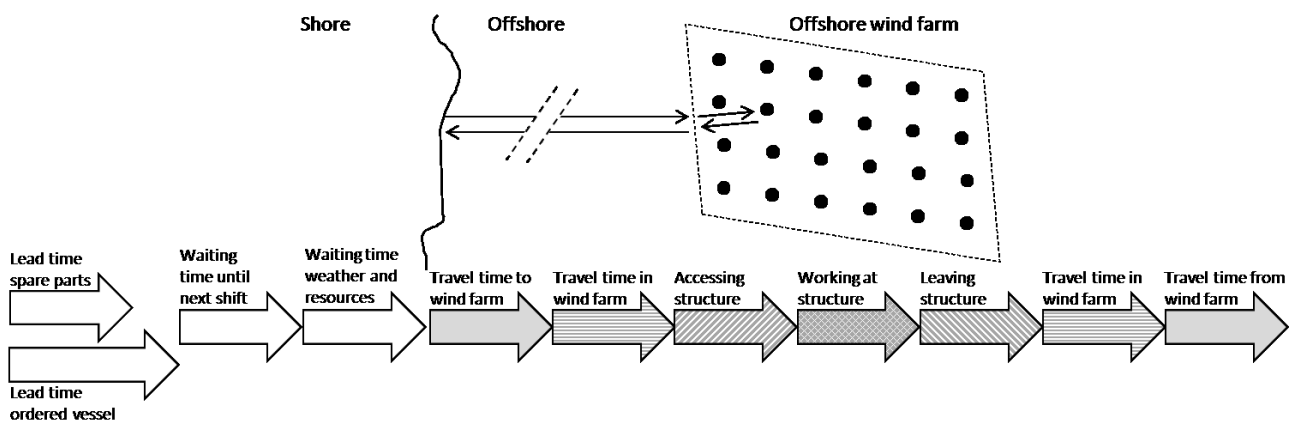


Figure 6 Time used for performing maintenance activities.

Failures prompting maintenance tasks can occur at any hour during the year. Different lead and waiting times are possible before a maintenance task can be performed. Lead time for spare parts and time to order a vessel is also considered in the model. A corrective maintenance task can only be scheduled at the beginning of a new shift. Therefore, if a failure occurs in one shift, there will always be a waiting time until the beginning of the next shift. Additional waiting time can occur for maintenance tasks due to adverse weather and if not enough resources as vessels and maintenance personnel are available. If a maintenance task is finally scheduled for a shift, different types of travel distances have to be considered. First of all, the vessel has to travel to the wind farm and reach its position in the wind farm. Then, the turbine or another offshore structure has to be accessed before the work can start. After finishing the work, the personnel have to leave the wind turbine and travel back.

The time the component is stopped due to failure or maintenance is dependent on the maintenance task and can be selected by the user in the case specific data. There are four different options for component down time due to maintenance.

1. Stop at fault / Stop at alarm

For corrective- and condition based maintenance the component can be set to shut down at the instant a fault or alarm occurs. The component will remain off until the maintenance task is completed and the personnel have left the component. If the maintenance task is not finished in one shift the component remains stopped also between the shifts.

2. Stop during repair

The component is stopped when personnel are accessing the turbine to start maintenance work, and remains stopped until the maintenance task is completed. If the maintenance task is not finished in one shift the component is stopped also between the shifts.

3. Stop during work

The component is stopped when personnel are working on the component, including access time. If the maintenance task is not finished in one shift the component will run as normal between the shifts.

4. Do not stop

The maintenance task has no impact on the operation of the component and the component is not stopped.

Unavailability of the maintained component for the different component down time options is also illustrated in Figure 7 and Figure 8.

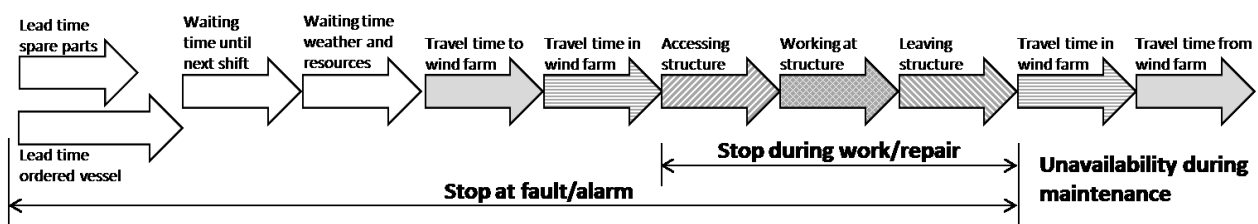


Figure 7 Unavailability of maintained components for different component down time options.

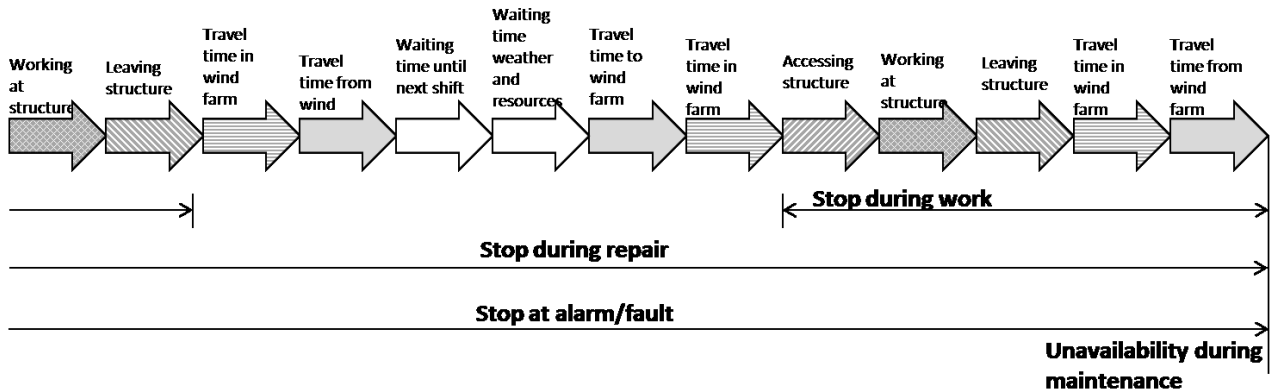


Figure 8 Unavailability of maintained component for different down time settings if maintenance task is not finished in one shift.

