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Report

Technical documentation of version 3.3 of the NOWIcob tool

NOWITECH deliverable DB.1-25

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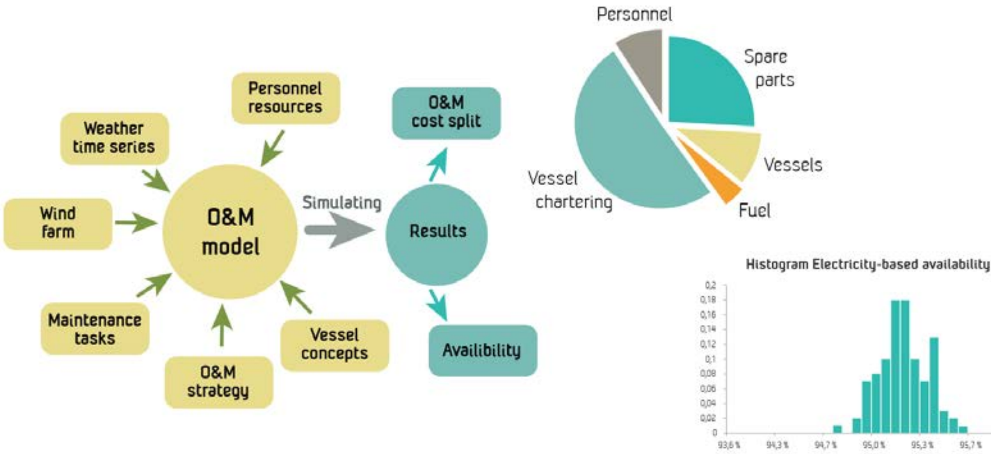

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ABSTRACT

This report describes version 3.3 of the NOWIcob model that has been developed primarily in the research projects NOWITECH, FAROFF and LEANWIND. 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 contains a general introduction to the capabilities of the model and updated descriptions of functionality and the underlying methodology.

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1 Introduction, background and motivation

This report describes the NOWIcob model (**N**orwegian **o**ffshore **wi**nd power life cycle **co**st and **b**enefit model). The model has been developed primarily in NOWITECH[1] WP5/WPB since 2011 as well as in FAROFF[2] since 2012 and in LEANWIND[3] since 2014. Some minor development has also been carried out under a separate support contract through 2015[4]. Chapter 7 provides an overview of what development is carried out under which projects. The descriptions in this report are related to version 3.3 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, Sperstad and Kolstad, 2015). For a more practical user guide, we refer to (Sperstad, Kolstad and Hofmann, 2017). For technical documentation focusing on the data structures of the MATLAB code, we refer to (Sperstad and Kolstad, 2017).

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 chapters (Chapter 2 – 5) explain the main structure of the model and which assumptions and functionalities are included in the model. The purpose of these chapters 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. Chapter 6 describes the activities undertaken to verify and validate the model. Chapter 7 summarises the history of changes made in the model. Finally, Chapter 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. Appendix C is a summary of important assumptions, restrictions and limitations of the NOWIcob model with regards to its domain of applicability.

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[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-founded by the Research Council of Norway

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

[4] Support on offshore wind maintenance and logistics studies, contract between Statkraft, SINTEF Energy Research and MARINTEK.

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 variables". The model combines both, the decision variables 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 decision variables and uncontrollable variables, 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 Monte Carlo iteration (Monte Carlo iteration). Due to the uncertainties, several Monte Carlo iterations 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.

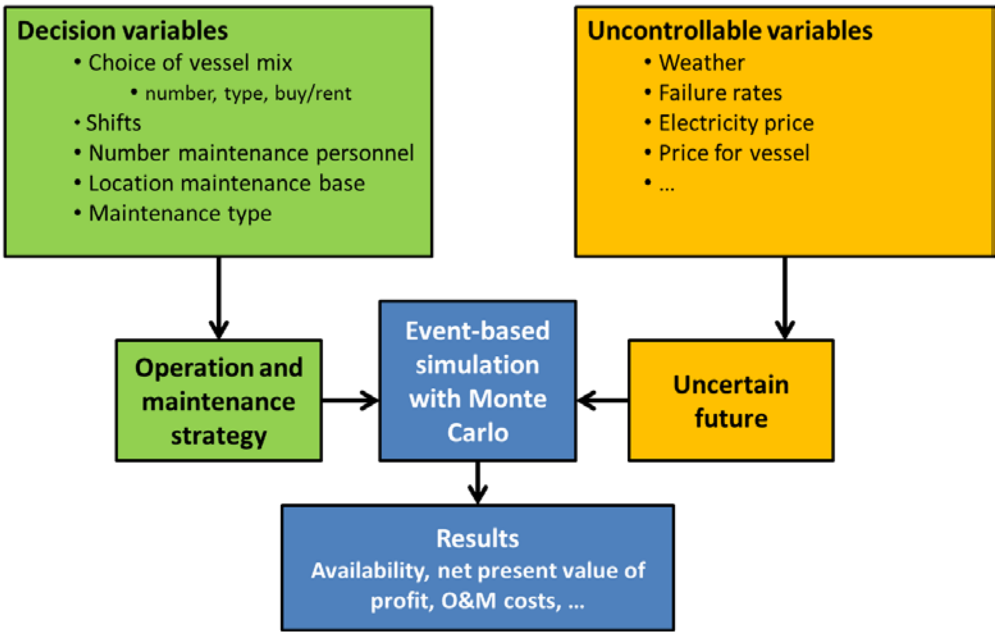

Figure 1. Decision variables and uncontrollable variables.

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.

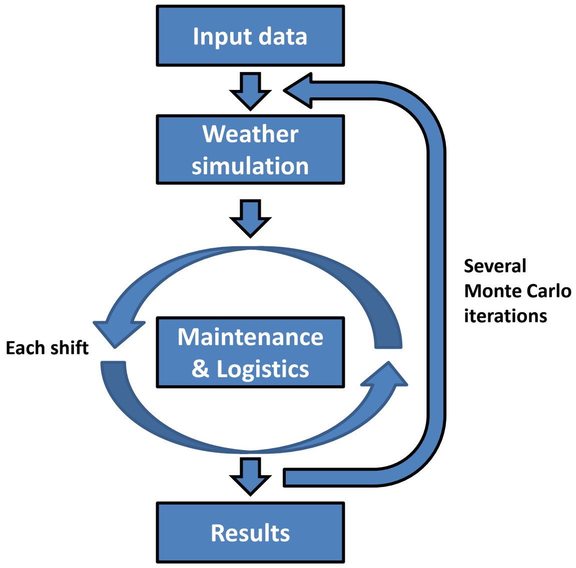

Figure 2. Simplified flow scheme of the model.

First of all, the input data for the specific case are imported and pre-processed. Then, the weather is simulated for each Monte Carlo iteration for the whole lifetime of the wind farm. The core of the model is the maintenance tasks and related logistics that are simulated shift by shift throughout the the pre-defined simulation period. Maintenance is defined as the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain an item in, or restore it to, a state in which it can perform a required function (European Committee for Standardization, 2010). 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 tasks as the maintenance organisation has time for that shift. Although the resulting wind turbine availabilities are calculated with a time resolution 1 hour, the time resolution of the logistics simulation for each shift is less than 1 minute. After all shifts in a Monte Carlo iteration are simulated, the result parameters are calculated. After all Monte Carlo iterations are performed, the results of all Monte Carlo iterations are collected and processed.

4 Input data

This chapter 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.

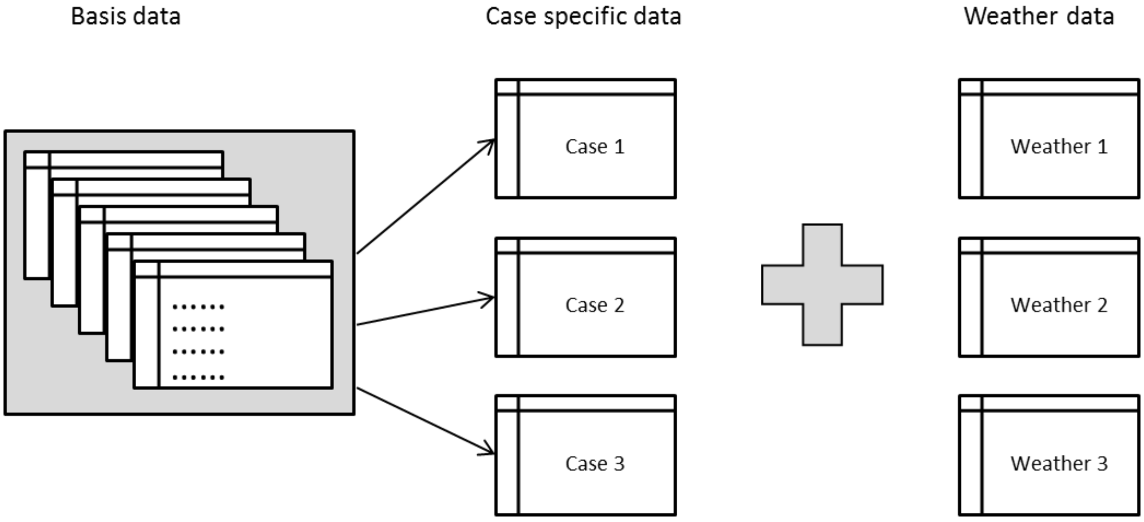

Figure 3. Input files to the model.

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:

- Simulation period in years
- Weather data file as a time series of different weather parameter (at least wind speed and significant wave height)
- Number of Monte Carlo iterations
- 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 technician 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
- Fraction of wind farm production lost if outage (only relevant for power transmitting components such as cables, substation transformers etc.)
  - Alternatively, the average lost production for the wind farm can be specified as a single input parameter

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 Predetermined preventive *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
- Active maintenance time, i.e. the part of the maintenance time when active maintenance is carried out, excluding logistic delays (European Committee for Standardization, 2010)
- Technician access to turbine needed?
  - Logistics time for transferring equipment to the turbine
  - Number of technicians needed for maintenance action
- Pre-inspection needed?
  - Time needed for performing pre-inspection
  - Technician access to turbine needed?
    - Logistics time for transferring equipment to the turbine
    - Number of technicians 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 technicians needed for the ability

Jack-up vessel maintenance action

Maintenance actions that require a jack-up vessel can be specified with up to three operation steps in addition to pre-inspection. Each operation steps may be performed immediately after the previous step. The following input parameters apply:

- Name of the jack-up vessel maintenance action
- Positioning/jack-up phase
  - Name of ability needed for the positioning/jack-up phase
  - Active maintenance time for the positioning/jack-up phase
- Lifting (repair/replacement) phase
  - Name of ability needed for the Lifting (repair/replacement) phase
  - Active maintenance time for the Lifting (repair/replacement) phase
- Separate vessel for technician transfer to turbine needed?
  - Logistics time for transferring equipment to the turbine
  - Number of technicians needed for maintenance action
- Jack-down phase
  - Name of ability needed for the jack-down phase
  - Active maintenance time for the jack-down phase

Predetermined preventive 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 campaign
- Start date (day of the year) for maintenance campaign
- Number of main components scheduled to be serviced each maintenance campaign
- Costs of 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
    - Pre-warning time as days in advance a failure can be discovered
    - When to start planning the condition based maintenance task. Either relative to the pre-warning, or the time of the expected failure.
    - Name of maintenance action to be performed in cases that turns out to be false alarms
    - Costs of spare part / consumables
    - Lead time to provide spare part / consumables
    - Average number of false alarms per year
    - If, and when the turbine is stopped if a potential failure is detected.
    - Does the main component have to be stopped during execution of the maintenance work?
    - Does the condition continue to deteriorate after the turbine is stopped?

