Properties of the O&M Cost Estimator (OMCE)

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Acknowledgement/Preface

This report is written as part of the research project D OWES in the context of the development of the *"Operation and Maintenance Cost Estimator (OMCE)"* by ECN. Within this OMCE project a methodology has been set up and subsequently software tools are being developed to estimate and to control future O&M costs of offshore wind farms taking into account operational experience. In this way it can support optimisation of O&M strategies. The OMCE project was funded partly by We@Sea, partly by EFRO, and partly by ECN (EZS).

The development of the specifications for the OMCE was carried out and co-financed by the Bsik programme 'Large-scale Wind Power Generation Offshore' of the consortium We@Sea (www.we-at-sea.org). The development of the event list and the programming of the OMCE-Calculator is carried out within the D OWES (Dutch Offshore Wind Energy Services) project which is financially supported by the European Fund for Regional Developments (EFRO) of the EU (www.dowes.nl).

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Abstract

ECN is developing the Operation & Maintenance Cost Estimator (OMCE), which is a tool consisting of software and procedures, that can be used (1) to monitor the actual O&M effort for wind farms in operation already and (2) to control and to optimise the costs of these wind farms for the coming period of e.g. 1, 2 or 5 years. To handle both aspects, processing of operational data and prediction of future O&M costs two major parts can be distinguished.

1. OMCE Building Blocks for processing of operational data.

   The main objective of these building blocks is to process all available data in such a way that useful information is obtained, which can be used on the one hand as input for O&M modelling and on the other hand to monitor certain aspects of the wind farm.

2. OMCE-Calculator for the assessment of the expected O&M effort and associated costs, taking into account the operational data as far as possible.

In this report the OMCE is described in detail with the aim to provide the reader not only information concerning the features of the tools, but especially to provide background information on the models applied and also to illustrate the capabilities by means of a number of examples.

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Summary

During the lifetime of a wind farm the costs of O&M have to be considered continuously.

During the *planning phase* of a wind farm an estimate of the expected O&M cost over the life time has to be made to support the financial decision making, and furthermore quite often an initial O&M strategy has to be set up. To support this process ECN has developed the O&M Tool, which is commonly used by the wind industry. With this computer program developed in MS-Excel it is possible to calculate the average downtime and the average costs for O&M over the life time of the wind farm.

During the *operational phase* of a wind farm it is important (1) to monitor the actual O&M effort and (2) to control and to optimise future O&M costs. To be able to control and subsequently to optimise the future O&M costs of these wind farms, it is necessary to accurately estimate the O&M costs for the next coming period of e.g. 1, 2 or 5 years, taking into account the operational experiences available at that moment. Several reasons are present for making accurate cost estimates of O&M of (offshore) wind farms. Examples are:

- to make reservations for future O&M costs (this is especially important for the party who is responsible for the financial management of the maintenance);
- operating experiences may give indications that changing the O&M strategy will be profitable, and then the costs need to be determined accurately in order to compare the adjusted strategy with the original one;
- before the expiration of the warrantee period, a wind farm owner needs to decide how to continue with servicing the wind turbines (new contract with turbine supplier or to take over the total responsibility) after the warranty period;
- if a wind farm is going to be sold to another investor, the new owner wants to have detailed information on what O&M costs he can expect in the future.

To support the process of monitoring, control, and optimisation ECN is developing the O&M Cost Estimator (OMCE). To handle both aspects, processing of operational data and prediction of future O&M costs two major parts can be distinguished:

1. OMCE Building Blocks for processing of operational data, where each building block covers a specific data set. Currently BB's are being developed for the following data sets:
    - *Operation and Maintenance;*
    - *Logistics;*
    - *Loads and Lifetime;*
    - *Health Monitoring.*

   The main objective of these building blocks is to process all available data in such a way that useful information is obtained, which can be used on the one hand as input for O&M modelling and on the other hand to monitor certain aspects of the wind farm.
2. OMCE-Calculator for the assessment of the expected O&M effort and associated costs for the coming period, where amongst others all relevant information provided by the OMCE Building Blocks is taken into account.

The Building Blocks 'Operation & Maintenance and 'Logistics' have the main goal of characterisation and providing general insight in the corrective maintenance effort that can be expected for the coming years. With respect to corrective maintenance important aspects are the failure frequencies of the wind turbine main systems, components, and failure modes. Furthermore, other parameters that are needed to describe the corrective maintenance effort are for instance the length of repair missions, delivery times of spare parts and mobilisation times of equipment. Within the OMCE project procedures and software have been developed that can be used by operators to analyse their data sets and generate input data needed for O&M modelling but only if the data are collected in a structured way, f.i. in accordance with the Event List specifications described in the current report.

For estimating the expected future condition based maintenance work load the Building Blocks 'Loads & Lifetime' and 'Health Monitoring' have been developed. The main goal of these

Building Blocks is to obtain insight in the condition or, even better, remaining lifetime of the main wind turbine systems or components. Within the OMCE project it was concluded that it was not possible to develop a software tool for analysing the data sets that apply to 'Loads & Lifetime' and 'Health Monitoring'. These data are often obtained from measurement systems from third parties and require experts to draw meaningful conclusions. The results need to be interpreted carefully and combined for instance with inspection results. Such procedures appeared to be too complicated to incorporate in software that can be used straightforwardly by wind farm operators. For the further development of the BB 'Loads & Lifetime' the *Flight Leader concept for Wind Farm Load Counting* is being developed by ECN and for the BB 'Health Monitoring' the description is limited to the lessons learned, some general procedures, and references to further reading.

In contrary to the ECN O&M Tool, the OMCE-Calculator is meant to be used during the operational phase of a wind farm, to estimate the required O&M effort for the coming period of 1 to 5 years, taking into account the operational experiences of the wind farm acquired during the operation of the wind farm so far. This implies that for the OMCE model it is not sufficient to determine long term yearly average numbers, but that another approach has to be followed, viz. simulation in the time domain, taking into account the random behaviour of the weather conditions and the random occurrence of failures. This approach allows that all kind of optimisation studies can be carried out, f.i. for contracting of ships or for setting up a warehouse for spares.