5.4 Result calculation

The results delivered by the model include discrete probability distributions (so called histograms) of several performance criteria. The results are saved in an Excel file for all simulation runs. Figure 9 shows an example of such a probability distribution. The performance criteria calculated by the model are:

- Availability (time and electricity based)
- Electricity production
- Net present value of income
- Net present value of lost income due to downtime
- Net present value of O&M cost
- Investment cost
- Net present value of profit
- Capacity factor
- Cost of energy
- Net present value of total O&M cost (i.e., O&M cost plus lost income due to downtime)

The following sections explain how the different model results are calculated.

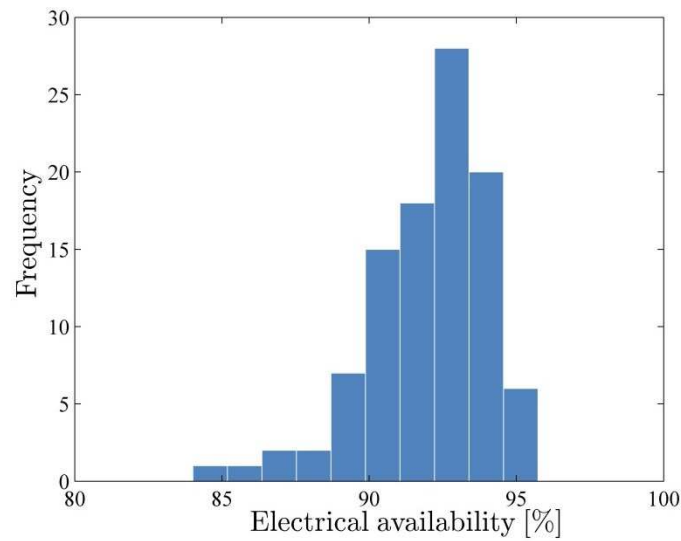


Figure 9 Example for probability distribution of the availability.

Availability

Two different definitions of availability are used in the NOWIcob model: time-based availability and electricity-based availability.

The availability based on time is defined as running time of the wind turbines (subtracting downtime due to failures and services but not the time the wind speed is below the cut-in value) divided by the life time of the wind turbines. Time-based or technical availability can be 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” (Tavner, 2012). See also Eq.1 from International Electrotechnical Commission (2010).

Electricity-based availability, on the other hand, is calculated based on the real and theoretical possible electricity production. Table 1 defines both measures of availability more precisely. Note that T_{lifetime} in the definitions can be replaced by shorter time intervals to estimate the availability over shorter intervals than the entire life time of the turbine. In the model, availability is calculated with a resolution of 1 hour.

Table 1 Definitions of availability.

Availability (time based)	Availability (electricity based)
$A_{\text{time}} = \frac{T_{\text{lifetime}} - T_{\text{downtime}}}{T_{\text{lifetime}}} \times A_{\text{trans}}$	$A_{\text{el}} = \frac{E_{\text{real}}}{E_{\text{theor}} \times \text{LOSS}_{\text{wake}} \times \text{LOSS}_{\text{el}}}$
T_{lifetime} – Lifetime of the wind turbine (e.g. 20 years)	E_{real} – Produced electricity considering downtime of the wind turbines and electrical infrastructure, wake losses and electrical losses
T_{downtime} – Downtime of the wind turbine due to failures and services	E_{theor} – Theoretical possible electricity production with 100% availability, taking into account wind speeds and power curves but neglecting any losses
A_{trans} – Time-based availability of main components that transport/transform electricity	

Electricity production

The electricity production, E_{real} , is used when calculating the electricity-based availability defined above. When calculating the electricity production, the model considers losses from wake effects in the wind farm and electrical losses in the electrical infrastructure, as for example the substation. Based on these assumptions, the equation for calculating the electricity production for all time steps t (here considering downtime) is as follows:

$$E_{\text{real}} = A_{\text{trans}} \times \text{Loss}_{\text{wake}} \times \text{Loss}_{\text{el}} \times \sum_{t=1}^s \sum_{j=1}^n (E_{\text{theor},j,t} \times A_{\text{prod},j,t})$$

$E_{\text{theor},j,t}$ – Theoretical possible electricity production with 100% availability of wind turbine j at time step t based on wind speed at time step t and power curve of wind turbine j

$A_{\text{prod},j,t}$ – Availability of wind turbine j at time step t .

$\text{Loss}_{\text{wake}}$ – Losses in electricity production due to wake effects in the wind farm

Loss_{el} – Losses of the produced electricity due to the electrical infrastructure

s – Number of time steps in the simulation, one time step is one hour, therefore $s = \text{years} \times 365 \times 24$

n – Number of wind turbines in the wind farm

Net present value of income

The net present value of income is the result of discounting the absolute income I_{abs} with a discount rate. 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.

$$I_{\text{abs}} = \sum_{m=1}^u (E_{\text{real},m} \times P_{\text{el},m})$$

I_{abs} – Absolute income from electricity production

$E_{\text{real},m}$ – Sum of produced electricity in month m

P_{el} – Electricity price in month m

Net present value of lost income due to downtime

$$I_{\text{lost}} = \text{LOSS}_{\text{wake}} \times \text{LOSS}_{\text{el}} \times \sum_{m=1}^u (E_{\text{theor},m} \times P_{\text{el},m}) - I_{\text{abs}}$$

- I_{lost} – Lost income due to downtime of the wind farm
 $E_{\text{theor},m}$ – Sum of produced electricity in month m
 P_{el} – Electricity price in month m

Net present value of O&M cost

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

- Spare part and consumable costs (fixed cost per maintenance task)
- Vessel fixed costs (yearly fixed costs)
 - Includes costs for transporting personnel to a mother ship (yearly fixed costs)
- Vessel fuel cost (variable)
- Vessel charter costs
- Personnel costs (yearly fixed costs)
- Location cost (yearly fixed costs)
 - Costs for using a location such as a harbour, platform etc. (yearly fixed costs)
 - Costs for transporting personnel to locations as 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 and therefore the fuel costs.