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
- Technicians available per shift
- Seasonal dependence of technician availability?
    - Start of the season
    - Stop of the season
    - Technicians available per shift off season

- Yearly fixed cost
- Resupplying of technicians needed? (e.g. location is an offshore platform)
    - Name of the vessel used for resupplying of technicians
    - Name of vessel ability used for resupplying of technicians
    - Days between resupplying of technicians

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
- Does the vessel have to be chartered on demand?
    - Mobilisation time
    - Charter duration
    - Mobilisation cost
- Seasonal dependence of availability?
    - Start season
    - Stop season
    - Available at another base off season?
        - Name of the base (referring to list *Locations*)
- Day rate
- 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
    - Technicians available per shift per vessel
    - Cost per year for transporting technicians to vessel
- Vessel is always offshore?
    - Technicians available per shift per vessel
    - Cost per year for transporting technicians to vessel
    - Resupplying of technicians needed? (e.g. location is an offshore platform)
        - Name of vessel ability used for resupplying of technicians
        - Days between resupplying of technicians
- Shifts the vessel can work (only day shifts, all shifts, 24 hours a day)

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 technicians 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 technicians access a main component?
    - Approaching time before technicians can access the turbine
    - Time for transferring one technician 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 – predetermined preventive
- 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

- 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

- 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

- Maintenance is defined per main component and/or subcomponent
- Three types of maintenance are considered: predetermined preventive, corrective and condition-based maintenance
- Predetermined preventive: defined by start date of the campaign in the year, duration between each campaign and how many components serviced in each campaign.
- 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
  - Detectability: probability to discover a failure before it occurs
  - Pre-warning time: time until the failure occurs
  - False alarms: number of false alarms per year
- The intensity of predetermined preventivemaintenance 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

- A defined maintenance action is assigned to each maintenance task
- One maintenance action can consist of a pre-inspection and the main maintenance operation
- Maintenance actions requiring jack-up vessels can consist of up to three operation steps with individual weather limits.
- For each of this two the following properties can be defined:
  - If access to a structure is needed
  - The time needed for performing the work
  - Number of technicians needed
- Optional extra abilities needed can be specified for the main maintenance task and the technicians 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
  - How many technicians there is space for
  - Fuel consumption (stationary and during traveling)
  - 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 vessel
- 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 (resupplied by a daughter vessel)
- Vessels can be chartered (defined order/mobilisation time and a given charter period and cost)
- Vessels are stationed at freely definable locations
- Different availability of vessels can be specified for two seasons (main season and off season)

Technicians

- Technicians at one location can be used by all vessels based at that location
- Vessels that are offshore for several shifts have their own dedicated technicians
- Mother vessels have their own dedicated technicians that can be used by the daughter vessels and the mother vessel itself
- Technicians can only execute one maintenance task per shift
- Different availability of technicians 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
- Electricity price is defined by a price scenario with monthly resolution

Results

- Energy-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 Monte Carlo approach and stochastic variables

For general background information on the methodology of discrete-event simulation and Monte Carlo, we refer to Banks et al. (1998). The Monte Carlo approach to simulation modelling is to treat some variables in the model as stochastic variables. The model variables that are considered as stochastic in NOWIcob are primarily

- the weather time series, as described in Section 5.2, and
- the times of failures, as described in Section 5.4.1.

In addition, probability distributions can be specified for the following variables:

- Mobilisation time of chartered vessel
- The lead time of spare parts
- The active maintenance time of maintenance tasks
- The pre-warning time for condition-based maintenance tasks.

The input parameters for which this functionality is enabled are also treated as stochastic variables throughout the simulation. It is possible to choose a normal distribution or a triangular distribution.

The Monte Carlo simulation approach implemented in NOWIcob utilizes the Mersenne Twister random number generator (RNG) provided with MATLAB to draw (pseudo-)random numbers for the stochastic variables. At the beginning of each simulation, the RNG is seeded with the default seed (0). This ensures that each time the same case is simulated, the model reproduces the same sequence of random numbers and hence the same results.

5.2 Weather simulation

The simulation of the weather is based on historical weather time series for the wind farm location. The model needs simulated weather time series for each Monte Carlo iteration 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 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 Monte Carlo iteration 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 Sperstad, Kolstad and Hofmann (2017)): 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.) 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.

The user 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.

5.3 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
- Technicians

5.3.1 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. The lead time for spare parts may be set as a fixed value or as a stochastic variable with a normal distribution or a triangular distribution.

5.3.2 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. It is possible to specify up to three abilities, in addition to access ability, for each vessel.

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, they can stay offshore for several days before they come back, or they are considered to always be offshore. It is also possible to specify which shifts the vessels can work: only one shift a day, all shifts (if more than one per day), or 24 hours a day. 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, charter duration and charter cost. After the order time, the vessel is available from the maintenance base as the owned vessels for the predefined charter duration. The order time can be set as a fixed value or be treated stochastically with a normal probability distribution or a triangular probability distribution.

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.

5.3.3 Technicians

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

5.3.4 Resupplying technicians at offshore maintenance bases[5]

Offshore maintenance bases and accommodation vessels will in reality need to resupply, or replace, the technicians staying onboard with regular intervals. This can be represented in the model using an optional functionality that is described briefly in this section. We will refer to both fixed offshore maintenance bases and accommodation vessels as offshore maintenance bases.

[5] This section is to a large degree based on LEANWIND Consortium (2015), chapter 6.3.1.

Fixed offshore maintenance bases can only be resupplied by a vessel having this location as its home port. One can then specify that one of these vessels will carry out the resupply operation at regular intervals. This resupply vessel leaves from the offshore maintenance base to shore with the technicians and come back with new technicians. The pool of technicians where these new technicians are taken from is not modelled explicitly, only how many technicians that are available to work on the offshore maintenance base any given shift. Separate weather limits applying for the resupply operation can be specified for the vessel. The resupply operation is assumed to take an entire working shift, and it is assumed that the weather restrictions must be fulfilled the entire working shift. The resupply intervals can be set in the input data.

If the weather is such that the resupply vessel is successful in resupplying the maintenance base with technicians in the shift where resupply is scheduled, the vessel will be unavailable for performing maintenance tasks the entire shift. If there is only one working shift, we for simplicity assume that all technicians at the offshore maintenance base are replaced the same shift. This means that the number of technicians at the maintenance base this shift will be set to be zero. If there are multiple working shifts, we assume that the technicians working day shifts will be replaced during the night shifts etc., and the number of technicians working will remain unchanged while resupplying takes place. If the resupply vessel is not successful in resupplying in the shift where resupply is scheduled, resupplying is set to be performed the next shift where the resupply vessel is available. This delay is registered as technician overtime as described in Sperstad, Kolstad and Hofmann (2017).

All accommodation vessels can be specified to be carrying out the resupply operation themselves by travelling onshore for one or more days at regular intervals. Mother vessels can also be specified to be resupplied by one of the daughter vessels, with the modelling otherwise as described above. If the mother vessel is working multiple shifts a day, the daughter vessel will be assumed to be working the same shifts.

5.4 Maintenance and logistics

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

5.4.1 Maintenance tasks and failure model

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

- Predetermined preventive
- Corrective
- Condition-based

Predetermined preventive 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 and the associated maintenance task is completed is calculated based on a homogeneous Poisson process (see, e.g., Rausand and Høyland, 2004, Ch. 7.2) 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. More precisely, for each failure category, the time t until the next failure is exponentially distributed with probability density function

$$p(t) = \lambda \, \mathrm{e}^{-\lambda t}. \qquad (1)$$

λ is the time independent hazard rate or failure rate and corresponds to a mean time to failure $\mathrm{MTTF} = 1/\lambda$.

In the simulation, the time to failure (TTF) is generated using the RNG and the formula

$$\text{TTF} = -\frac{1}{\lambda}\ln u, \tag{2}$$

where u is drawn from a uniform distribution between 0 and 1.

Note that λ corresponds to the rate of occurrence of failures (1/MTBF) only if the time to repair is zero (and MTTR = 0)[6]. MTBF and MTTR are abbreviations for mean time between failures and mean time to repair, respectively, and MTBF = MTTF + MTTR (Rausand and Høyland, 2004, p. 367). The simulated rate of occurrence of failures typically also deviates from the expected rate of occurrence (1/MTBF) because a Monte Carlo approach is used in simulating the stochastic failure process. As the number of Monte Carlo iterations goes to infinity, the simulated rate of occurrence of failures approaches the expected rate of occurrence of failures. The deviation decreases when increasing the failure rate, the number of turbines, the length of the simulation period or the number of Monte Carlo iterations.

The time to repair is a function of the dynamics of the simulation for each failure instance, depending on logistic delays, weather delays, etc. In addition, the time to repair depends on the active maintenance time for the given maintenance task, which is defined as an input parameter to the model. Furthermore, the model allows the user to specify a probability distribution for the active maintenance time, either by a normal distribution, or a triangle distribution.

The failure rates can be set to be time-dependent with a yearly resolution, i.e. the hazard rate λ_y varies with the year y but is constant within each year. This allows for modelling failure rates developing over time due to ageing or other effects. In this way, a time-dependent failure rate, e.g. a bathtub curve, can be modelled. If this functionality is used, the time to failure is generated by first calculating the value of the reliability function (Rausand and Høyland, 2004, p. 17) R_y at the end of each year y:

$$R_y = \prod_{y'=y_{\text{current}}}^{N_{\text{years}}} \left(\mathrm{e}^{-\lambda_{y'}\Delta t_{y'}}\right), \tag{3}$$

Here Δt_y is the number of hours remaining of year y and the failure (hazard) rate λ_y is measured in failures per hour.[7] Then, the year that the failure occurs is determined by drawing a uniformly distributed number u between 0 and 1 and finding the year y_{failure} such that

$$R_{y_{\text{failure}}} \leq u < R_{y_{\text{failure}}+1}. \tag{4}$$

Finally, if $y_{\text{failure}} > y_{\text{current}}$, the time to failure is calculated using the formula

$$\text{TTF} = \sum_{y'=y_{\text{current}}}^{y_{\text{failure}}-1} \Delta t_{y'} + \frac{1}{\lambda_{y_{\text{failure}}}}\left(\ln R_{y_{\text{failure}}-1} - \ln u\right). \tag{5}$$

Otherwise, if the failure is occurring in the current year, the formula is the same as in Eq. (1) but with using $\lambda_{y_{\text{current}}}$ instead of λ.

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[6] In the definition of MTTR we use, logistics delays etc. are included. Alternatively, one could have replaced MTTR by the mean downtime, MDT.

[7] In the model, each year is assumed to have 8760 hours.

5.4.2 Condition-based maintenance[8]

Condition-based maintenance is defined in the model as follows. For each failure category (component / failure mode), it can be specified whether condition monitoring is able to give an early warning for a potential failure or not. If so, the overall probability that a potential failure is detected and a warning is given (p_{det}) must be specified, together with the pre-warning time (T_{det}) The pre-warning time is the number of days between the warning and when the failure would have occurred if the warning had not been given. This pre-warning time is an input parameter specified either as a fixed number (average pre-warning time), so that the time available for performing the condition-based maintenance task is always the same, or as a stochastic variable with a normal distribution or a triangular distribution.

Note that p_{det} and T_{det} are dependent on the degradation process $X(t)$ (e.g. fast or slow degradation, linear or exponential degradation, etc.), the inspection strategy (e.g. how frequent inspections are carried out and type of inspection method used). The latter also includes the effectiveness of the inspection method that could be expressed by the Probability Of Detection (POD), which is the probability to detect a flaw of a given size which can develop to a failure (e.g. a crack that can lead to fracture) when the inspection/detection method is applied once. For more information about degradation models and their application in offshore wind O&M modelling we refer to Hofmann, Sperstad and Slimacek (2013) and Welte and Slimacek (2013). Assuming that inspections are carried out according to a schedule with time intervals (τ) between each inspection, and assuming that these intervals are shorter than the time interval between the earliest point in time when the potential failure/flaw can actually be detected and the time when the failure will happen (i.e. the PF-interval, T_{PF}), then T_{det} is shorter than T_{PF}. This is illustrated conceptually in Figure 4 but is not modelled explicitly in the NOWIcob model. This means that the effects of different degradation speed, different inspection intervals and strategies and different detection capabilities of various inspection methods on pre-warning time and overall detection probability must be incorporated in the two values of p_{det} and T_{det}. T_{PF} is the theoretical maximum pre-warning time that can be reached with condition-based maintenance. With continuous monitoring/continuous inspections and a POD of 100% as soon as the potential failure becomes detectable, we could assume $T_{det} = T_{PF}$ and $p_{det} = 100\%$.