It may be clear that such a tool with these features is not of interest for operators only, but also for other stakeholders (owners of wind farms, wind turbine manufacturers, etc.).

The OMCE is described intensely in the current report with the aim to provide the reader not only information concerning the features of the tools, but especially to provide background information on the models applied and also to illustrate the capabilities by means of a number of examples.

1. Introduction

1.1 Background

Several European countries have defined targets to install and to operate offshore wind energy and according to these targets more than 40 GW offshore wind power is expected for the year 2020. With an average turbine size of about 5 - 10 MW, four to eight thousand wind turbines should be transported, installed, operated and maintained. When not only the European plans are considered, but all international developments as well, these numbers are much higher. So worldwide the required effort for operation and maintenance (O&M) of offshore wind farms will be enormous, and control and optimisation of O&M during the lifetime of these offshore wind turbines is essential for an economical exploitation. At the moment O&M costs of offshore wind farms contribute substantially (2 to 4 €ct/kWh) to the life cycle costs, so it may be profitable to check periodically whether the O&M costs can be reduced so that the total life cycle costs can be reduced [Ref. 1, Ref. 2, Ref. 3].

During the *planning phase* of a wind farm an estimate of the expected O&M cost over the life time has to be made to support the financial decision making, and furthermore quite often an initial O&M strategy has to be set up. To support this process ECN has developed the O&M Tool [Ref. 4, Ref. 8]. With this computer program developed in MS-Excel it is possible to calculate the average downtime and the average costs for O&M over the life time of the wind farm. Both preventive and corrective maintenance can be considered. To analyse corrective maintenance the failure behaviour of the wind turbine has to be modelled and a certain maintenance strategy has to be set up , i.e. for each failure or group of failures it has to be specified how many technicians are needed, how these technicians are transferred to the wind turbine (small boats, helicopter, etc.) and whether a crane ship is needed. By carrying out different scenario studies the most effective one can be considered for more detailed investigations and technical assessment. The long term yearly costs and downtime are calculated and for this purpose it is sufficient to assume a constant failure rate of the wind turbines over the life time, hence it is assumed that the number of failures of a certain type is constant over the years. With this assumption the annual cost and downtime for a certain failure equals the product of number of failures of this type per year, and the downtime or cost associated with this type of failure. The total cost is a simple summation over all failures assumed to occur. So the determination of the annual cost and downtime is a straightforward operation. Once the model has been set up, the effect of adjusting an input parameter is visible immediately, which makes the O&M Tool a powerful tool commonly used by the wind industry. However, the straightforward method based on long term average values introduces some limitations as well. As the actual variation in failure rate from year to year is not considered, the tool is not really suitable to estimate the O&M effort for the coming period of e.g. 1, 2 or 5 years, which is required to control and optimise O&M of a wind farm in the operational phase. For this reason ECN initiated the idea of developing the “O&M Cost Estimator” (OMCE), as a tool that could be used by operators of large offshore wind farms.

W.r.t. O&M during *operation* of a wind farm it is important (1) to monitor the actual O&M effort and (2) to control and to optimise future O&M costs. For both aspects operational data available for the wind farm are required. To be able to control the future costs and when possible to optimise the O&M strategy a computer tool is desired to estimate and to analyse the expected cost for the coming period. To support the process of monitoring, control, and optimisation ECN has started the development of the O&M Cost Estimator [Ref. 6, Ref. 7, Ref. 8]. To handle both aspects, processing of operational data and prediction of future O&M costs two major parts can be distinguished:

1. OMCE Building Blocks for processing of operational data, where each building block covers a specific data set. Currently BB’s are being developed for the following data sets:
    - *Operation and Maintenance;*
    - *Logistics;*

- *Loads and Lifetime;*
- *Health Monitoring;*

The main objective of these building blocks is to process all available data in such a way that useful information is obtained, which can be used on the one hand as input for the OMCE-Calculator and on the other hand to monitor certain aspects of the wind farm.

2. OMCE-Calculator for the assessment of the expected O&M effort and associated costs for the coming period, where amongst others all relevant information provided by the OMCE Building Blocks is taken into account.

In contrary to the ECN O&M Tool, the OMCE-Calculator is meant to be used during the operational phase of a wind farm, to estimate the required O&M effort for the coming period, taking into account the operational experiences of the wind farm acquired during the operation of the wind farm so far. This implies that for the OMCE model it is not sufficient to determine long term yearly average numbers, but that another approach has to be followed, viz. simulation in the time domain. Furthermore the feedback of operational experience is of great importance for the OMCE model. This approach enables the possibility to include features not straightforward possible in the O&M Tool, such as clustering of repairs at different wind turbines, spare control, optimisation of logistics of offshore equipment, and so on.

1.2 Structure of the report

The OMCE is described intensely in the current report with the aim to provide the reader not only information concerning the features of the tools, but especially to provide background information on the models applied and also to illustrate the capabilities by means of a number of examples. For the final user of the OMCE BB's or the OMCE-Calculator, separate user manuals and possible more in depth technical descriptions will be made.

The remaining of this report can roughly be split up in four major parts.

Part I: In Chapter 2 general information concerning O&M of offshore wind farms is given, while in Chapter 3 the OMCE project is addressed in a general way.

Part II: In the chapters 4 through 8 the OMCE Calculator is described.

Part III: In the chapters 9 through 15 the OMCE Building Blocks are described.

Finally, the status of the development and the future plans are described in Chapter 16.