Investment cost

The investment cost is the sum of the investment costs for the main components in the wind farm; for example wind turbines, sub stations, etc. It can be used for calculating a profit.

Net present value of profit

The net present value of profit is a performance criterion for the profitability of the wind farm. It is calculated with the following equation:

$$\text{Net present value} = \text{Net present income} - \text{Net present O\&M cost} - \text{Investment cost}$$

The investment cost is specified per main component and are input to the model. These numbers are only used for the calculation of the net present value and no other place in the model.

Capacity factor

The capacity factor is the electricity produced given 100 % wind farm availability divided by the electricity production given that all turbines produced at their rated power at all times. No losses are included in this definition of the capacity factor.

Cost of energy

Cost of energy or levelised cost of energy is the constant electricity price that would cause the project to break even when income and costs are discounted to year 1.

Net present value of total O&M cost

The net present value of the total O&M cost is the total cost due to operation of the wind farm including lost income due to downtime. It is calculated with the following formula (all values in net present values):

$$\text{Total O\&M cost} = \text{O\&M cost} + \text{Lost income due to downtime}$$

5.4.1 Economic sensitivity add-on

This add-on is developed as deliverable number D5.1-63 in NOWITECH WP5. If activated, the economic sensitivities add-on will write selected simulation results, for each year in the simulation to an Excel workbook designed for studying sensitivities regarding economical parameters. In this way sensitivity to economic parameters can be studied without having to run the simulations several times. The input parameters to the sensitivity study are:

- Discount rate
- Fixed personnel cost
- Fuel price
- Electricity price
- Fixed cost and charter cost for up to 10 different vessels
- Cost of up to 10 different maintenance tasks

If more than 10 maintenance tasks are specified in the case specific data, the model will sort them by which task has the largest influence on the cost and which task occurs the most times during the life time of the wind farm.

The add-on performs calculations to illustrate the effect a change in the input parameters have on the following performance parameters:

- Cost of energy
- Net present value of profit
- Net present value of total O&M cost

6 Model verification and validation

Verification and validation (V&V) is essential when developing a simulation model. Verification of a simulation model will be defined as ensuring that the *computerized model* is implemented according to the specifications of an underlying *conceptual model* of the system (Sargent, 2013). Validation of the simulation model is defined as ensuring that the model is sufficiently accurate for its intended applications (Sargent, 2013). This involves substantiating that the conceptual model is in fact a good enough representation of the actual system within the domain of applicability of the model. Verification is often an internal process, carried out by the model developers, whereas validation involves external experts and users.

There are no universally specified guidelines for what it means to require a simulation model to be verified and validated (Kleindorfer et al., 1998). One position is that models are never entirely validated because it is not practicable to assess correspondence between a system and a model for the system for its entire domain of applicability (Sargent, 2013). 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 that are not observed today. This is the case for nascent industries such as offshore wind energy, where novel and untested O&M strategies are considered 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 in and increase the credibility of the model (Sargent, 2013).

A number of approaches and methods have been used for verifying and validating the NOWIcob model. One main effort was the formation of a so-called offshore wind O&M modelling group with other researchers. The offshore wind modelling group was used for both verification and validation purposes, and the methods used will be explained more in detail in the following section. Other methods used for V&V are presented in Section 6.2 and Section 6.3, respectively.

6.1 Offshore wind O&M modelling group

In early 2013, the "offshore wind O&M modelling group" was formed as an informal forum for discussing computer models for operation and maintenance of offshore wind farms. The group consists of participants from SINTEF Energy Research, MARINTEK, the University of Strathclyde, the University of Stavanger, NTNU and EDF who are developing or using models similar to the NOWIcob model in their research work.

Such collaboration allows for *intercomparison* or *code-to-code-comparison* (Robertson et al., 2013) of different simulation models for increasing the credibility of the models. The intention of the group was to verify and partly validate the models by running clearly defined cases and to compare and discuss results. If the researchers have made reasonable assumptions about the structure of their models, then there should be a convergence of the results with a given set of inputs and similar sensitivities when changing input values. In addition to a generic base case, the analyses were performed for several other cases to reveal model behaviours over a wide range of inputs. Many of the cases were designed to measure the performance of the modelled wind farm when the system is stressed, i.e., when the maintenance requirements of the wind farm exceeds the available maintenance resources. Observed differences in results between the models were also discussed to understand major assumptions in the different models and their impact on the results.

During 2013, a reference case was defined that could be run meaningfully on all models. Sensitivity analyses based on this base case were subsequently performed for four of the models: The NOWIcob model of SINTEF Energy Research, the ECUME model of EDF, and the models of the University of Strathclyde and the University of Stavanger.

As of the writing of this report, a paper based on this analysis and the code-to-code-comparison process leading up to it (Dinwoodie et al., 2014), has been accepted for publication. Comparison of the results provided insight into the similarities and differences and the strengths and weaknesses of the respective models. Similar trends in the model sensitivities increase our confidence in the correctness of the implementations and accuracy of the models in their common domain of applicability. The results showed that differences in the results can be explained to a large extent by differences in modelling assumptions. One characteristic of the NOWIcob model that one should be aware of is that the model is relatively optimistic in scheduling and execution of maintenance tasks. In other words, the heuristics utilize the crew transfer vessels and technicians available rather efficiently; in reality, offshore logistics and maintenance operations will probably not be that streamlined. Although the NOWIcob results for the availability are consistently close to the average for all four models, they are also consistently slightly above the average. On the other hand, we estimate somewhat higher O&M costs than the average because the NOWIcob model is not assuming a very efficient utilization of jack-up vessels, leading to relatively high jack-up charter costs.

In summary, the comparison with other models based on different reference cases showed that the NOWIcob model has no discrepancies in results compared to the other models that cannot be reasonably accounted for. We therefore regard the model to have been successfully verified. Furthermore, our preliminary conclusion is that the underlying conceptual model is at least as reasonable as those of the other models, meaning that the NOWIcob model gives a fairly accurate representation of reality.