[8] This section is to a large degree based on LEANWIND Consortium (2015), chapters 6.4 and 7.2.

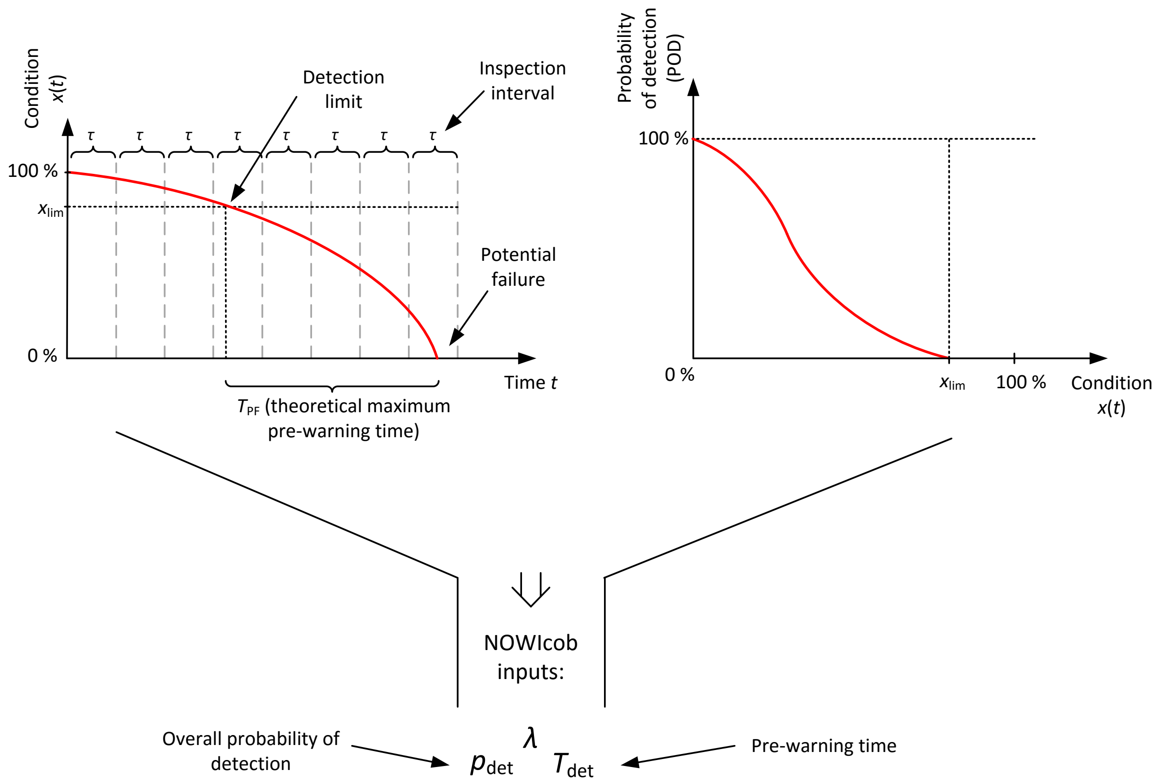

Figure 4. Conceptual illustration of degradation of the condition of a component (left) and the probability of detection of this degradation (right) together with the input parameters representing these processes in the NOWIcob model.

If maintenance can be performed during the time window T_{det}, then a condition-based maintenance task is performed instead of the normal (corrective) task for the failure category. The time to repair T_R, i.e. the time from issue of the pre-warning to completion of the maintenance task, depends on the active maintenance time for the task in question plus logistic delays, including weather delays. The active maintenance time is defined as a model input parameter, whereas logistic delays are calculated during the simulation of each maintenance task. For each potential failure in the model, one can either have that $T_R < T_{det}$ so that one has time for performing condition-based maintenance before failure occurs, or one can have that $T_R > T_{det}$. Different alternatives are included in the model if it turns out that a condition-based maintenance task will not be completed in time. This is illustrated in Figure 5. If the potential failure is not detected at all, this will also lead to failure and a corrective maintenance task.

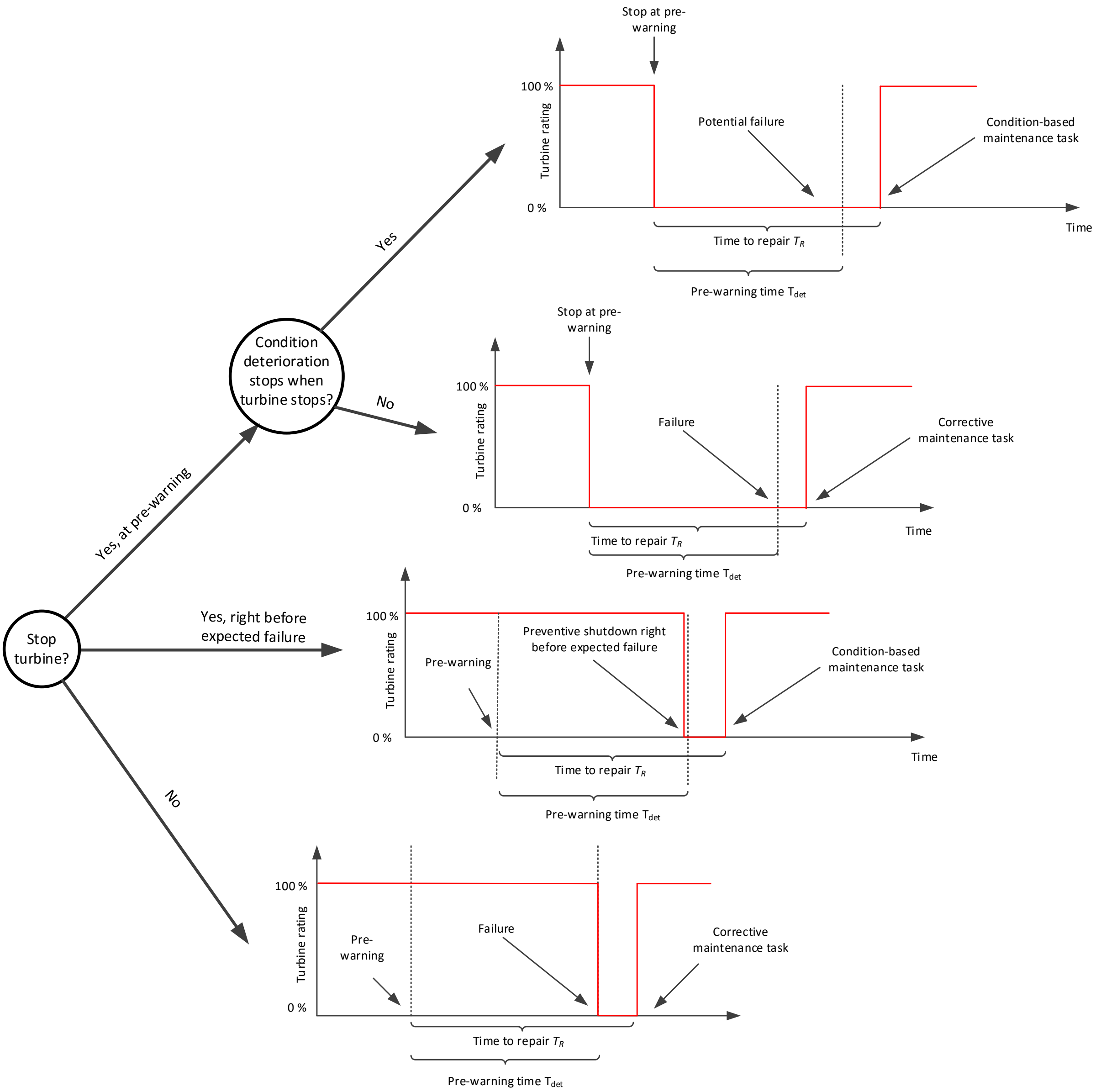

Figure 5. Possible options of condition monitoring if $T_R > T_{det}$.

The model includes two different options for when to start planning the condition-based maintenance task, e.g. start scheduling vessels to go offshore. The condition-based maintenance action can either be scheduled a given number of days after the pre-warning or a given number of days before the potential failure is expected to occur.

The repair costs, technician man-hour requirements, vessel requirements etc. can be specified to be different for the corrective maintenance task and the condition-based maintenance task. In addition to specifying the corrective and condition-based maintenance tasks, the user can also specify maintenance tasks for false alarms. This means that a number of false alarms are expected to occur due to the use of a given sensor or condition monitoring system. The times when such false alarms occur are stochastic and also generated with a Poisson process as described in Section 5.4.1. Pre-inspection operation step following detection of potential failures are not illustrated in Figure 5.

To summarize, repeated inspections or continuous condition monitoring is not modelled explicitly, hence the implication of different inspection intervals cannot be represented explicitly. Furthermore, component degradation and probability of detection are not modelled explicitly. When using the simulation model, the aspects mentioned above must be translated into the two parameters p_{det} and T_{det} (cf. Figure 4). This means that the effects of different degradation speed, different inspection intervals and strategies and different detection capabilities of various inspection methods on pre-warning time and overall detection probability must be incorporated in the two values of p_{det} and T_{det}. See also Welte et al. (2017b) for further discussion. Another simplification in the modelling is that the repair costs and resource requirements for the repair operation in reality would depend on the condition.

5.4.3 Predetermined preventive maintenance

Predetermined preventive maintenance tasks are specified to occur based on a time schedule during predetermined campaign periods, e.g. annual service of the wind turbines. As described by Sperstad, Kolstad and Hofmann (2017), the schedule of these preventive maintenance campaigns is specified by the following parameters.

- *Maintenance campaign interval* [years]: Time interval between each maintenance campaign of that type
- *Start date* [dd.mm.]: The date of the year that one starts to schedule this type of preventive maintenance tasks
- *Main components per maintenance campaign:* The number of components one schedules to maintain each maintenance campaign. (Default is that all main components of that type of main components are scheduled each maintenance campaign.)

How the schedules are determined in the model based on these parameters is illustrated below for three simple examples. For all the examples, it is assumed that there are six main components (i.e. turbines) in the wind farm. Figure 6 illustrates annual service campaigns for these main components starting the 1st of May each year, i.e. *maintenance campaign interval* = 1 year and *start date* = 01.05. For the case illustrated in Figure 7, there is still one maintenance campaign per year, but each main component is maintained only every second year; here *maintenance campaign interval* = 1 year, *start date* = 01.05., and *main components per maintenance campaign* = 3. For the third example, Figure 8 illustrates a case where the main component is maintained annually but half of the components are maintained during a spring campaign and the other half is maintained during an autumn campaign. For this case, *maintenance campaign interval* = 0.5 year, *start date* = 15.03., and *main components per maintenance campaign* = 3.

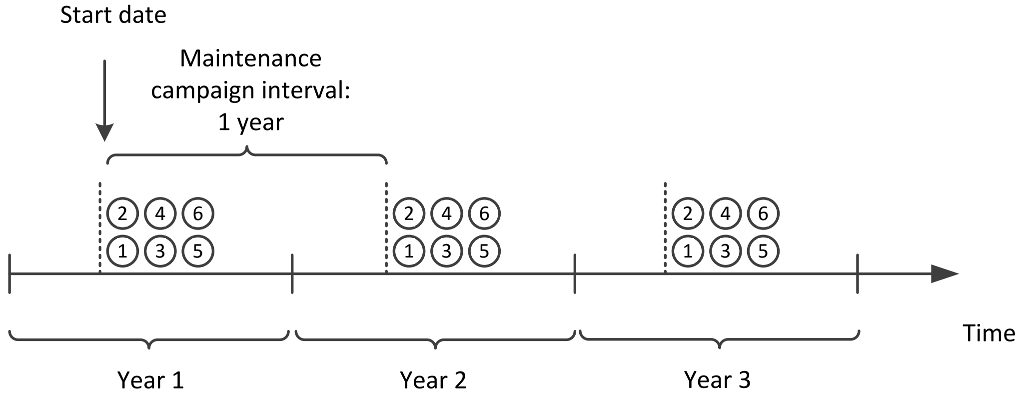

Figure 6. Illustration of pre-determined preventive maintenance campaigns for *maintenance campaign interval* = 1 year and *start date* = 01.05.