Part I:
Modelling O&M Aspects of Offshore Wind Farms

2. Modelling O&M of offshore wind farms

2.1 O&M aspects

A typical lay-out of an offshore wind farm is sketched in Figure 2-1. The wind farms consist of a number of turbines, switch gear and transformers (mostly located within the wind farm) and a substation onshore to feed in the electrical power into the grid. The first wind farms are located in shallow waters at short distances from the shore in order to gain experiences with this new branch of industry. Presently, most offshore wind farms are located at distances typically 8 to 30 km from the shore in water depths of 8 to 30 m. Usually mono-piles are being used as a sub-structure and the turbine towers are mounted to the mono-piles by means of transition pieces. The size of an offshore wind farm is 50 to 200 MW and consists of turbines with a rated power of typically 1 to 3 MW. Future wind farms are planned further offshore and will consist of larger units, typically 5 MW and larger, and the total installed capacity will be 200 to 500 MW, but also wind farms with a capacity in the order of 1 GW are considered. New and innovative substructures are presently being developed to enable wind turbines to be sited in deeper waters and to lower the installation costs, see Figure 2-2.

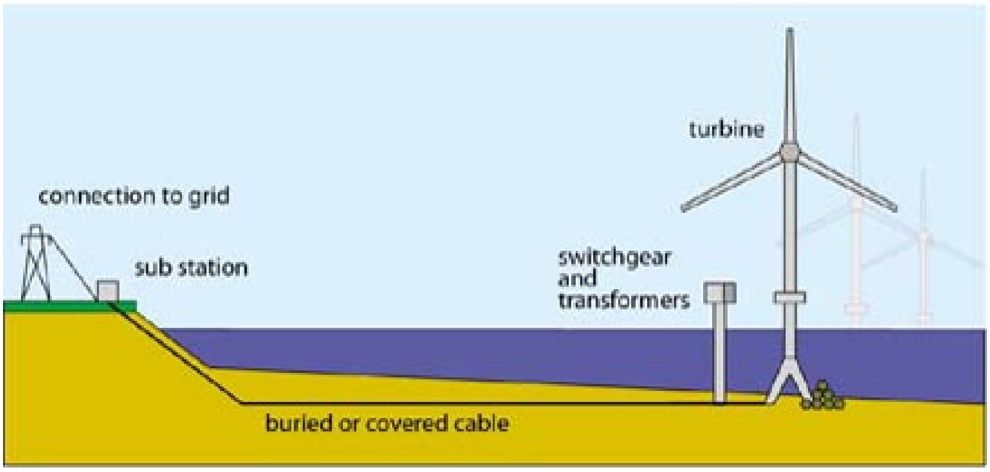


Figure 2-1: *Typical lay-out of an offshore wind farm [Ref. 9]*

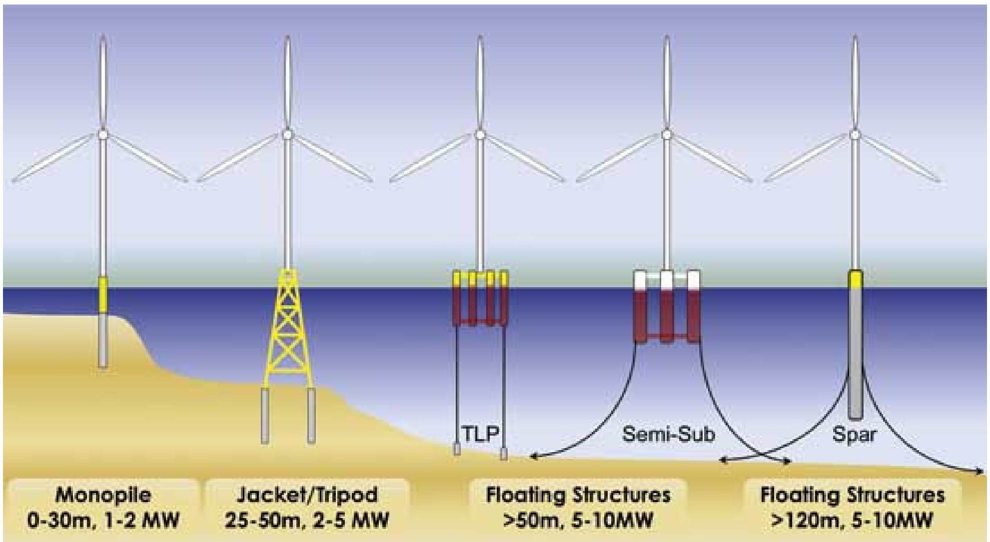


Figure 2-2: *Sub-structures[Ref. 10]*

All systems and components within the wind farm need to be maintained. Typically for preventive maintenance, each turbine in a wind farm is being visited twice a year and each visit has a duration of 3 to 5 days. In addition a number of visits for corrective maintenance are needed due to random failures. Public information about corrective maintenance is very limited, but numbers of 5 visits or more are not unrealistic. In the future it is the aim to improve the turbine reliability and maintainability and reduce the frequency of preventive maintenance to no more than once a year. The number and duration of visits for corrective maintenance should be decreased also by improved reliability and improved maintainability. With the use of improved condition monitoring techniques the effects of random failures can be reduced by applying condition based maintenance. In addition to the turbine maintenance, also regular inspections and maintenance are carried out for the sub-structures, the scour protection, the cabling, and the transformer station. During the first year(s) of operation the inspection of substructures, scour protection, and cabling is done typically once a year for almost all turbines. As soon as sufficient confidence is obtained that these components do not degrade rapidly operators may decide to choose longer inspection intervals or to inspect only a sub-set of the total population.