6.2 Verification

In addition to the activities in the modelling group, other measures were put in place to assure the verification of the model during the development process. An important part of the verification process is making sure that presumed correct results also remain correct after extending, modifying and optimizing the model. In other words, model results should be reproducible, and if one is no longer able to reproduce a given set of results after, e.g., implementing new functionality, one should be able to identify and explain the reason for the discrepancy. To this end, we have defined a number of benchmark cases that are run at regular intervals in the model development. The results of these cases are compared with those produced the last time the benchmark case was run. The benchmark cases are described briefly in Table 2, and both input data and benchmark results should be stored together with the source code of the model. One must also remember to keep track of the pre-generated synthetic weather time series used if not using the historic weather data. After making code changes that changes the logic or assumptions of the model, one can no longer expect to get identical results as before, and one needs to store and document updated versions of the result files after running the benchmark cases.

Table 2 Description of benchmark and reference cases.

Case name	Description
Modelling_group_benchmark	Benchmark case based on the base case used in the Modelling group. This is a "minimal" benchmark case, meaning that very few optional parameters are given values and few optional functionalities are in use. Nevertheless, it can be used to verify that the core functionalities of the model are still operating as expected after a code update that is not expected to change the output.
Maximal_benchmark	Loosely based on Modelling_group_benchmark, but being a "maximal" in contrast to a "minimal" benchmark case. This means that almost all optional functionalities are used and all parameters are given values. In this way, one can test the entire model with one case: If one runs the case and gets the same result as before making a change to the model, one can be sure that this change did not inadvertently change any of the features or functionalities of the model. Many of the choices and parameter values of this case are not very realistic.
5MW_reference_wind_farm	Based on Modelling_group_benchmark, but using more of the parameters, making it a slightly more realistic case. It is used not as much as a benchmark case as a reference for reasonable input data and a base case for sensitivity analyses; see Hofmann and Sperstad (2013).

Besides the benchmark cases, the following additional verification measures were undertaken, as listed below. See Sargent (2013) for descriptions of these and other verification (and validation) techniques.

- Redundant calculations of simulation results. Example: Calculating unavailability in a different manner than contributions to downtime, as well as using a third way to log maintenance tasks. This makes one able to cross-verify the results by checking for consistency.
- Sensitivity studies (Hofmann and Sperstad, 2013) to look for counterintuitive behaviour in the model's mapping of inputs to outputs.
- Modularisation of the code, allowing unit testing of auxiliary functionality.
- Systematic walkthrough of the simulation logic during code execution when introducing new functionalities.
- Two developers were involved, allowing one of them to review code for new functionalities implemented by the other.
- Extreme condition testing and degenerate tests (e.g., setting the failure rate or the number of technicians to zero).

6.3 Validation

It may sometimes be difficult to distinguish between verification and validation, and several techniques and tests are used both for verification and validation. For instance, measures such as sensitivity analysis, extreme condition testing and logic walkthrough from the list in Section 6.2 above also aids towards model validation. The comparison with other models in the offshore wind modelling group described in Section 6.1 should also be regarded as a validation effort.

In addition, a validation process was performed together with industry partners where face validity (Sargent, 2013) was checked continuously by experts on the system the model is meant to represent. During development, especially within the FAROFF project, the model was presented several times to the industry partners and main characteristics, model features and assumptions were discussed. This was done to ensure that the model represents reality closely enough for the intended applications and thus can be used for analyses. A test phase was performed during the autumn of 2013. During this phase, a beta version was made available for the industry partners so they could run their own, realistic cases with the model. This process was used also to validate the results of the model and to discover assumptions and limitations that prevent an effective use of the model.

7 Changelog

This chapter provides a history of the development of the model from version 2 onwards, summarising the functionalities added and the changes made to the model that may influence the results.

7.1 Changes in version 3

Version 3 of NOWIcob was released January 2014. The following functionalities have been added during 2013 since the previous version of the NOWIcob model (version 2, completed December 2012). Several of these functionalities were developed fully or partially within FAROFF. Work on restructuring, clarifying, verifying and optimising the code is not reported here.

- Seasonal availability of vessels and technicians
- More complex weather model and weather limit representation (only partially implemented in the user interface)
- More detailed modelling of access (introducing separate time parameters for mobilisation, access and logistics/lifting)
- Improved modelling of chartering of vessels (introducing charter duration and charter cost)
- Calculation of fuel costs
- Calculation and output of utilization and split of downtime and O&M costs
- More user-friendly graphical user interface (in Excel)
- Several new output sheets in result files for, e.g., summarising the main results
- Improved traceability of simulations (including metadata and input data in output files)
- Stand-alone version of the simulation tool that can be run without having MATLAB installed
- Automatic sensitivity analysis

7.2 Changes in version 3.1

The following functionalities have been added during 2014 for the release of model version 3.1 in December 2014. The new functionalities are not considered sufficient to create a new, full model version.

- Improved simulation speed
- Economic sensitivity add-on (enabling sensitivity studies of economical parameters without running new simulations)
- Detailed options regarding down time of main components during faults and maintenance
- Time-based availability by year and month of the year presented in results sheet.
- Implementation of multi-parameter weather model in the GUI: The user can now specify which of the weather parameters will be taken into account in the weather model, the resolution for each of them, and the direction of the boat landing.
- Implemented user option to specify prioritisation of maintenance tasks.

Changes in the model and bug fixes made from version 3 to version 3.1 that may affect the results:

- The default prioritisation of maintenance task has been changed so that corrective maintenance always is given priority to time-based maintenance.
- Some coding errors have been corrected in the estimation of the contributions to unavailability; it is now more accurate, but still to be regarded as an estimate.
- Bug fixed that could give incorrect results if using different turbine types having more than one power curve.
- Very minor changes in availabilities due to simplification in method for calculating availabilities.