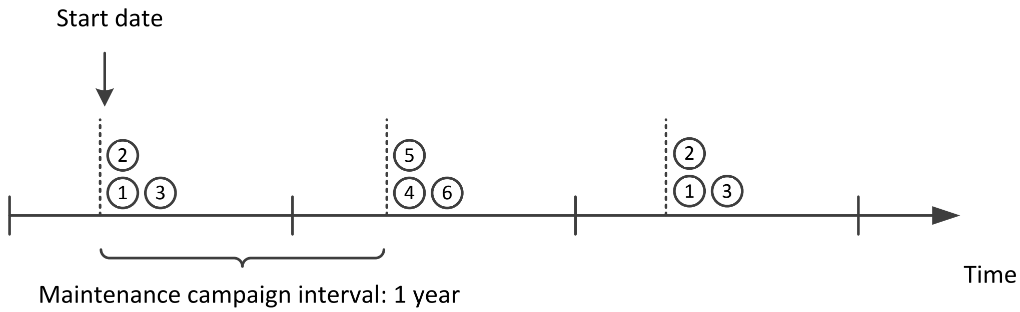

Figure 7. Illustration of pre-determined preventive maintenance campaigns for *maintenance campaign interval* = 1 year, *start date* = 01.05., and *main components per maintenance campaign* = 3.

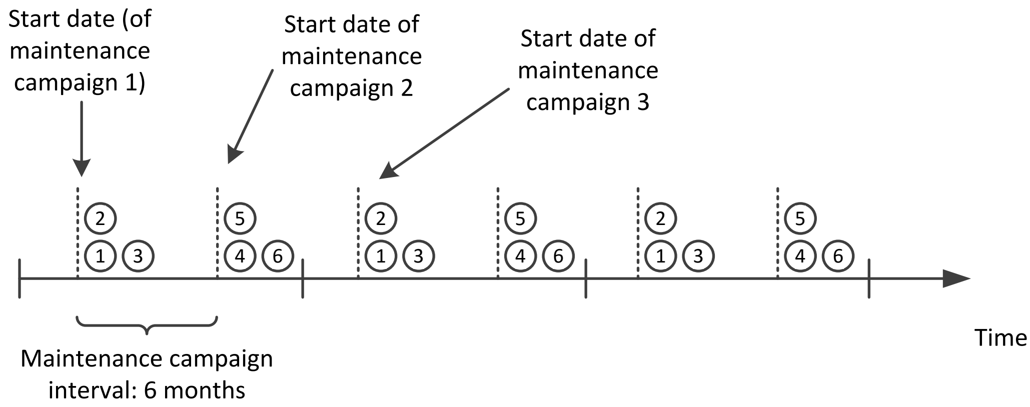

Figure 8. Illustration of pre-determined preventive maintenance campaigns for *maintenance campaign interval* = 0.5 year, *start date* = 15.03., and *main components per maintenance campaign* = 3.

5.4.4 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 in the following order:

1. Whether the turbine is stopped at failure or alarm
2. Type of maintenance task:
    i. Corrective maintenance is given the highest priority,
    ii. then condition-based maintenance,
    iii. and then predetermined preventive maintenance.
3. 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.
4. 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 Sperstad, Kolstad and Hofmann (2017) 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). If a maintenance task can be completed during the shift for any of the vessels, the model will prioritise to use vessels that are already assigned to a maintenance task in the wind farm even if no fuel costs are specified. Conversely, the model will prioritise to distribute maintenance tasks and technicians on several vessels if this allows more maintenance to be done in the shift.

5.4.5 Logistics during the execution of a maintenance task

All scheduling of the maintenance tasks executed in a shift is done by the model at the beginning of the shift. If new maintenance tasks have to be executed, the model checks if technicians, 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. Vessels are assigned to maintenance tasks and technicians for each task are assigned to access vessels during task scheduling as specified in Section 5.4.3.

It is possible to work with a maintenance task over several shifts, if it cannot be finished in one shift. Then the technicians 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 sequentially. If a vessel serves several maintenance tasks in one shift, the travel in the wind farm is considered as illustrated in Figure 9.

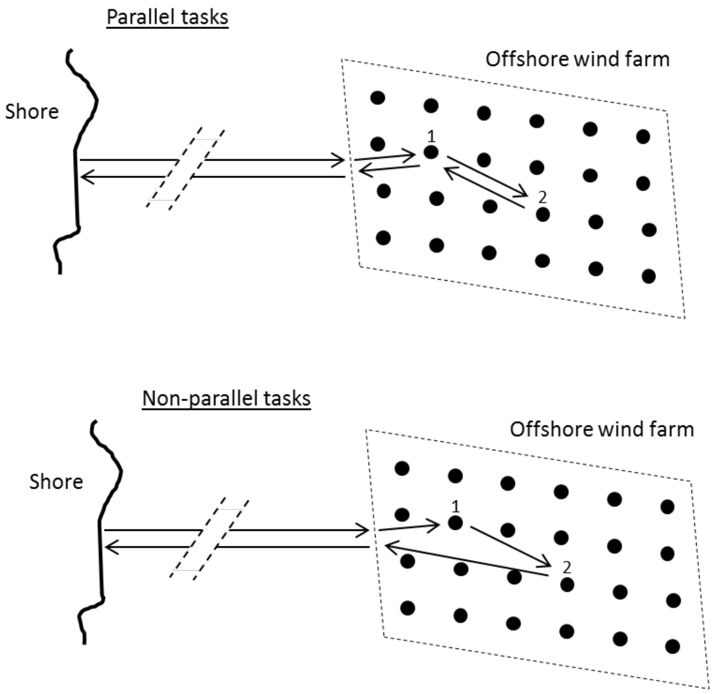

Figure 9. Travel time in wind farm for several tasks.

The model does not consider an optimized travel route and is based on the simplification that an access vessel will pick up the technicians 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.

Access vessels, i.e. crew transfer vessels or other vessels transferring technicians to wind turbines, can serve several maintenance tasks in parallel. Figure 10 illustrates an access vessel serving one and two maintenance task in one shift. If the access vessel is serving two maintenance tasks in one shift the vessel has to travel out to the wind farm, travel within the wind farm to the location of the first task and then transfer the technicians onto the structure. These technicians will be picked up again at the latest possible moment. In this example, this will be right before the weather window ends. Otherwise, it would be at the end of a shift. The access vessel then travels to the second maintenance task, while the technicians are working on the first turbine. Also these technicians 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 technicians are picked up right away after the work is finished and first then the transport to the next maintenance task will be done.

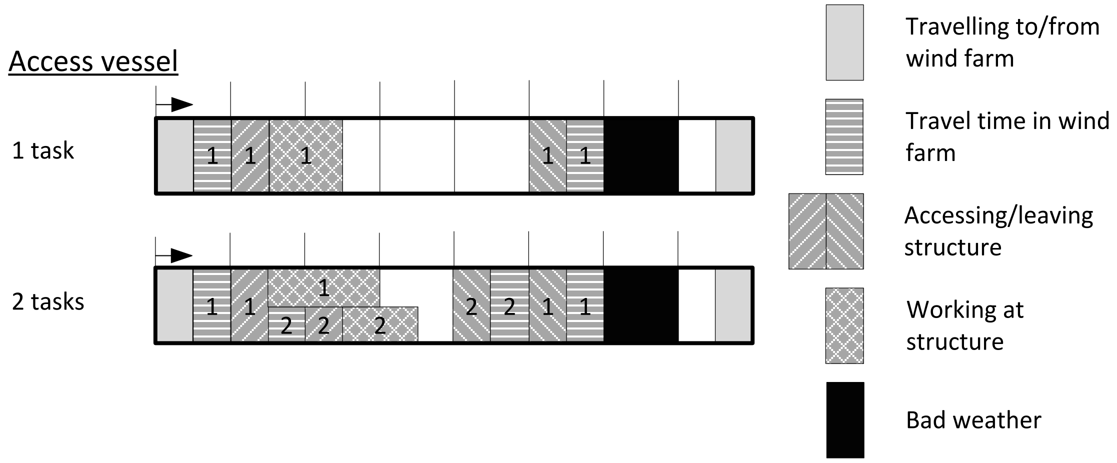

Figure 10. Example of scheduling of one and two maintenance tasks, requiring access, in one shift.

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. The user interface limits the number of possible subtasks to 2: One main operation step and one optional pre-inspection operation step. One exception is for maintenance tasks requiring jack-up, where one maintenance task can consist of three operation steps and the operation steps may follow immediately after each other (see Chapter 5.4.6).

5.4.6 Maintenance tasks requiring jack-up vessels

Jack-up vessels can only serve one maintenance task at a time. Maintenance actions requiring jack-up vessels can be modelled with up to three different operation steps. This is illustrated in Figure 11. In this example the three operation steps are called "Positioning / jack-up", "Lifting", and "Jack-down". Each operation step may have different weather limits. First the jack-up vessel travels to the right location before it starts on the positioning and jack-up phase of the operation, followed by the lifting phase and finally the jack-down phase. Each operation step may follow immediately after the previous. In the example Figure 11 it is assumed that the jack-up vessel is stationed in the wind farm and that the task is completed in one shift. It is possible to work on a task for several shifts if the task is not completed in one shift. Jack-up vessels can also be set to work 24 hours a day. Once the jack-up vessel has completed all operation steps in a maintenance task it is available to travel to the next location.

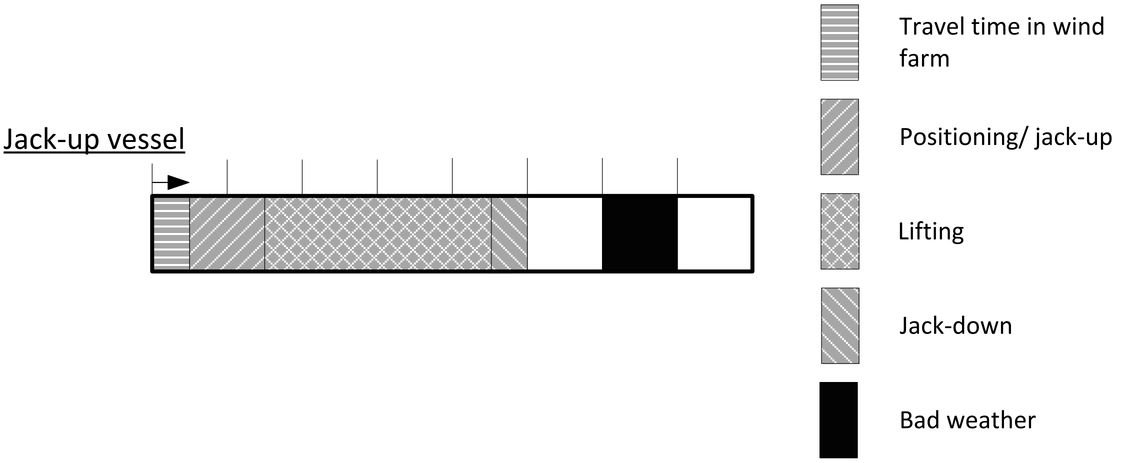

Figure 11. Example of maintenance task requiring jack-up.

5.4.7 Vessel transit time

The travel time for the vessels to/from the wind farm, and within the wind farm, are calculated based on the vessels traveling speed, the distance between the maintenance base and the wind farm, and the average distance between wind turbines in the wind farm. The model distinguishes between the average distance between turbines for planned (preventive) maintenance tasks and unplanned (corrective) maintenance tasks as it is assumed that planned maintenance task are scheduled for neighbouring turbines for the same shift.

5.4.8 Access and transfer time

The weather limits determining whether or not it is possible to access a turbine is set in the same way as for other vessel abilities, and is described in Chapter 4.1. If the metocean conditions are such that the turbines are accessible, the transfer of technicians and equipment from the access vessel to the turbine is modelled with the following, deterministic transfer time:

$$\begin{aligned}\text{Transfer time} = \ & \text{Approach time} \\ & + \text{Transfer time per tech.} \times \text{Number of techs.} \\ & + \text{Logistics time},\end{aligned} \quad (6)$$

Here, the approach time is the time from the access vessel is in the vicinity of the wind turbine to when it is ready for technician transfer. The logistics time is the time needed for lifting equipment and spare parts from the vessel to the turbine transition piece. The approach time and transfer time per technician are properties of the access vessel whereas the lifting time is a property of the maintenance task.