The maintenance aspects relevant for offshore wind farms are among others:

- **Reliability of the turbines**. As opposed to onshore turbines, turbine manufacturers design their offshore turbines in such a way that the individual components are more reliable and are able to withstand the typical offshore conditions. This is being done by reducing the number of components, choosing components of better quality, applying climate control, using automatic lubrication systems for gearboxes and bearings, etc. Often, the turbine control is modified in such a way that not all single failures lead to a stand still. Making better use of the diagnostics and using redundant sensors can assist in this.
- **Maintainability of the turbines.** If offshore turbines fail, maintenance technicians need to access the turbines and carry out maintenance. Especially in case of failures of large components, offshore turbines are being modified to make replacements of large components easy, e.g. by making modular designs, or by building in an internal crane to hoist large components, see for example Figure 2-3.

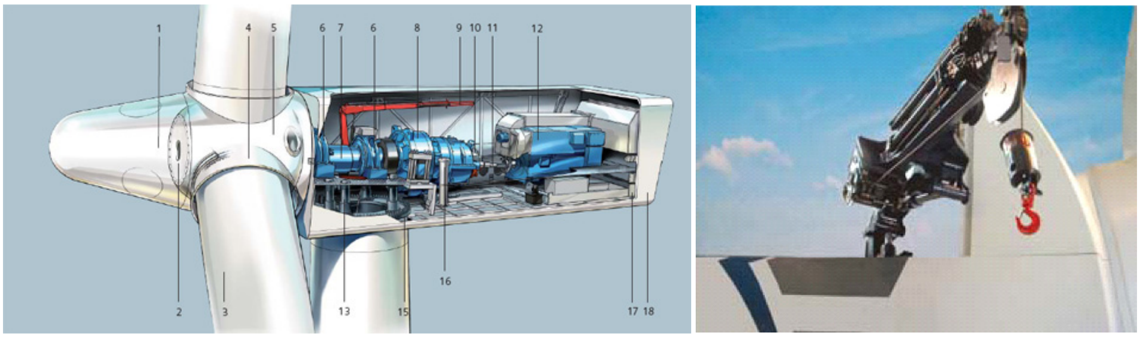


Figure 2-3: *Examples of internal cranes in the Siemens 3.6 (left) and Repower 5M (right) turbines*

- **Weather conditions.** The offshore weather conditions, mainly wind speeds and wave heights, do have a large influence on the O&M procedures of offshore wind farms. However, also fog or tidal flows may influence the accessibility. The maintenance activities and replacement of large components can only be carried out if the wind speed and wave heights are sufficiently low. Preventive maintenance actions are therefore usually planned in the summer period. If failures occur in the winter season, it does happen that technicians cannot access the turbines for repair actions due to bad weather and this may result in long downtimes and thus revenue losses.
- **Transportation and access vessels.** For the nowadays offshore wind farms, small boats like the Windcat, Fob Lady, or SWATH boats are being used to transfer personnel from the harbour to the turbines. In case of bad weather, also helicopters are being used, see Figure 2-4. RIB's (Rigid Inflatable Boats) are only being used for short distances and during very good weather situations. The access means as presented in Figure 2-4 can also transport

small spare parts. For intermediate sized components like a yaw drive, main bearing, or pitch motor it is often necessary to use a larger vessel for transportation, e.g. a supply vessel. New access systems are being developed to allow personnel transfer even under harsh conditions. An example which has been developed partly within the We@Sea program is the Ampelmann (www.ampelmann.nl).

Figure 2-4: *Examples of transportation and access equipment for maintenance technicians; clockwise: Windcat workboat, Fob Lady, helicopter, and SWATH boat*

- **Crane ships and Jack-up barges.** For replacing large components like the rotor blades, the hub, and the nacelle and in some cases also for components like the gearbox and the generator, it is necessary to hire large crane ships, see Figure 2-5.

Figure 2-5: *Examples of external cranes for replacement of large components; Jack-up barge ODIN (left) and crane ship Sea Energy (right)*

- **Vessel and personnel on site all the time.** When going further offshore the time to travel from the harbour to the wind farm will increase, so that the technicians will have only limited production time, may be less than 5 hours. Advantage of having a vessel and personnel on-site all the time is that technicians are able to work a full day. For corrective maintenance this will imply that the total downtime can be reduced while for preventive maintenance less technicians are required. Figure 2-6 shows an impression of the Sea Energy's Ulstein X-bow, which can take 24 to 36 technicians.

Figure 2-6: *Impression of Sea Energy's Ulstein X-bow [Ref. 26]*

2.2 Types of maintenance

When looking at a general level, maintenance can be subdivided in preventive and corrective maintenance. Corrective maintenance is necessary to repair or replace a component or system that does not fulfil its designed purpose anymore. Preventive maintenance is performed in order to prevent a component or system from not fulfilling its designed purpose. Both preventive and corrective maintenance can be split up further and depending on the type of application different levels of detail are used. In the CONMOW project [Ref. 11, Ref. 12] it is shown that when considering wind turbine technology the following categories seem appropriate, see also Figure 2-7.

- Preventive maintenance;
  - Calendar based maintenance, based on fixed time intervals, or a fixed number of operating hours;
  - Condition based maintenance, based on the actual health of the system;
- Corrective maintenance;
  - Planned maintenance, based on the observed degradation of a system or component (a component is expected to fail in due time and should be maintained before the actual failure does occur);
  - Unplanned maintenance, necessary after an unexpected failure of a system or component.

Both condition based preventive maintenance and planned corrective maintenance are initiated based on the observed status or degradation of a system. The main difference between these two categories is that condition based preventive maintenance is foreseen in the design, but it is not known in advance when the maintenance has to be carried out, while the occurrence of planned corrective maintenance is not foreseen at all. This is illustrated by the examples below.

Example condition based preventive maintenance
The oil filter has to be replaced several times during the lifetime of the turbine. To avoid calendar based maintenance the oil filter is monitored and the replacement will be done depending on the pollution of the filter. So it is not the question **if** this maintenance has to be carried out, but **when** it has to be done.

Example planned corrective maintenance
During the lifetime of the turbine it appears that the pitch motors show unexpected wear out and have to be revised in due time to avoid complete failure. Until this revision, if carried out in due time, the pitch system is expected to function properly. On contrary to the example above this type maintenance was initially **not** foreseen, but as it is not necessary to shut down the turbine, the maintenance can be planned such that it can be carried out at suitable moment.