8 Further development and challenges

Version 3 of the NOWIcob model was developed in the projects FAROFF and NOWITECH and reached its final level with regards to the functionalities needed in these projects. For implementing the model in the business processes of the involved industry partners, a formal license agreement was developed that specifies the rights when using the model. This contract has been used as an instrument to give interested parties access to the model for their analyses. Smaller development, support or analysis tasks may be commissioned by the interested parties under separate contracts. One possible challenge is to balance specific needs of interested parties with the development plans in long-term research projects as NOWITECH and LEANWIND.

Even though the model as of this version (i.e., version 3.1) is regarded as complete, it will be developed and applied further in research projects as LEANWIND and NOWITECH. In LEANWIND, NOWIcob is to be used as an O&M strategy model to evaluate different O&M and logistics strategy options (e.g., jack-up vessel campaigns or when to replace components with possible incipient failures). The main development challenge for 2015 will be to implement the functionalities necessary for analysing these strategy options accurately, e.g., the modelling of jack-up vessel operations and condition monitoring.

In addition to model development, the verification and validation of the model will continue for the next year. Although model version 3 was regarded as verified to a large extent and validated to a certain extent (cf. Section 6), the challenge still remains of ensuring and improving the accuracy of the model. This is the case in particular for model features that have not been investigated in that great detail, e.g., the realism of the actual logistics scheduled for each shift or the charter schemes and associated costs assumed for jack-up vessels. Continuing the V&V process is also important to be able to document the verification and validation of the model more thoroughly.

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Appendix

A Overview about functionalities and assumptions in the model

This table was developed in connection with the verification and validation process described in Section 6.1 and outlines the modelling assumptions for the core functionality of the NOWIcob model.

Weather	
Weather model time resolution	Hourly resolution
Weather data parameter value resolution	Flexible, but typically using bin widths of 0.1 m for wave height states and 1 m/s for wind speed states
Weather forecast	Perfect weather forecast for the entire shift (i.e., the model can use all weather data for the shift when scheduling the shift)
Seasonality of weather characteristics	Taken into account by having different weather characteristics for each month in the Markov chain model
Correlations between weather parameters (wind speed, wave height etc.)	Taken into account by using Markov chain model based on weather states defined by all weather parameters
Inhomogenities in sea state etc. in the wind farm	Not taken into account
Weather requirement for maintenance personnel working on turbine	There needs to be acceptable weather for personnel transfer/access for the entire scheduled working duration of the task that shift
Failure model	
Failure model structure	Each type of fault / failure mode is associated with a maintenance task, and the maintenance task defines (indirectly; see under <i>Vessels</i>) the resources required to carry it out
Failure process / failure time distribution	Poisson process with exponential distribution of time to next failure, but failure rate can be set to vary in time with yearly resolution
Correlation between preventive maintenance and failure rates	The intensity (maintenance intervals) of preventive (time-based) maintenance does not affect failure rates
Correlation between failures	Assumed to be no common-mode failures or other correlations between failures for different turbines, components, etc.
Multiple failures on the same turbine	After a failure of one category has caused the turbine to stop, failures of other categories may still occur on the same turbine while it is down. (The assumption is that the probability of multiple, simultaneous failures on the same turbine is low.) New failures of the same category cannot occur before the previous failure of that category is repaired. The turbine is down until all failures are repaired, but there is no coordination between maintenance tasks if several failures need to be repaired on the same turbine.
Correlation between environmental loads and failure rates	Assumed to be no correlations between wind speeds and the rate (or the times) of failures

Power production	
Downtime after fault/alarm	It is optional for each maintenance task whether the turbine is powered down immediately after failure or when condition monitoring gives alarm, or whether the turbine is first powered down when the actual work on the maintenance task has started. The turbine is returned to full production immediately after repair is complete and technicians have had time to leave the turbine (see, however, <i>Time of pick-up of maintenance personnel from turbine</i> under <i>Logistics</i>)
Downtime during maintenance	For each shift (or weather window) while the maintenance task is carried out, the turbine is powered down immediately before crew transfer vessel (CTV) arrives at the turbine and is powered on again immediately after technicians have had time to leave the turbine (see, however, <i>Time of pick-up of maintenance personnel from turbine</i> under <i>Logistics</i>). If a maintenance task runs over several shifts, it is optional whether the turbine is powered on again between the shifts or not.
Power curve	There is no power production above the cut-out wind speed or below cut-in speed, but it is assumed that power production is restored immediately after wind speed is reduced to the cut-out speed again
Wake effects	Are taken into account as a single value for average reduction in power production compared to theoretical yield without wake effects
Downtime of electrical infrastructure (substations, cables, etc.)	Is typically taken into account as a single value for average reduction in power production compared to theoretical yield with no downtime for electrical infrastructure. (Although the model in principle has the capability to model failure and maintenance of electrical infrastructure with an average reduction in total wind farm production associated with downtime of each component of the electrical infrastructure.)
Maintenance tasks	
Maintenance Structure	Maintenance tasks are classified as either time-based maintenance or corrective maintenance (as well as condition-based maintenance tasks)
Splitting of maintenance tasks in operation steps	Maintenance tasks can be split in operation steps (e.g. pre-inspection and the actual repair) that must be carried out sequentially. Only one operation step for a maintenance task can be carried out each shift. Lead time for spare parts is only considered for the main task and not for pre-inspection.
Tasks with too long work duration for a single shift	A maintenance task (or, more precisely, an operation step) can be split over several shifts (or, more precisely, weather windows) if there is not time to complete it in one shift. It is required, however, that the work performed in each given weather window is above a certain lower working time limit.
Cumulative or single trip repairs	No distinctions; all maintenance tasks (of sufficient length; see above) can be split over several shifts (i.e. performed cumulatively), and one would not need a long enough weather window to perform the entire operation on a single trip.
Coupling between maintenance tasks and vessels	One task may require several vessels (with several different vessel abilities), and the model dynamically assigns vessels to maintenance tasks. A fixed vessel type can also be assigned to a given maintenance task (or, more precisely, maintenance action).
Opportunistic maintenance	No modelling of opportunistic maintenance (e.g. performing scheduled preventive maintenance for a turbine together with necessary corrective maintenance)
Tasks not requiring vessels to be carried out (can be done remotely)	Remotely performed maintenance tasks or operation steps can be specified, but are scheduled as ordinary maintenance tasks (i.e. cannot be performed before beginning of next shift, and only one operation step can be carried out each shift)