5.4.9 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 12.

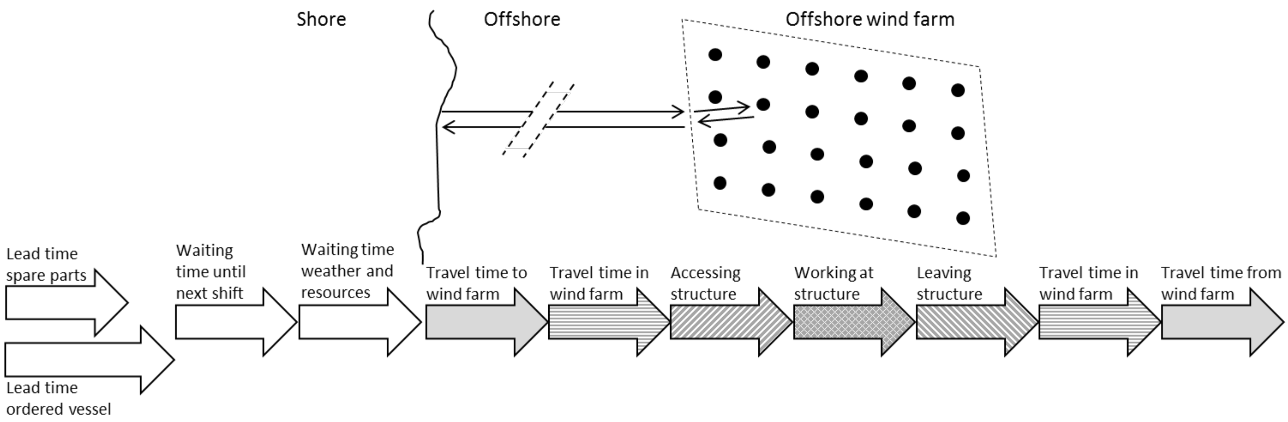

Figure 12. Time used for performing maintenance activities.

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 technicians 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 technicians 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 failure / Stop turbine at pre-warning**
   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 technicians 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 technicians 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 active maintenance**
   The component is stopped when technicians 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 10 and Figure 11.

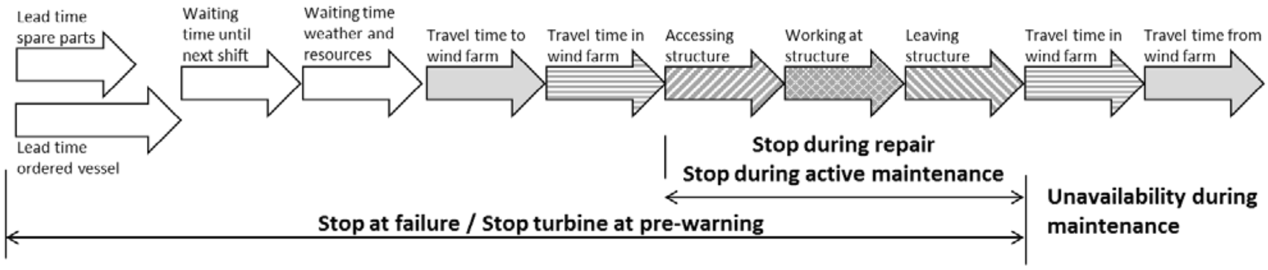

Figure 13. Unavailability of maintained components for different component down time options.

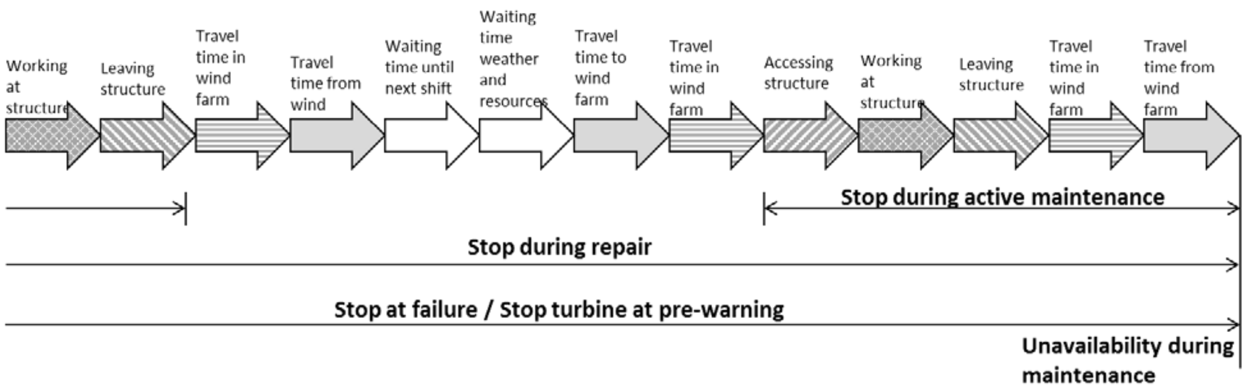

Figure 14. Unavailability of maintained component for different down time settings if maintenance task is not finished in one shift.

5.5 Result calculation

The results delivered by the model include histograms (as discrete estimates of probability distributions) of several performance parameters. The results are saved in an Excel file for all Monte Carlo iterations. Figure 15 shows an example of such a probability distribution. The performance parameters calculated by the model are:

- Availability (time and energy 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. More detailed results for the utilization of vessels and technicians and the break-down of contributions to unavailability is available in separate results spreadsheet, and we refer to Sperstad, Kolstad and Hofmann (2017) for more detailed explanation.

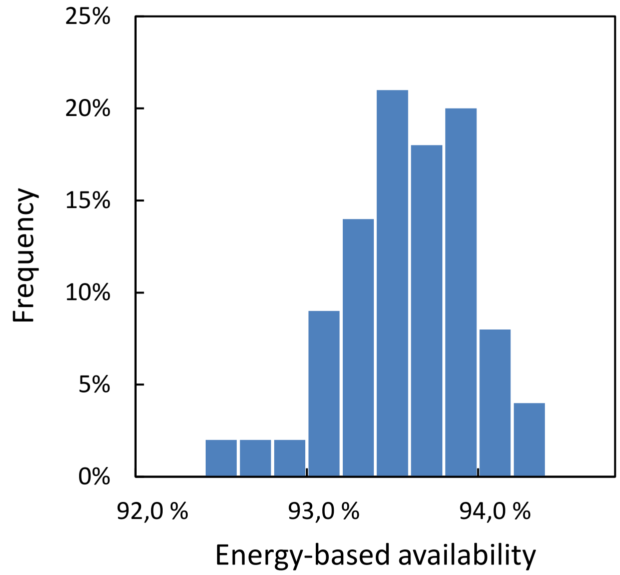

Figure 15. Example for probability distribution of the availability.

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

Time-based availability 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 or above the cut-out 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 (2011).

Energy-based availability, on the other hand, is calculated based on the real and theoretical possible electricity production. Table 1 below defines both measures of availability more precisely. For more detailed discussion of energy-based or production-based measures of wind turbine availability, we refer to the standard IEC TS 61400-26-1 (International Electrotechnical Commission, 2014). Because the definition of energy-based availability given below was implemented in the model prior to the publication of this standard, we give no guarantee that this implementation conforms entirely with this standard. Note also 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. Also note that for wind farms with multiple turbine types with different rated power, the average time-based availability of the wind farm is calculated by weighting the contribution from each turbine by its rated power. (This is not shown in Table 1 to avoid complicating the formula.)

Table 1. Definitions of availability.

Availability (time based)	Availability (energy based)
$$A_{\text{time}} = \frac{T_{\text{lifetime}} - T_{\text{downtime}}}{T_{\text{lifetime}}} \times A_{\text{trans}}$$	$$A_{\text{el}} = \frac{E_{\text{real}}}{E_{\text{theor}} \times (1 - \text{Loss}_{\text{wake}}) \times (1 - \text{Loss}_{\text{el}})}$$
T_{lifetime} – Lifetime of the wind turbine (e.g.20 years) T_{downtime} – Downtime of the wind turbine due to failures and services A_{trans} – Time-based availability of main components that transport/transform electricity	E_{real} – Produced electricity considering downtime of the wind turbines and electrical infrastructure, wake losses and electrical losses E_{theor} – Theoretical possible electricity production with 100% availability, taking into account wind speeds and power curves but neglecting any losses

Electricity production

The electricity production, E_{real}, is used when calculating the energy-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. Losses due to downtime of the electrical infrastructure can be modelled in two ways, and we first describe the simplest (default) alternative in which these losses are modelled by a single user-specified loss factor $(1 - A_{\text{trans}})$. Based on these assumptions, the equation for calculating the electricity production for all time steps *t* (here considering downtime) is as follows:

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

$E_{\text{theor},j,t}$	–	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*
$A_{\text{turbine},j,t}$	–	Availability of wind turbine *j* at time step *t*
A_{trans}		Time-based availability of main components that transport/transform electricity
$\text{Loss}_{\text{wake}}$	–	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 = years × 365 × 24
n	–	Number of wind turbines in the wind farm

Alternatively, lost production due to downtime of electrical infrastructure can be modelled in a more detailed, bottom-up manner by specifying electrical infrastructure components associated with failure categories and corresponding maintenance tasks and the fraction of the wind farm production that is lost during outage of the component. For each of these components, henceforth referred to as transmitting components, the availability can thus be calculated for each time step in the same manner as for the wind turbines. For this alternative, the electricity production, considering downtime of both turbines and transmitting components, is calculated using the following approximation:

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

$$A_{\text{trans},t} = \bar{A}_{\text{trans},1,t}\times \ldots\times\bar{A}_{\text{trans},m,t}$$

$$\bar{A}_{\text{trans},l,t} = 1 - f_l\times(1 - A_{\text{trans},l,t})$$

$A_{\text{trans},t}$	–	Approximate average availability of electrical infrastructure at time step t
$A_{\text{trans},l,t}$	–	Availability (0 or 1) of transmitting component l at time step t
f_l	–	Fraction of the average wind farm production that is lost during downtime of transmitting component l
$\bar{A}_{\text{trans},l,t}$	–	Effective availability (0 to 1) of transmitting component l at time step t, accounting for the average fraction of wind farm production lost
m	–	Number of transmitting components in the wind farm

This approximation assumes a radial topology of the electrical infrastructure in which transmitting components of different types are connected in series, as illustrated by an example in Figure 16. Furthermore, it does not account for how the individual wind turbines and the individual transmitting components are connected. Although still a relatively crude simplification, this approximation is nevertheless more accurate than modelling the availability of the electrical infrastructure by a single factor: It captures the time dependence of the availability of transmitting components and it is exact for a time step in the case that all wind turbines are available and only one transmission component of each type is down at a time.

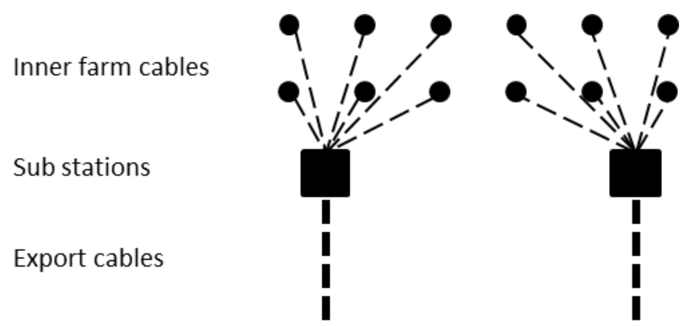

Figure 16. Example of assumed layout for electrical infrastructure in the model.

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.