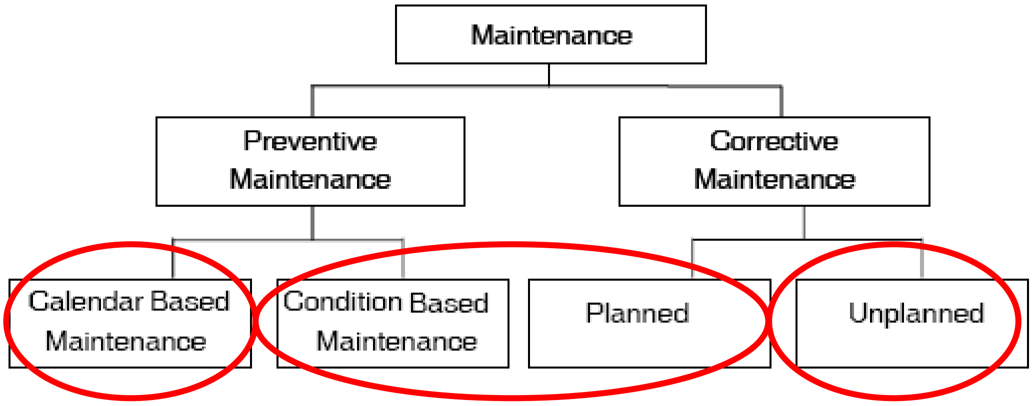


Figure 2-7: *Schematic overview of the different types of maintenance [Ref. 11]*

Considering the limited differences between condition based preventive maintenance and planned corrective maintenance, the planning and execution of both categories will probably be similar in practice. Hence, only three types of maintenance have to be considered:

- Unplanned corrective maintenance
- Condition based maintenance
- Calendar based maintenance

For offshore wind energy, condition based maintenance is preferred above unplanned corrective maintenance since it can be planned on time. Spare parts, crew and equipment can be arranged on time and the turbine can continue running during bad weather conditions. Consequently, revenue losses can be limited.

2.3 Cost estimation

Generally, the costs for maintaining an offshore wind farm will be determined by both corrective and preventive maintenance. In Figure 2-8, the different cost components are schematically drawn. The O&M costs consist of preventive maintenance costs which are usually determined by one or two visits per year. After 3 or 4 years the preventive maintenance costs can be somewhat higher due to e.g. oil changes in gearboxes. On top of that there are corrective maintenance costs which are more difficult to predict. At the beginning of the wind farm operation the corrective maintenance costs can be somewhat higher than expected due to teething troubles. Finally, it might be that major overhauls (e.g. replacement of gearboxes or pitch drives) are foreseen once or twice per turbine lifetime.

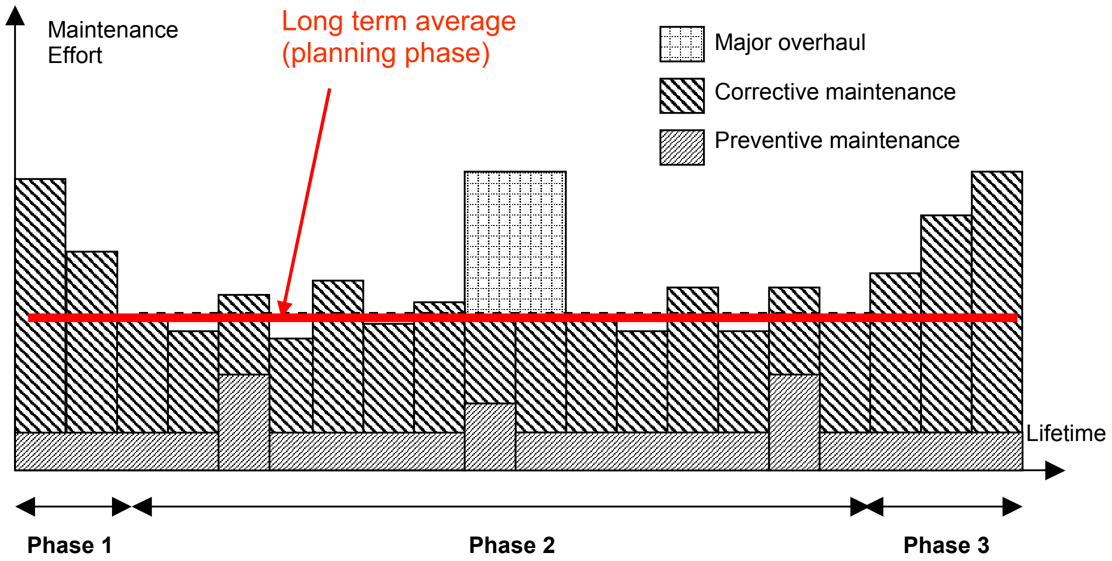


Figure 2-8: *Schematic overview of the maintenance effort over the lifetime of a turbine. In reality, none of the lines is constant; the actual maintenance effort will vary from year to year.*

For many technical systems three phases can be identified over the lifetime and this is also schematically drawn in Figure 2-8.

Phase 1: During the commissioning period, the burn-in problems usually require additional maintenance effort (and thus cost). Time should be spent on finding the right settings of software, changing minor production errors, etc. During this period the maintenance effort usually decreases with time.

The turbine manufacturer usually provides a contract to the customer with a fixed price for the first five years of operation. The contract includes commissioning, preventive and corrective maintenance, warranties and machine damage.

Phase 2: During this phase random failures might be expected, and the failure rate is more or less constant over this period. However in reality the actual maintenance effort will vary from year to year and will fluctuate around the long-tem average value, which is displayed in Figure 2-8 by the red line.