Time of scheduling of maintenance tasks	Planning and scheduling maintenance tasks only at the beginning of shift; no response will be made to failures before beginning of the next shift
Prioritisation of maintenance tasks to be scheduled	By default prioritised by: 1) Whether the task is a corrective task (and not preventive; condition-based maintenance tasks have priority between corrective and preventive), 2) whether the maintenance task is already started, 3) whether a vessel has been chartered (ordered) for the task.
Prioritisation of which vessels to use for maintenance tasks	Vessel combination prioritised first by how much of the maintenance tasks there is time to do using that combination, then by the variable costs of using the vessels
Scheduling of preventive maintenance	Starting to schedule tasks for the year from a given start date, trying to start a given number of new tasks each day; no last day defined for period for preventive maintenance. If a preventive maintenance task is delayed for longer than its maintenance interval (e.g. more than one year for annual services), the task is cancelled.
Maintenance tasks requiring more maintenance personnel on the turbine than there's space for on a single vessel	Assumed that a single maintenance tasks cannot require this many technicians
Event trees or decision trees for maintenance tasks	Manual inspections assumed to always identify failure successfully, maintenance decisions are deterministic, and repair is assumed to always be successful
Stochasticity of input parameters	No stochastic variation in such parameters as work duration, lead time, etc.
Personnel	
Definition of maintenance teams	Maintenance personnel are split in teams dynamically depending on how many are needed for the different maintenance tasks (but a single team cannot be split on several vessels)
Localisation of maintenance personnel	Number of personnel available per maintenance base or per vessel that can stay offshore for several shifts are specified, and these are regarded as independent technician pools.
Non-maintenance personnel	Only maintenance personnel / technicians are included explicitly, other personnel or crew may be included implicitly in the cost of operating the vessel / base. Personnel needed for e.g. handling lifting operations on chartered jack-up vessels are assumed to be included in the charter of the vessel, and are not taken into account explicitly.
Work schedules and rotation	Work schedules for individual workers are not modelled; it is assumed that what is given as input is an average of available personnel, factoring in rotation, days off, sick leaves, etc.
Time for briefing/debriefing, preparation, acclimatization, breaks, etc.	Not taken into account explicitly, but is factored into shift length or work/transfer duration. The effect of sea-sickness on technician efficiency (and the effect of weather and vessels on the presence or absence of sea-sickness) is not taken into account.
Seasonality in personnel availability	A fixed number of maintenance personnel are available for each base throughout the year as default. (But it can be specified that the number is different in a given period during the year.)

Vessels	
Vessel types	Vessel types are indirectly associated with the failures/tasks they serve through a list of abilities for each type and a list of abilities needed for each maintenance task.
Variable costs	The variable costs being calculated for the vessels are fuel costs; day rates (excluding fuel costs) are regarded as fixed costs for vessels at a long-time charter (i.e. always available to be used at the wind farm). The fuel consumption is estimated using one fuel consumption rate for the time it is travelling and another fuel consumption rate for the rest of the shift (during which the vessel is assumed to be offshore and stationary).
Vessels staying offshore for several shifts	Vessel types can be defined to be several-shift vessels following a rotation where they stay offshore for a fixed number of days before coming back to resupply etc. for a fixed number of days.
Localisation of vessels	A number of vessels (of each type) is defined for each location/base (daughter vessels are assigned to their mother vessels, but mother vessels are assigned to a home base even though they may stay offshore all the time). Each vessel can only be assigned to a single base (at a time; see, however, <i>Seasonality in vessel availability</i>).
Handling of extreme weather	Vessels cannot be offshore in a shift with extreme weather (when it would not be acceptable for vessel to stay offshore), and vessels staying offshore for several shifts need to come back to their safe haven.
Seasonality in vessel availability	A fixed number of vessels are available for each base throughout the year as default. (But it can be specified that some vessel types are only available in a certain period during the year, or that they are available from another base in this period.)
Different shifts for different vessels?	The same shifts apply for all vessels (both owned and chartered vessels).
Vessel speed	All vessels travel at constant speed irrespective of weather conditions, urgency and distance from wind turbines or bases. (Reduced speed on approach to turbines can be taken into account by the mobilisation time for access.)
Chartering of vessels	
Are vessels owned or chartered?	Each vessel type is defined to either be owned by the wind farm (or being assumed to be available on a long-time charter of several years) or chartered in when needed for maintenance tasks
Ordering of multiple vessels for a task	Only one vessel can be ordered for each task
When is the vessel ordered?	The vessel is ordered at the beginning of the first shift after the failure prompting the vessel charter has occurred (or has been diagnosed by inspection or been predicted by the condition-monitoring system, if applicable).
Mobilisation time	The order lead time / mobilisation time / time to wait for the vessel to be available is constant for each vessel. However, if the spare part lead time is longer than the order lead time, the vessel will not be available before the spare parts have arrived.
Mobilisation costs	A fixed cost can be associated with the chartering of a vessel. (This parameter is set independently from the parameter deciding how long the mobilisation time will be.) The fixed charter cost includes both mobilisation costs and day rates.
Charter period	A chartered vessel is assumed to be staying for a fixed, predefined period from the time it is available after being ordered. During the charter period, the vessel can be used for work on other maintenance tasks than the one it was originally ordered for.