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

I_{abs}	–	Absolute income from electricity production
$E_{real,m}$	–	Sum of produced electricity in month *m*
P_{el}	–	Electricity price in month *m*

Net present value of lost income due to downtime

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

I_{lost}	–	Lost income due to downtime of the wind farm
$E_{theor,m}$	–	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 technicians to a mother vessel (yearly fixed costs)
- Vessel fuel cost (variable)
- Vessel charter costs
- Technician 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 technicians 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):

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

5.5.1 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 technician 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 originally consisted of participants from SINTEF Energy Research, MARINTEK (now SINTEF Ocean), 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. A paper based on this analysis and the code-to-code-comparison process leading up to it has been published by Dinwoodie et al. (2015). This publication also includes documentation of the offshore wind farm reference cases that were defined in the process. 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.

As a spin-off activity from the offshore wind O&M modelling group, a detailed comparison between NOWIcob and the ECN O&M Tool was also carried out together with NREL within the framework of IEA Wind Task 26 ("Cost of Wind Energy"). In this comparison, the tools were applied for the estimation of levelised cost of energy (LCOE) contributions for a reference wind farm. This reference wind farm can be regarded as an extension of the reference cases published in Dinwoodie et al. (2015) and includes more details and explanations. The documentation of the reference wind farm and the code-to-code comparison was published as an IEA Wind report (Smart et al., 2016).

In the offshore wind O&M modelling group, work has also been carried out on the use of simulation models such as NOWIcob for optimizing the O&M vessel fleet. Throughout 2014 and 2015, the four models mentioned above were compared with an offshore wind fleet size and mix optimisation model developed by MARINTEK (Stålhane, Halvorsen-Weare and Nonås, 2015) and the ECN O&M Tool (Obdam, Braam and Rademakers, 2011) for a number of cases with different types and numbers of access vessels. A paper based on this analysis has since been published by Sperstad et al. (2017).

One characteristic of the NOWIcob model that has been identified in the activities described above 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 other models, they are also consistently slightly above the average. Consequently, compared to other models, the NOWIcob model may in some cases find fewer and/or less advanced vessels to be the preferred vessel fleets. 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 with regards to the model features relevant for the reference cases. 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 values are specified for very few of the optional parameters and that 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 values are specified for all parameters. 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 has been 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).
NOWIcob_base_case	Updated reference case representative of conventional offshore wind farms based on LEANWIND Consortium (2015) and Smart et al. (2016); recommended starting point (base case) for setting up a case in NOWIcob.
NOWIcob_base_case_ JU_campaigns	Variation of NOWIcob base case assuming a pre-determined campaign period jack-up vessel charter strategy instead of a charter-on-demand strategy.

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, i.e. calculating the same quantity in different ways. 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.
- Visualisation of the logistics activities carried out within each shift as they are represented by the model.
- For each newly implemented model feature, test cases are prepared to verify that the influence on the result of enabling the functionality is reasonable. All such test results are documented in a memo.

- 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 the same techniques and tests are sometimes 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.

During 2015, a verification and validation activity has been carried out in NOWITECH which included a model validation workshop together with NOWITECH partners. In parallel, a model validation workshop was also arranged in the LEANWIND partners involving external industrial partners. A result of this verification and validation activity is a summary of important assumptions, restrictions and limitations of the NOWIcob model which has been adapted to an Appendix C of the present report. This appendix and the updated version of the present chapter comprises the NOWITECH deliverable DB.1-3, which reports on the verification and validation activity.

As described in Chapter 8, the NOWIcob model has since 2014 been licensed to a number of industrial partners. The application of the model by these partners has led to valuable feedback for the continued validation of the model. The model has also been applied to real wind farm projects in collaboration with industrial partners more specifically for validation purposes. Through these cases, the applicability and accuracy of NOWIcob and other O&M models developed in NOWITECH have been tested and improvements have been made accordingly. (See Welte et al. (2017a) for more information about the other NOWITECH O&M models.) However, validation is a continuous process, and in practice one can never expect any model to be validated absolutely (Sargent, 2013). Although some existing models are reported to have been validated against other models or against historical data to some extent, it is often hard to ascertain their domain of validity. That is, if the models are used to represent different features of wind farm projects than those they have been validated against, it is hard to know whether models still produce valid and accurate results

Dedicated validation collaborations include 1) a case study carried out by a European wind farm operator and 2) an activity related to the LEANWIND project together with SINTEF Ocean and offshore wind developers/owners/operators ScottishPower and Iberdrola.

Insights obtained through the former (1) include:

- An unambiguous user interface is very important for ensuring that the user represents the cases she/he intends to study in a reasonable manner.
- NOWIcob is less well suited for studying tactical problems such as investigating the detailed maintenance logistics during a particular summer campaign. (Some improvements in the representation of such campaigns were subsequently introduced for v.3.3 of the model, however.) Clear information to the user about the domain of applicability is therefore important, cf. Appendix C.

In the latter model validation collaboration (2), the NOWIcob model was benchmarked with the O&M modelling tool used by the offshore wind farm developer for the application of estimating energy-based wind farm availability (with some key sensitivities) for a real wind farm project. Based on these comparisons and discussions with O&M experts within the collaboration, the following findings and conclusions were made regarding the validity of NOWIcob:

- The two models broadly agree on sensitivities but agree to a less extent on the absolute values of the availability.
- Differences in how the jack-up vessel charter strategy is modelled was identified as the likely reason behind the majority of the difference between the two models. (None of the models were identified as having generally more reasonable modelling assumptions than the other.)
- The relatively high level of detail of NOWIcob's modelling of logistic delays within the wind farm was identified as another source of discrepancy. However, the impact of different modelling assumptions is case dependent, and accurate modelling of vessel travel within the wind farm is likely to be even more important for larger wind farms.
- To understand reasons for model discrepancies, investigating the downtime breakdown is seen to be very useful. However, it was shown how an unambiguous one-to-one comparison between models is challenging due to different definitions of downtime categories. Such comparisons must also be carried out with additional caution because only an approximate break-down of the downtime is generated by NOWIcob.
- As models have different strengths and weaknesses, it has proven useful to be able to use multiple models to assess the expected availability of an offshore wind farm project and understand sensitivities. Using multiple models may also increase the insight into uncertainties due to modelling assumptions and into the domain of validity of different models.

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. As mentioned in Chapter 1, these functionalities are developed through a number of different projects. Therefore we also show in Table 3 an overview over which projects different functionalities of the model is developed through. For a brief description of the projects, we refer to the footnotes in Chapter 1.

Table 3. Overview over which projects different functionalities of the model is developed through.

Project	Functionality	Year(s) of development
NOWITECH	Core model functionality, verification and validation, general code maintenance and documentation	2011–2017
FAROFF	Multi-parameter weather model, access modelling, automatic sensitivity analysis, detailed results spreadsheets, user interface, detailed results spreadsheets	2012–2013
LEANWIND	Economic sensitivity analysis, downtime options for maintenance tasks, shift options for vessels, jack-up vessel maintenance actions, stochastic input parameters, more detailed modelling of condition-based and pre-determined preventive maintenance tasks.	2014–2017
Support contract	Resupplying of offshore maintenance bases, result output for time-dependence of energy-based availability and yearly technician utilization	2015

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). 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 vessel and technician utilization
- Calculation and output of O&M cost split and break-down of downtime
- 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 predetermined preventive 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.

7.3 Changes in version 3.2

Version 3.2 of the NOWIcob model released in December 2015 corresponds to the LEANWIND O&M strategy model that is part of the LEANWIND deliverable D4.2. The following functionalities have been added during 2015 for the release of model version 3.2:

- Improved modelling of maintenance tasks requiring jack-up vessels. Jack-up vessel maintenance actions can now be modelled with up to three different operation phases (not including pre-inspection). This makes it possible to specify different weather limits, for the positioning/jack-up phase, lifting phase, and the jack-down phase. Each operation step may follow immediately after the previous.
- More detailed modelling of shift structure and vessel ability. It is now possible to determine which shift a vessel is able to work. Three options are available: only day shifts (only the first shift of the day if there are several shifts), all shifts, and 24 hours a day. This allows for detailed modelling of different vessel concepts, and significantly improves modelling of chartered vessels typically working 24 hours a day, e.g. jack-up vessels.
- Added functionality for stochastic treatment of several input variables. It is now possible to specify the mobilisation time for chartered vessels, lead time for spare parts, active maintenance time for maintenance tasks, and pre-warning time for condition-based maintenance tasks with a probability distribution. Either a normal distribution or a triangular distribution can be chosen. Implementing functionality for resupplying offshore maintenance bases and mother vessels.
- Added prioritisation option "Prioritise maintenance tasks that stop the turbine" in the input field "Prioritisation of maintenance tasks" in input spreadsheet "1".
- Also the time-dependence of energy-based availability is plotted in results spreadsheet "Results - availability".

Changes in the model and bug fixes made from version 3.1 to version 3.2 that may affect the results:

- Simplification of the algorithm for chartering vessels (in conjunction with implementing new, optional modelling of jack-up vessel operations) can cause slight differences in results due to the modelling of precisely when chartered vessels will be available in the wind farm.
- Fixed bug that in some cases resulted in overestimation of weather delays: If weather conditions in a given shift prevent a vessel from carrying out work at a maintenance task, the vessel could wait one more shift than necessary before attempting again. The bug could have resulted in pessimistic weather delays for harsh weather conditions.
- Implementing correction of weather modelling to correct for inaccuracy due to the weather criteria being compared with binned weather parameters values (since weather states are discrete). The correction takes the binning into account so that weather criteria are now compared with the original weather parameter values (if using historic weather time series, or approximating continuous weather states if using synthetic weather time series). Previous model versions may have given somewhat optimistic results with respect to weather criteria, corresponding to an increase of the limiting significant wave height value of approximately 5 cm.
- Including electrical infrastructure availability in time-dependent time-based availability and fixed error in weighted average over months for yearly average (fixing discrepancy to result spreadsheet "Results – availability").
- Fixed bug that caused power curves to be zero for all wind speeds if not a value for zero wind speed were given in power curves data in Input_basis.xlsx.
- Fixed errors in setting seasonality of technician and vessel availability:
    - Bug which results in making the season stop one day before it should
    - Error making the seasons for all years come continuously (in sequence) if there are multiple years instead of being spread across the years. This only affected the vessel travel times if different home ports were used for different seasons.

7.4 Changes in version 3.3

The following functionalities have been added during 2016 and the first half of 2017 for the release of model version 3.3 in October 2017:

- Functionality to make it possible to choose when to initiate condition-based maintenance task relative to the pre-warning time or relative to the time of expected failure. (Three new input parameters were added for the table for condition-based maintenance.)
- Detailed bottom-up modelling (i.e. as failure categories with associated maintenance tasks) implemented for lost production due to downtime of electrical infrastructure.
- Improved functionality for predetermined preventive maintenance scheduling, as described in Section 5.4.3: support for multiple campaign periods per year and support for distributing components over different campaign periods.
- Improved functionality for time-dependent failure rates, as described in Section 5.4.1. This removes previous inaccuracies when the failure rate per turbine per year was $\ll 1$.
- NOWIcob is integrated in the LEANWIND financial model, where NOWIcob forms the OPEX module. See (Sperstad, Kolstad and Hofmann, 2017) for more details on running NOWIcob as part of the LEANWIND financial model.

Changes in the model and bug fixes made from version 3.2 to version 3.3 that may affect the results:

- Added fix to prevent travel time within wind farm from being added for every shift for jack-up vessels that are fixed to a turbine and has worked there also the previous shift.
- Change for condition-based task with pre-inspection where turbine is shut down when work starts: Now turbine will start up again between shifts during pre-inspection and start up again after pre-inspection is completed.
- A condition-based task including pre-inspection now is "transformed" to a corrective maintenance if one gets time to start the pre-inspection before the time of potential failure but one does not get time to start the subsequent main part of the maintenance task. (Previously it was enough to have started the pre-inspection to avoid having the condition-based maintenance being "transformed" to corrective maintenance.) Fixed bug that caused inaccuracy in calculation of availability and downtime break-down for maintenance tasks where turbine should be stopped when work starts and remains off until work is completed.
- Made various fixes for bugs causing inaccuracies in the calculation of availability and downtime break-down for condition-based maintenance tasks.
- Hard-coded the number of predetermined preventive maintenance tasks of a failure category to be scheduled per shift to 8 as this input parameter was removed from the case input spreadsheet.
- Fixed bug when running NOWIcob as the OPEX module of the LEANWIND financial model: Estimates for all but the last Monte Carlo iteration for the output parameters were overwritten during the simulation before the output was written to OPEX_Output.xlsm.