After say about 10 years of operation, it is very likely that some of the main systems of the turbines should be revised, e.g. pitch motors, hydraulic pumps, lubrication systems, etc. With the offshore turbines, no experience is available up to now on how often a major overhaul should be carried out. The exact point in time at which the overhaul(s) should take place is presently not known, perhaps after 7 years, 15 years, or not at all. The major overhaul in fact is to be considered as “condition based maintenance”.

Phase 3: At the end of the lifetime it is likely that more corrective maintenance is required than in the beginning of the lifetime. It is presently unclear how much more this will be.

Figure 2-8 schematically shows the variation in O&M effort over the years that should be considered to assess the expected costs and downtime. If one is interested in the average O&M costs over the lifetime the yearly variation is not of importance and the annual costs can be determined based on long term average values of failure rate costs, etc. This approach is used in the O&M Tool, which is briefly described in Appendix A. This approach is especially suitable in the planning phase of new project.

It is clear from Figure 2-8 that the costs in a certain year may deviate significantly from the long term average value. Due the randomness of the occurrences of failures it may occur that in one year the number of failures is much higher than average and in another year much less. In case the number of failures is higher than average it may occur that the downtime per failure is higher than average due to the unavailability of ships or spares. On the other hand if the number of failures is less than average the cost of equipment per failure may be higher, because of overcapacity. In both situations it is assumed that the number of ships is allocated based on the average failure rate. So if one is interested not only in the average value of the cost but also in expected variation, the cost estimation should be based on the actual occurrences of failures, which can be modelled by means of a Poisson process [Ref. 13]. However this implies that the cost estimation should be done based on time simulation taking into account operational data, which has been applied in de OMCE-calculator.

2.4 Modelling approach

Before an O&M model can be set up first the process of the different types of maintenance should be clear, which is outlined in Section 2.4.1 through 2.4.3. The overall maintenance process is described in Section 2.4.4.

2.4.1 Unplanned corrective maintenance

Unplanned corrective maintenance is performed after a component or system in a wind turbine fails, which causes the turbine to shut down. A typical maintenance process of unplanned corrective maintenance is shown schematically in Figure 2-9.

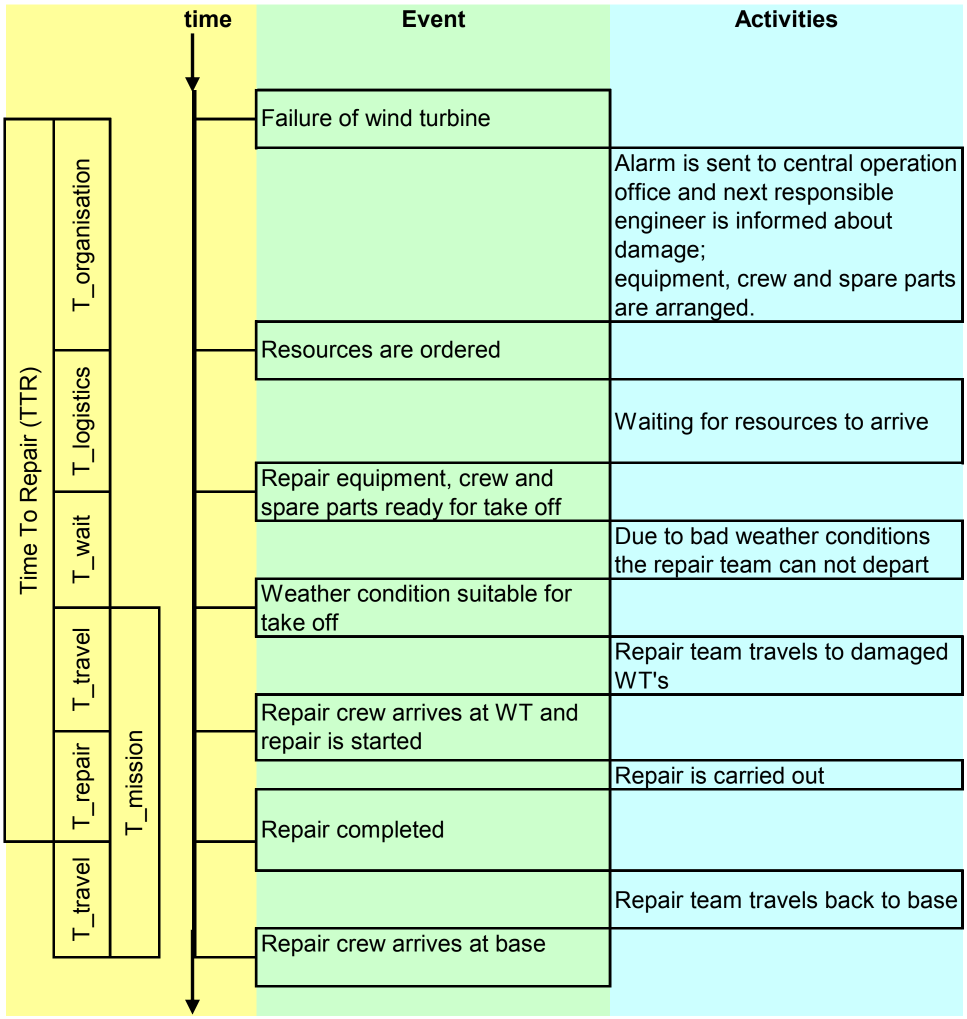


Figure 2-9: *Maintenance process for unplanned corrective maintenance*

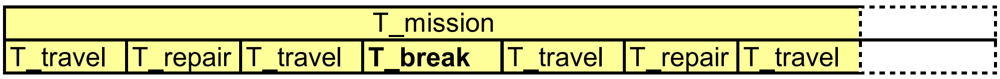
When moving from top to bottom in the scheme the following phases can be distinguished:

- **Failure of a wind turbine**;
  - In case a failure occurs in one of the turbines in an offshore wind farm an alarm message is sent to the operator.
  - Depending on the error message the operator decides how to continue. For instance. the following options might be applicable.
    - A maintenance crew will be sent to the turbine to carry out the repair. This situation is depicted in Figure 2-9.
    - First an inspection team will be sent to the turbine and based on the inspection report a maintenance team will be sent to the turbine to carry the repair later on. For the inspection the process depicted in Figure 2-9 is applicable also, when the inspection is interpreted as a special type of repair.
    - After the inspection two options are applicable. The first option is that the turbine is started again after the inspection, and if maintenance is required it can be categorized as condition based maintenance. The second option is that the turbine is kept shut down until the repair has been completed. In this case the process depicted in Figure 2-9 has to be repeated. After the inspection where the process will end with “inspection completed” instead of “repair completed”, the process will start again with the organisation phase for the repair, during which the result of the previous phase are analysed. In fact a sequence of phases may occur. F.i. after an inspection it is concluded that a more specialised inspection is needed to determine the actual damage and subsequently the repair is carried out. And after the replacement of a main component first an inspection is needed before commissioning of the wind turbine.
- **Ordering resources**. The operator makes the necessary arrangements for the maintenance crew and the equipment required (vessel, helicopter, etc) and spare-parts. Once all logistic activities have been completed the maintenance crew, the required equipment and the spare-parts are available and the trip to the turbine can start. This time period (T_logistics) depends largely on the availability of crew, equipment and spare-parts, which on their turn depend mainly on the maintenance policy of the company.
- **Ready for takeoff** to perform the maintenance action. Although everything is in principle ready for takeoff it may happen that the weather forecast during the period the mission has to be carried out (T_mission) is such that it is not allowed or irresponsible to take off. This interval is denoted as T_wait. The length of this interval is dependent on the duration of the mission and the weather limits applicable for the equipment to be used. For a helicopter wave conditions are not important, but fog together with the wind speed are of importance; for a (supply) ship both the wind speed and the wave height have to be less than the specified maximum values. Due to its dependency on weather conditions (wind speed and or wave height) the duration of this interval shows large inherent scatter.
- **Weather conditions are suitable for takeoff**.
  - After a certain amount of time the weather conditions will be suited to complete the mission.
  - The maintenance crew travels to the wind turbine.
- **Start of the maintenance action**.
  - The maintenance crew arrives at the wind turbine in the offshore wind farm.
  - The maintenance work on the wind turbine is carried out.
- **End of the maintenance action**.
  - The maintenance activity is completed.
  - The wind turbine is restarted. As mentioned above in case of an inspection it may occur that the repair will be carried out later on, while in the meantime the turbine is kept shutdown.

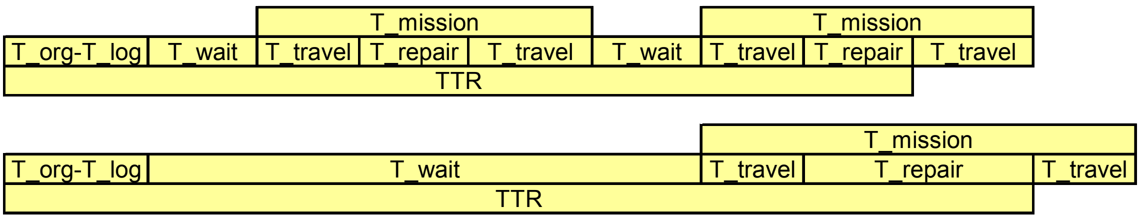
- **End of mission.**
  - The maintenance crew travels back to the harbour.
  - Equipment and crew is available for next activity.

The process described above is relatively basic, but is highly suitable to obtain insight in the whole process, as still the most important phases during an unplanned corrective maintenance action are covered. To use the process outlined as starting point for the development of a computational model the following two refinements should be considered.

1. The process depicted in Figure 2-9 suggests that the repair can be completed during one shift. In practice a repair can be extended over a couple of days, and in this situation the crew will travel back to the harbour or hotel ship at the end of the working day and will travel back to the turbine the next morning. This can be depicted schematically as follows, where T_break denotes the period the crew stays overnight.



2. The process depicted in Figure 2-9 suggests that the repair should be completed in one dense period. Sometimes it is possible to split up the repair in a number of separate missions, as depicted below. The advantage is that in general the total waiting time for two shorter missions is less than the waiting time for one longer mission, hence the total downtime will be less.



2.4.2 Condition based maintenance

Condition based maintenance, which can be either condition based preventive maintenance or planned corrective maintenance, will be initiated based on the observed status or degradation of a certain component. The typical process of a condition based maintenance action is, in general, similar as is shown in Figure 2-9 for unplanned corrective maintenance. Basically three main differences can be distinguished.

1. The start of the maintenance process is not the failure of a wind turbine but the indication that a certain wind turbine component needs maintenance during the foreseeable future.
2. The maintenance is planned in such a manner that the waiting time due too bad weather conditions is limited or excluded. (It should be noted that this might become difficult if equipment has to be ordered beforehand, f.i. for a crane ship.)
3. The wind turbine is only shut down during the actual repair or replacement of the component.

In case of planned corrective maintenance it is expected that the component will fail in the foreseeable future, if no maintenance will be carried out. Obviously this prediction can only be made for a limited number of components in a wind turbine, since for predicting the remaining lifetime of a component either (or a combination of) data from load measurements, condition monitoring systems or visual inspections are required.

2.4.3 Calendar based maintenance

Calendar based maintenance will be initiated according to the planning initially made according to the procedures provided by the manufacturer. Both types of preventive maintenance, calendar based and condition based, are necessary in order to prevent unexpected failures of the various wind turbine components to happen and furthermore to prevent deterioration of the turbine due to slow degradation of certain wind turbine components. The typical preventive maintenance process is very similar to the scheme for unplanned corrective maintenance, as described in section 2.4.3. The three main differences are:

1. The start of the maintenance process is not the occurrence of a failure but the calendar indicating that preventive maintenance should be performed.
2. The maintenance is planned in such a manner that the waiting time due too bad weather conditions is limited or excluded.
3. The turbine is only shut down during the actual work on the turbine.