Tasks not finished within charter period	If a task is scheduled for maintenance (either starting or continuing a maintenance task), but the charter period of the chartered vessel needed for the task has expired at the time step it is scheduled for, a new vessel has to be ordered at this time step.
Bundling of maintenance tasks	No bundling strategy; if ordering of vessels is necessary for the maintenance task, this is done immediately after the failure (has been diagnosed). (See <i>When is the vessel ordered?</i>)
Logistics	
Separation of vessel travel in travel to wind farm and travel within wind farm	A vessel traveling from a base to a wind turbine first has to travel a predefined distance to the edge of the wind farm and then a predefined average distance within the wind farm from the edge to the turbine. A vessel already being in the wind farm has to travel the same average distance within the wind farm for each new turbine it visits.
Travel distances within wind farm for corrective (unplanned) maintenance	An average distance between two random turbines is used. (There is no routing optimization.)
Travel distances within wind farm for preventive (planned) maintenance	The distance travelled within the wind farm can be specified to be shorter than for unplanned maintenance, typically of the order of the average distance between neighbouring turbines. (This also applies to the distance from the edge of the farm to the first turbine visited for a vessel coming from shore.)
Several wind farms or clusters of wind turbines	A single, homogenous wind farm is assumed.
Personnel transfer to different turbines	CTVs can deploy personnel to an arbitrary number of turbines without having to wait for them by the turbines, thus allowing the different maintenance teams from the same CTV to perform a number of different maintenance tasks in parallel.
Are vessels participating in maintenance tasks sequentially or in parallel?	A maintenance task (or more precisely: an operation step) needs to be completed before a vessel can move on to a different maintenance task, the only exception being transfer of personnel.
Limit on number of parallel tasks	There is in principle no limit for how many teams of technicians that can be deployed to different turbines to work in parallel.
Several tasks for the same maintenance team	A maintenance team can only be used for one task during a shift. Example: If there is 1 CTV and a shift with several short maintenance tasks requiring a team of all technicians there is space for on the vessel, the access vessel cannot redeploy the team to work on a second task after the first one is finished no matter how much time is left of the shift.
Transfer of personnel for heavy-lift maintenance tasks	For maintenance tasks requiring jack-ups and other heavy-lifting capabilities, technicians either have to be transferred to the turbines by separate access vessels (CTVs), or there must be a separate technician pool at the heavy-lifting vessel if technicians are to be transferred to the turbine from the heavy-lifting vessel.
Transfer of personnel between vessels	Except for transfer between mother vessels and their daughter vessels, maintenance personnel cannot be transferred from one vessel to another
Logistics of spare parts	Spare part storages or supply vessels necessary for transporting spare parts from land are not modelled (but may factor in waiting time and cost in the lead time and spare part cost defined for the failure mode).

Dependence of access time on vessel or access solution	The access time is the time from the access vessel is in the vicinity of the wind turbines to the technicians are transferred to the turbine and ready to work. This equals a "mobilization time" for the vessel (an approach time, a constant term determined by the vessel and/or access solution) plus a transfer time per technician times the number of technicians. (In addition comes the logistics time defined below). The same mobilisation and transfer times are assumed also after technicians have finished their work for that shift. This mobilization time and transfer time is defined for each vessel type specified in the model, i.e., for each combination of a type of vessel and a type of access system.
Dependence of access time on maintenance task	A logistics time for lifting etc. before technicians are able to do any work within the wind turbine is defined for each operation step of the maintenance task. The same logistics time is assumed also after technicians have finished their work for that shift.
Time of pick-up of maintenance personnel from turbine	CTVs stay offshore until the end of the shift (if not hindered by weather making it unacceptable for the vessel to stay offshore) and pick up personnel at the latest possible time. (This is handled this way in the model for technical reasons, however, and turbine power production is calculated assuming that technicians can start leaving immediately after finishing work.)
Offshore accommodation vessels (mother vessel etc.)	
Can a vessel offering technician accommodation stay offshore for multiple shifts?	Yes, a crew transfer vessel can be specified to not need to travel back and forth to the maintenance base each shift
Modelling of refueling/resupplying, etc.	After a given number of days, the vessel will travel to the maintenance base immediately after the last shift to stay there for a predefined number of days before travelling back to be ready offshore before the beginning of the new shift
How many technicians at accommodation vessels will be available to work each shift?	The number of technician on the accommodation vessel able to do work each shift is specified as an input parameter. The value must be smaller or equal to the number of technicians there is space for on the vessel (at one time) divided by the number of shifts.
Can mother vessels themselves transfer technicians to turbines?	Yes, a mother vessel can be allowed to travel around in the wind farm to transfer technician just as the daughter vessels. Both daughter and mother vessels can be used for this in the same shift.
If both mother and daughter vessels can transfer technicians, which will be used?	In choosing which vessels technicians will be transferred by, priority is given to the fastest vessel that is able to transfer technicians.
Time delay for launch and recovery of daughter vessels	Not modelled; there is no time delay for launching daughter vessels from the mother vessel or recovering them

B Literature

This chronological literature list contains all references related to the development and application of the NOWIcob model. This appendix is included with the documentation of the model to provide background (provenance) and a complete list of relevant references including those that were not necessary and natural to cite in the main part of this report. A brief description of the contents of the reference is given with each item. Many of the references are NOWITECH deliverables internal to the NOWITECH project, and for these the NOWITECH deliverable number is stated with the title of the deliverable.

Hofmann, Matthias (2010). *State of the art of models for offshore wind farms with an emphasis on O&M strategies (D5.1-5)*, report no. TR A7013, SINTEF Energy Research, Trondheim.
State of the art report on existent models and methods.

Hofmann, Matthias; Eggen, Arnt Ove; Rød Hansen, Mari; Løkken Walter, Erik; Storch, Michael (2010). *Overview of available data and specification of additional data needs (D5.4-4, Part 2)*, project memo no. AN 10.12.103, SINTEF Energy Research, Trondheim.
Project memo with relevant input data for models and analyses in NOWITECH WP5 compiled for wind turbine concepts, failure rates, maintenance and vessels.

Hofmann, Matthias; Nonås, Lars Magne; Halvorsen-Weare, Elin E. (2010). *Description of a framework and structure for a life cycle cost and benefit model for offshore wind farms – NOWIcob (D5.1-2)*, report no. TR F7405, SINTEF Energy Research, Trondheim.
High-level description and requirement specification of the NOWIcob model; prepared prior to development and at a stage when a closer integration with optimisation algorithms was envisioned.