8 Development and application of the NOWIcob model: retrospective and outlook

This chapter gives a retrospective summary of the development and application of the NOWIcob model together with some perspectives on future research work on offshore wind O&M modelling. Applications from the perspective of validation has already been described in Chapter 6.3, and possible applications of O&M models more generally in the context of NOWITECH are also discussed by Welte et al. (2017a). The number and maturity of O&M models has increased substantially since the development of NOWIcob started in 2011, and for an updated state of the art description we refer to Welte et al. (2017a).

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 use the model for their analyses. Although user licenses were primarily granted to partners of the research projects contributing to funding the development of NOWIcob, licenses have since also been granted for collaborations of mutual interest for the licensee and SINTEF Energy Research. The license agreement does not give access to the source code of the model but only to using an executable version.

At the time of writing, a total of 13 licenses have been granted to the following parties:

- NOWITECH partners (four user licenses granted: Statkraft, Statoil, Kongsberg, DNV GL)
- LEANWIND partners (two user licenses)
- European offshore wind farm operator (one user license, granted to a student intern)
- European research institute (one user license for non-commercial use for a specific project)
- European consultancy (one user license for a test version)
- Norwegian master students (two user licenses, but more students have used the model for their master thesis, cf. Appendix B, as the license agreement was prepared at a later point in time)
- European master students / universities (two user licenses for use for master theses)

Smaller development, support or analysis tasks have been commissioned by the interested parties under separate contracts. Notably, NOWIcob was used in a project with Statkraft for their investment decision for the Dudgeon Offshore Wind project. The model was also used extensively by Statkraft in their development of other offshore wind projects during 2015, with support by SINTEF Energy Research through a separate contract. In the continuing development of the model, the specific needs of interested parties have been balanced with the development plans in the long-term research projects NOWITECH and LEANWIND, and a single, identical model version has been maintained across all projects.

In LEANWIND, NOWIcob was adopted and used as the LEANWIND O&M Strategy model to evaluate different O&M and logistics strategy options (LEANWIND Consortium, 2015). The LEANWIND O&M Strategy model was furthermore adapted as an OPEX module that was integrated in the overall LEANWIND full life-cycle financial model (LEANWIND Consortium, 2016), which is at the time of writing being used to validate and evaluate different innovations developed in the LEANWIND project. NOWIcob thus contributes to these evaluations by estimating wind farm availability and O&M costs for different wind farm scenarios.

In addition to the industrial applications described in the paragraphs above and in Chapter 6.3, the NOWIcob model has also been applied to a large number of more academic case studies and investigations. A complete list of published results related to NOWIcob, most of which are publically and openly available, is provided in Appendix B. These publications demonstrate a wide range of possible applications, including estimation of O&M costs, availability and LCOE, optimisation of the CTV or O&M access vessel fleet, optimisation of the jack-up vessel charter strategy, optimisation of the timing of annual services, and cost-benefit analysis of condition monitoring and of remote inspection. Much research work has also been devoted to investigating the impact of different modelling assumptions (e.g. failure and degradation modelling, and the dependence of vessel accessibility on multiple metocean parameters) and on establishing reference data sets that can be used by the research community for benchmarking and to further model verification and validation.

After the conclusion of the NOWITECH and LEANWIND projects in 2017, NOWIcob remains in the ownership of SINTEF Energy Research to be used as an in-house analysis tool and as SINTEF Energy Research's background in potential new research and/or innovation projects. License agreements for using test versions of the tool can be granted on a case-to-case basis, and access to the tool and/or analyses using the tool could also be provided to interested parties under separate contracts.

Through the work on developing and applying the NOWIcob model, a number of research challenges for the future of offshore wind O&M modelling has been identified. Based on this, an outlook for the research field in the more general context of O&M modelling work within the NOWITECH project is given by Welte et al. (2017a). Two likely trends for the future can be highlighted: 1) As strategic O&M decision support tools for the offshore wind industry (such as NOWIcob) have reached maturity, the industry is getting increasingly ready for using decision support tools also for operational (i.e. short-term) decisions. 2) As the size of offshore wind farm projects and their distance to shore increases, so does the solution space of O&M and logistics decisions, and the benefits of complementing simulation models by optimisation models become more apparent. The research work related to NOWIcob, within NOWITECH as well as in related projects, has contributed to laying the necessary foundations for meeting these research challenges.

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Appendixes

A Overview of 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 technicians working on turbine	There needs to be acceptable weather for technician transfer/access for the entire scheduled active maintenance time of the task that shift (but a task can often be split across multiple shifts)
Height above sea level for wind speed data	The model expects wind speed data for hub height, and the same wind speeds are used for estimating power production, assessing operability of e.g. lifting operations and assessing accessibility of technicians.
Failure model	
Failure model structure	Each failure category is associated with a maintenance task, and the maintenance task defines (indirectly; see under *Vessels)* 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 maintenance does not affect failure rates
Correlation between failures	Assumed to be no common-cause 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 failure/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, *Time of pick-up of technicians from turbine* under *Logistics*)
Derating of turbines	Derating and other operational strategies in response to condition monitoring or inspections are not modelled explicitly.
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, *Time of pick-up of technicians from turbine* under *Logistics*). 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 at and 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 input value for average reduction in power production compared to theoretical yield without wake effects
Downtime of electrical infrastructure (substations, cables, etc.)	Is taken into account in one of two ways: a) As a single input value for average reduction in power production compared to theoretical yield with no downtime for electrical infrastructure, or b) by calculating the availability of individual components of the electrical infrastructure in the same manner as for the wind turbines by associating them with failure categories and corresponding maintenance tasks.
Maintenance tasks	
Types of maintenance tasks	Maintenance tasks are classified as either predetermined preventive 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, or different operation steps of jack-up vessel operations) that must be carried out sequentially. Lead time for spare parts is not considered for pre-inspection but only for the subsequent operation step(s). The subsequent operation step(s) can never be carried out in the same shift as the 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 minimum 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 possible subsequent operation steps cannot be carried out in the same shift). However, one can specify that the maintenance task only incurs turbine downtime for the actual active maintenance time.
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 turbine is stopped at failure/alarm 2) maintenance type, in the following order: i) corrective, ii) condition based, iii) predetermined preventive; 3) whether the maintenance task is already started, 4) whether a vessel has been chartered (ordered) for the task. However, other prioritisation options can be chosen by the user.
Prioritisation of which vessels to use for maintenance tasks	The possible combinations of vessels to use for a task are prioritised first by how much of the maintenance task there is time to do using that combination, then by the variable costs of using the vessels. If possible and if everything else is equal, a vessel that is already scheduled to go offshore is used rather than scheduling a new vessel to go offshore.
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 technicians on the turbine than there's space for on a single vessel	Assumed that a single maintenance task cannot require so many technicians; however, no warning will be given if the user specifies that more technicians are required than what a single vessel can transfer
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. However, unsuccessful inspections can be modelled implicitly through condition-based maintenance tasks; see also entry below on stochasticity.
Stochasticity of input parameters	The mobilisation time of chartered vessel, the lead time of spare parts, the active maintenance time of maintenance tasks and the pre-warning time for condition-based maintenance tasks can be specified to be stochastic.
Technicians	
Definition of maintenance teams	Technicians 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 technicians	Number of Technicians 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 technicians are included explicitly, other personnel or crew may be included implicitly in the cost of operating the vessel / base. Technicians 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 technicians, 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 technician availability	A fixed number of technicians 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.)
Different types of technicians	The model does not explicitly consider that different maintenance tasks may require different levels of competence and experience of the technicians or that one may have separate technician pools e.g. for preventive and corrective maintenance.
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, *Seasonality in vessel availability*).
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?	It can be specified for each vessel whether it can only work day shifts, both day shifts and shifts, or whether they can work 24 hours a day (if the specified working shifts do not cover 24 hours a day). Daughter vessels have to be working the same shifts as their mother 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 approach time for access.)
Vessel failures	Vessels and vessel equipment (access systems, lifts, launch and recovery systems, etc.) are not assumed to be subject to failures
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

Chartering of multiple vessels for a task	Only one vessel can be chartered for each task
When is the vessel charter?	The vessel is chartered 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 mobilisation time before the vessel is available to work in the wind farm can be set to be constant or stochastic for each vessel. If the spare part lead time is longer than the mobilisation 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 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 chartered. During the charter period, the vessel can be used for work on other maintenance tasks than the one it was originally chartered 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 chartered at this time step.
Bundling of maintenance tasks	No bundling or batch repair strategy; if ordering of vessels is necessary for the maintenance task, this is done immediately after the failure (has been diagnosed). (See *When is the vessel ordered?)*
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.
Technician transfer to different turbines	CTVs can deploy technicians 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 a vessel that is only participating with transfer of technicians.
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 technicians for heavy-lift maintenance tasks	For maintenance tasks requiring jack-up vessels and other heavy-lifting capabilities, technicians either have to be transferred to the turbines by separate access vessels (CTVs), or one must assume a separate technician pool at the jack-up vessel if technicians are to be transferred to the turbine from the jack-up vessel.
Transfer of technicians between vessels	Except for transfer between mother vessels and their daughter vessels, maintenance technicians 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 category).
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 an approach time for the vessel (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 approach 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 technicians 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 technicians 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 refuelling/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. One can also specify that one of the daughter vessels are taking care of resupplying the vessel at predefined intervals.
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 1of 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.

Conference paper 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.

Conference paper with a 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.

Hagen, B. A. L. (2013). *Sensitivity Analysis of O&M Costs for Offshore Wind Farms*. Master thesis, Norwegian University of Science and Technology.

Master thesis investigating different methods of sensitivity analysis of results from NOWIcob.

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 which was later, when updated for v.3.1 of the NOWIcob model, remade into a deliverable in the NOWITECH project.

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.

Conference paper investigating 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.

Conference paper investigating the 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.

Holmstrøm, K.-M. H. (2014). *How can advanced failure modelling contribute to improving life-cycle cost analyses of offshore wind farms in models like NOWIcob?* Master thesis, Centre for Alternative Technology, University of East London.

Master thesis on the implementation of a non-homogeneous Poisson process in NOWIcob to investigate the effect of a more accurate modelling of time-dependent rate of occurrence of failures.

Dinwoodie, I.; Endrerud, O.-E. V.; Hofmann, M.; Martin, R.; Sperstad, I. B. (2015): Reference Cases for Verification of Operation and Maintenance Simulation Models for Offshore Wind Farms. *Wind Engineering*, vol. 39, pp. 1–14.

Journal paper 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.

Hofmann, M.; Sperstad I. B.; Kolstad, M. (2015). *User guide for the NOWIcob tool (D5.1-75)*, report no. TR A7372, v. 2.0; SINTEF Energy Research, Trondheim.

Based on the user guide of model version 3 (Hofmann and Sperstad, 2014), Practical user guidelines for the NOWIcob model], having the same report number, but as of v.2.0 the report is regarded as a NOWITECH deliverable.

Hofmann, M.; Sperstad I. B.; Kolstad, M. (2015). *Technical documentation of the NOWIcob tool (D5.1-66)*, report no. TR A7374, v. 2.0; SINTEF Energy Research, Trondheim.

Technical documentation of model version 3.1 of NOWIcob. Based on documentation of model version 3 (Hofmann and Sperstad, 2014), having the same report number.

LEANWIND Consortium (2015). *Optimised maintenance and logistic strategy models (D.4.2).*

Report deliverable in the EU FP7 project LEANWIND describing work in LEANWIND Task 4.2 ("Strategy optimisation") and Task 4.3 ("Reliability based design implications"). Among other work, it describes the development of NOWIcob as an O&M strategy model in the LEANWIND project as well as *case studies applying NOWIcob for the optimisation of some aspects of the O&M and logistics strategy (jack-up vessel campaign periods, CTV fleet composition and annual service campaign period timing).*

Sperstad, I. B.; McAuliffe, F. D.; Kolstad, M.; Sjømark, S. (2016): Investigating key decision problems to optimise the operation and maintenance strategy of offshore wind farms. *Energy Procedia*, vol. 94, pp. 261–268.