Hofmann, Matthias; Heggset, Jørn; Nonås, Lars Magne; Halvorsen-Weare, Elin E. (2011). A concept for cost and benefit analysis of offshore wind farms with focus on operation and maintenance. *Proceedings of the 24th International Congress on Condition Monitoring and Diagnostics Engineering Management (COMADEM 2011)*. Stavanger.
Conference paper based on the description and requirement specification in [Hofmann, Nonås, Halvorsen-Weare (2010)].

Hofmann, Matthias (2011). A Review of Decision Support Models for Offshore Wind Farms with an Emphasis on Operation and Maintenance Strategies. *Wind Engineering*, vol. 35, pp. 1–15.
Review article based on state of the art report on existent models and methods [Hofmann (2010)].

Hofmann, Matthias; Halvorsen-Weare, Elin E.; Nonås, Lars Magne; Vatn, Jørn (2011). A framework and model for optimizing maintenance and logistics activities. *Proceedings of EWEA OFFSHORE 2011*. Amsterdam.
Conference paper on early version of the NOWIcob model including simple case study on influence of access criteria on availability.

Hofmann, Matthias; Nonås, Lars Magne; Keppler, Robert Max (2012). *User manual and technical documentation NOWIcob model (D5.1-12)*, memo, SINTEF Energy Research, Trondheim.
Documentation for model version 1 of NOWIcob.

Scheu, M.; Matha, D.; Hofmann, M.; Muskulus, M. (2012). Maintenance strategies for large offshore wind farms. *Energy Procedia*, vol. 24, pp. 281–288.

Conference paper using model version 1 of NOWIcob, including a Markov chain weather model, to investigate the effect of different vessel fleets on the availability and production losses of an offshore wind farm.

Hofmann, Matthias; Sperstad, Iver Bakken (2012). *User manual and documentation NOWIcob model – 2. model version (D5.1-30)*, report no. TR F7289, SINTEF Energy Research, Trondheim.

Documentation for model version 2 of NOWIcob.

Hofmann, Matthias; Sperstad, Iver Bakken; Slimacek, Vaclav (2013). *Input to the NOWIcob model from other tools and models (D5.1-30)*, report no. TR F7303, SINTEF Energy Research, Trondheim.

Investigation of how NOWIcob could be extended and/or augmented by incorporating input from models for failures or degradation, turbine costs, wake effects, and electrical losses.

Hofmann, Matthias; Sperstad, Iver Bakken (2013). NOWIcob – A tool for reducing the maintenance costs of offshore wind farms. *Energy Procedia*, vol. 35, 2013, pp. 177–186.

Conference paper with model description and a simple illustration of use. Standard reference for the NOWIcob model. Partially based on the documentation of model version 2 of NOWIcob [Hofmann and Sperstad (2012)].

Hagen, B., Simonsen, I., Hofmann, M.; Muskulus, M. (2013). A multivariate Markov Weather Model for O&M Simulation of Offshore Wind Parks. *Energy Procedia*, vol. 35, pp. 137–147.

On the development and benchmarking of the multi-parameter weather model subsequently implemented in NOWIcob.

Hofmann, M.; Sperstad, I. B. (2013). Analysis of sensitivities in maintenance strategies for offshore wind farms using a simulation model. *Proceedings of EWEA OFFSHORE 2013*. Frankfurt.

Simple illustration of use of sensitivity analysis for relevant parameters for offshore wind farm O&M.

Andersen, M. A.; Aursand, E. G. (2013). Analyse av kommersielt potensial for NOWIcob. NTNU Technology Transfer AS, Trondheim.

A market feasibility study analysing the commercial potential has been carried out by NTNU Technology Transfer AS. English translation of title: Analysis of commercial potential for NOWIcob.

Software Licence Agreement – Non-Exclusive (2014).

Software license for using the NOWIcob tool.

Hofmann, M., Sperstad I. B. (2014). *Technical documentation of the NOWIcob tool (D5.1-53)*, report no. TR A7374; SINTEF Energy Research, Trondheim.

Technical documentation of model version 3 of NOWIcob. Based on documentation of model version 2 [Hofmann and Sperstad (2012)], but user guide was separated out as a separate report (TR A7372).

Hofmann, M.; Sperstad, I. B. (2014). *Practical user guidelines for the NOWIcob model*, report no. TR A7372, SINTEF Energy Research, Trondheim.

Report prepared within the FAROFF project (SINTEF project no. 12x789).

Sperstad, I. B.; Halvorsen-Weare, E. E.; Hofmann, M.; Nonås, L. M.; Stålhane, M.; Wu, M. (2014). The effects of using multi-parameter wave criteria for accessing wind turbines in strategic maintenance and logistics models for offshore wind farms, *Energy Procedia*, vol. 53, pp. 221–230.

Investigation of the effect of using a single value for the limiting significant wave height vs. more complex wave criteria as the criteria for accessing the turbines for the access vessels.

Hofmann, M.; Sperstad, I. B. (2014). Will 10 MW wind turbines bring down the operation and maintenance cost of offshore wind farms? *Energy Procedia*, vol. 53, pp. 231–238.

Investigation of implications for O&M costs (including the lost revenue due to downtime) of going from 5 MW wind turbines to 10 MW wind turbines.

Netland, Ø.; Sperstad, I. B.; Hofmann, M.; Skavhaug, A. (2014). Cost-benefit evaluation of remote inspection of offshore wind farms by simulating the operation and maintenance phase. *Energy Procedia*, vol. 53, pp. 239–247.

Conference paper on using NOWIcob for cost-benefit analysis of remote inspection of offshore wind farms

Dinwoodie, I.; Endrerud, O.-E. V.; Hofmann, M.; Martin, R.; Sperstad, I. B. (2014): Reference Cases for Verification of Operation and Maintenance Simulation Models for Offshore Wind Farms. *Wind Engineering* (in press).

Article with documentation of the verification process of different offshore wind O&M simulation models (NOWIcob and three other, similar models) by code-to-code comparison, including the definition of reference cases for benchmarking and verification and results from this model comparison.



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