Conference paper with three case studies demonstrating the application of NOWIcob to the decision problems 1) timing of jack-up vessel charter periods for pre-determined heavy maintenance campaigns, 2) selecting the size and composition of the CTV fleet, and 3) timing of annual service (predetermined preventive maintenance) campaigns. The paper was based on results in LEANWIND Consortium (2015).

LEANWIND Consortium (2016). *Economics Model Report (D.8.2).*

Report deliverable in the EU FP7 project LEANWIND describing work in WP8 ("Economic and Market Assessment") on the development of the LEANWIND full life-cycle financial model. NOWIcob has in LEANWIND been adapted and integrated in this financial model as the OPEX module and is responsible for estimating wind farm availability and O&M costs.

Smart, G.; Smith, A.; Warner, E.; Sperstad, I. B.; Prinsen, B.; Lacal-Arántegui, R. (2016): *IEA Wind Task 26 – Offshore Wind Farm Baseline Documentation*. IEA Wind. (Available online: http://www.nrel.gov/docs/fy16osti/66262.pdf.)

Report in IEA Wind Task 26 ("Cost of Wind Energy") where NOWIcob and the ECN O&M Tool are benchmarked and applied in the estimation of OPEX for the LCOE calculation for a reference wind farm (the IEA Wind Task 26 offshore wind farm baseline). This reference case can be regarded as an extension of the reference cases presented in Dinwoodie et al. (2015) and includes more details and explanations.

Gallala, M. R. (2016). *Surrogate-based optimisation using artificial neural networks – Identifying profitable O&M strategies for offshore wind farms through stochastic simulations*. Master thesis, Norwegian University of Science and Technology.

Master thesis investigating the use of surrogate models for global optimisation of offshore wind O&M strategies. The NOWIcob model was incorporated in an optimization model based on an artificial neural network (i.e. the surrogate model). Simulations using NOWIcob were used to train the artificial neural network, and this surrogate could then be used to more efficiently explore the solution space.

Welte, T. M.; Sperstad, I. B.; Sørum, E. H.; Kolstad, M. L. (2017a). Integration of Degradation Processes in a Strategic Offshore Wind Farm O&M Simulation Model. *Energies*, 10, 925.

Journal paper investigating the impact on results of fully integrating a degradation process in the NOWIcob model compared to using a simplified representation based on the modelling of condition-based maintenance that was already implemented in NOWIcob.

Sperstad, I. B.; Stålhane, M.; Dinwoodie, I.; Endrerud, O.-E. V.; Martin, R.; Warner, E. (2017): Testing the robustness of optimal access vessel fleet selection for operation and maintenance of offshore wind farms. Ocean Engineering, vol. 145, pp. 334–343.

Journal paper applying NOWIcob and five other offshore wind O&M models to vessel fleet optimisation and comparing how the models rank different O&M vessel fleets. The reference case used for the comparison was based on Dinwoodie et al. (2015).

LEANWIND Consortium (2017). *O&M, Integration of tools and systems (D.4.7).*

Report deliverable in the EU FP7 project LEANWIND including reports on work carried out in Task ("Strategy optimisation") after the finalization of D4.2. In addition to the work reported in Welte (2017a), this includes a case study on cost-benefit analysis of condition monitoring systems carried out in collaboration with Kongsberg.

Welte, T.M.; Sperstad, I.B.; Espeland Halvorsen-Weare, E.; Netland, Ø.; Nonås, L.M.; Stålhane, M. (2017b). O&M modelling. In *Offshore wind energy technology*, Anaya-Lara, O.; Tande, J.O.; Uhlen, K.; Merz, K., Eds. Wiley: Chichester, West Sussex, UK (in press).

Book chapter in a book written in conjunction with the conclusion of the NOWITECH project. The book chapter puts the research work related to NOWIcob and other O&M decision support tools developed in NOWITECH in a wider perspective. It also provides an updated overview of the state of the art of strategic offshore wind farm O&M modelling and an outlook on trends and possible future developments in the research field.

C Limitations to validity and domain of applicability

This appendix gives an overview of important assumptions, restrictions and limitations that affect the domain of applicability of NOWIcob and the validity of its results. As discussed in Section 6.3, the overview was prepared as a part of the activity on verification and validation of O&M and logistics models in NOWITECH starting in 2015. The intention is to give a better understanding of the domain of applicability as well as some guidance to using the model for different scenarios and interpreting the results. The overview in Appendix A gives is a more complete list of assumptions but does not discuss their implications for the use of the model. The contents of this appendix is based on a similar overview prepared for a LEANWIND deliverable (LEANWIND Consortium, 2015).

C.1 Failure model

- There is no explicit modelling of how the intensity of preventive maintenance (e.g. service or inspection intervals) affects the failure rates. Therefore, the model is not particularly applicable to optimization of maintenance intervals. See, however, Welte et al. (2017a) and LEANWIND Consortium (2017) for further discussion of the applicability of the model for such purposes.
- It is assumed there are no common-cause failures or other correlations between failures for different turbines, for different components within a turbine, etc. The model has mainly been applied with relatively high-level failure data sets, in accordance with the level of detail in failure data currently available. The model performs relatively well (i.e. with acceptable accuracy and improved efficiency) with a small number failure categories aggregated to a wind turbine level.
- One assumption is that turbines that are down due to maintenance do not generate new failures associated with the same maintenance task. On the other hand, failures that are generated while the turbines are operating may occur at points in time when the turbine is already down due to a previous failure associated with a different maintenance task. This can contribute to overestimating the maintenance requirement for turbines that are down for a substantial period.
- In general, the accuracy and credibility of the model is lower for cases where the resulting availability is relatively low, e.g. when one gets time-based availabilities $\ll 90$ % (as an order of magnitude estimate). There are several reasons for this:
    - As indicated in the point above, one underlying assumption of the model is that downtime (MTTR) is relatively small compared to time to next failure (MTTF). When the availability becomes very low, this may no longer be a good approximation, which means that the accuracy decreases.
    - The variance of the NOWIcob results typically increases when the availability decreases because random effects (e.g. major failures and bad weather) then tend to have a higher impact for the individual Monte Carlo iterations.
    - If availabilities are very low, this can be because the specified maintenance resources are clearly inadequate, resulting in an increasing backlog of maintenance tasks. The model is not constructed to represent reasonable O&M responses in such cases and it may therefore be outside its domain of applicability.

C.2 Metocean conditions

- Inhomogeneities in metocean conditions within the wind farm and accessibility are not taken into account. This would probably be more important to take into account for an operational rather than a strategic model, and it might be more important for larger wind farms than those commissioned to date.
- Using synthetic weather time series generated by the weather model may in some cases produce results with statistically significant differences from results using the "historical" weather time series. In

particular, this may be the case if the metocean time series are relatively short (in the order of 5 years or less) and/or if the time resolution is large (more than around 3 hours). Discrepancies are particularly notable if the case is such that the availability results are low (≪ 90 %). If in doubt as to the applicability of the weather model for a specific metocean data set and/or for a specific wind farm case, one may always choose to use "historical" weather time series.

C.3 Maintenance tasks

- It is generally assumed that all maintenance tasks can be split over multiple shifts if necessary due to available weather windows. This is also the case for operational phases of jack-up vessels that in reality would require a single, continuous weather window. This over-optimism in the modelling approach can to some extent be mitigated by increasing the minimum working duration that is allowed for maintenance tasks.
- Derating and other operational strategies in response to condition monitoring or inspections are not modelled explicitly. When maintenance tasks are modelled as corrective and not condition-based or preventive, this may lead to overestimating the lost revenue due to major replacements. In reality, some of these maintenance tasks will be condition-based in the sense that the turbine may e.g. be derated before one is ready to carry out the replacement. Possibly one would even be able to operate the turbine until the low-wind season before the replacement is scheduled.
- The model is primarily designed to consider typical years of the operational phase of the wind farm. This means that there is only limited functionality for modelling e.g. major overhaul campaigns requiring extra jack-up vessels and other resources for particular years.

C.4 Offshore logistics

- Travel times within the wind farm are modelled in a simplified manner, using average internal distances within the wind farm. According to sensitivity analyses (Hofmann and Sperstad, 2013) this may be acceptable for such strategic models as applied to most of today's wind farm projects (with relatively small distances between turbines). However, more detailed modelling may be relevant for larger wind farms with greater distances between individual turbines. It could also be more relevant for operational day-to-day scheduling of maintenance activities.
- It is assumed that the same average internal wind farm distance has to be travelled by a vessel for each new turbine that is visited in a shift. If the number of turbines visited becomes larger, the average distance travelled between each visit may become smaller even for corrective maintenance tasks if one assumes intelligent vessel routing. This is not considered explicitly in the model.
- The current model may tend to underestimate the effects of increasing distance to shore when a shore-based maintenance strategy is assumed. The following effects are not modelled explicitly: acclimatisation time for technicians after transit, the effect of sea sickness or actual vessel speed on the sea state, and the dependence of the acceptable minimum working durations with the transit duration needed to reach the turbines.
- The model assumes a perfect weather forecast within each shift and is relatively optimistic in its modelling of the utilisation of available resources and weather windows. Each shift is scheduled such that the teams of technicians get as much time to work on the turbines as allowed by the weather window. This is done even if it involves vessels leaving offshore for several hours of transit only to be able to do a few hours of work and possibly only with a few technicians. This may not always be acceptable for the wind farm or vessel operators in practice. This over-optimism in the modelling approach can to some extent be mitigated by increasing the minimum working duration that is allowed for maintenance tasks.
- Real-world jack-up vessel charter agreements come in a number of different variations and are typical a matter of negotiations and tactical/operational considerations that varies from case to case. Such

complexities are not fully captured by the model, and it is hence not applicable to operational and tactical decision support for jack-up vessel chartering. Although there is scope for more advanced modelling of jack-up vessel charters, for NOWIcob the choice was been made to instead rely on a somewhat simplified modelling approach that is believed to be a fair approximation on average.

- This modelling approach is, however, applicable to strategic decision support e.g. for charter strategies involving pre-determined heavy maintenance campaigns, as described in Sperstad et al. (2016) and LEANWIND Consortium (2015).
- When a jack-up vessel is modelled as being chartered (ordered) on-demand, the vessel is modelled as being available for a fixed charter period. When the vessel is not needed for the entire period, it will still remain at the wind farm, and the full, pre-agreed charter cost is incurred. This may lead to jack-up vessel charter costs being overestimated in the model. However, the model outputs information about how much the chartered vessel is in fact utilised, and this can be used to consider the charter costs more realistically.
- Alternatively, for more realistic modelling of on-demand jack-up vessel chartering, the model can be "calibrated" by running simulations for several values of the charter duration and choosing the results with the best trade-off between charter costs and downtime. In this way one avoids overestimating charter costs and/or downtime due to maintenance tasks requiring jack-up vessel. Alternatively, modelling jack-up vessel charters as pre-determined campaign periods may be a convenient alternative to reduce simulation efforts and simplify the modelling assumptions.

C.5 Technicians

- One restriction is that each team of technicians can only work on one maintenance task for each weather window. This means that if each maintenance task is very short and there is a long weather window available that shift, the number of tasks that can be completed during the shift may be underestimated.
- A single technician pool is assumed for corrective and preventive maintenance. In cases where specific maintenance tasks are in practice carried out by a different pool of technicians than the rest of the tasks (the OEM or a third-party contractor, e.g.), it may be recommended to remove these tasks from the list of ordinary maintenance tasks and estimate their cost or downtime contribution separately. Alternatively, e.g. for maintenance actions requiring jack-up vessels, it is recommended to set up these maintenance actions as not requiring access (i.e. not requiring technicians from the "ordinary" pool of technicians).
- For the two reasons listed above, in addition to the optimistic assumption on resource utilisation mentioned in Chapter 3, the model may give relatively optimistic results if used to optimise the number of technicians that are needed.

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