2.4.4 Maintenance process

In the previous sections the process for the different types of maintenance (unplanned corrective, condition and calendar based) has been outlined. It is explained that in principle the overall process depicted in Figure 2-9 is applicable to all three types, where one should be aware that when looking at a more detailed level several differences are present. The process is elaborated from the viewpoint of one separate wind turbine. In real-life the maintenance manager has to deal with one or probably more wind farms, where random failures do occur in different turbines in the same period, and where the repair of the latest failures has to be scheduled in connection with preventive and corrective maintenance already scheduled before. This interaction is especially of importance in the logistic phase of the process.

In practice the different maintenance activities will probably be managed in different manners, but the following approach is assumed to be realistic. When planning of maintenance activities is started, at first the planning of the calendar based maintenance is made because the effort for this is accurately known. If condition based maintenance is foreseen in the near future, this will be planned too and probably with a higher priority to avoid unwanted stand still. However, this planning may be interrupted as soon as unexpected failures occur and unplanned maintenance is required and it has to be decided how to combine all these maintenance activities. It is obvious that when different alternatives can be considered, it is necessary to assign each type of maintenance with a certain priority in order to be able to structure the interaction between the different types of maintenance. Important for defining priorities is the status of the wind turbine during the maintenance process. For calendar based and condition based maintenance the turbine is shut down only during the period when actual work on the turbine is carried out. For unplanned corrective maintenance the turbine is shut down from the moment the failure occurs until the maintenance action is completed. Therefore it is essential to ensure that the whole maintenance process is completed as fast as possible in order to minimise downtime and revenue losses. In case the unplanned maintenance and planned maintenance coincide and due to limited resources both activities cannot be carried out simultaneously it looks obvious to postpone calendar based or possibly condition based maintenance to avoid unnecessary downtime. However, when postponing this kind of maintenance too much, unexpected failures may occur due to deferred maintenance leading to increased downtime and revenue losses, which should be avoided. Hence it is assumed that calendar based maintenance is not postponed in favour of corrective maintenance, but both types of maintenance are combined when possible.

3. OMCE Project

3.1 Background and objectives

As part of the Bsik programme 'Large-scale Wind Power Generation Offshore' of the consortium We@Sea [Ref. 14], ECN initiated the idea of developing the Operation & Maintenance Cost Estimator as a tool that could be used by operators of large offshore wind farms to monitor the O&M effort for wind farms in operation already and to control the costs of these wind farms for the coming period of e.g. 1, 2 or 5 years. To be able to control and subsequently to optimise the future O&M costs of these wind farms, it is necessary to accurately estimate the O&M costs for the next coming period, taking into account the operational experiences available at that moment. Several reasons are present for making accurate cost estimates of O&M of (offshore) wind farms. Examples are:

- to make reservations for future O&M costs (this is especially important for the party who is responsible for the financial management of the maintenance);
- operating experiences may give indications that changing the O&M strategy will be profitable, and then the costs need to be determined accurately in order to compare the adjusted strategy with the original one;
- before the expiration of the warrantee period, a wind farm owner needs to decide how to continue with servicing the wind turbines (new contract with turbine supplier or to take over the total responsibility) after the warranty period;
- if a wind farm is going to be sold to another investor, the new owner wants to have detailed information on what O&M costs he can expect in the future.

It may be clear that such a tool with these features is not of interest for operators only, but also for other stakeholders (owners of wind farms, wind turbine manufacturers, etc.).

The above mentioned initiative of ECN resulted in the OMCE-project with the main objective to develop methods and tools that can be used to estimate the future O&M effort and associated costs for the coming period of f.i. 1, 2 or 5 years, taking into account the operational experiences of the wind farm acquired during the operation of the wind farm so far. The objective is to determine not only the expected values for characteristic O&M parameters, but also to quantify the effect of uncertainties due to the random occurrence of failures, due to variability of the weather conditions, and the due to the uncertainty in the operational data. The O&M Cost estimator is developed in such a way that cost estimates can be made at any point in time during the operational phase. However, it is a prerequisite that at least 2 to 3 years of operational data are available.

The development of the specifications for the OMCE was carried out within the Bsik programme '*Large-scale Wind Power Generation Offshore'* of the consortium We@Sea. At the moment that the We@Sea project finished in 2009, the D OWES (Dutch Offshore Wind Energy Services) project [Ref. 16] was started, and within this project the development of the Event List (see Chapter 11) and the programming of the OMCE-Calculator (see Chapters 4 - 8) were carried out.

3.2 Description of the OMCE concept

3.2.1 Overall structure

The OMCE is designed to determine the O&M effort and associated costs for the coming period (say the next 1, 2 or 5 years) taking into account the operational experience available at that moment. That's why two major modules can be distinguished in the overall structure of the OMCE as depicted in Figure 3-1.

1. The OMCE Building Blocks
   To proces operational data four so called OMCE Building Blocks (BB)[1] have been specified, each covering a specific data set.
   - BB *Operation and Maintenance;*
   - BB *Logistics;*
   - BB *Loads and Lifetime;*
   - BB *Health Monitoring;*

   The main objective of these building blocks is to process all available data in such a way that useful information is obtained, which on the one hand can be used for monitoring purposes and which on the other hand can be used to specify the input for OMCE calculator. If convenient other types of building blocks can be included.
2. The OMCE-Calculator
   The main objective is to determine the expected O&M effort and associated costs for the coming period, where amongst others all relevant information provided by the OMCE Building Blocks is taken into account. Three types of maintenance are included, viz. calendar based maintenance, condition based maintenance and unplanned corrective maintenance.

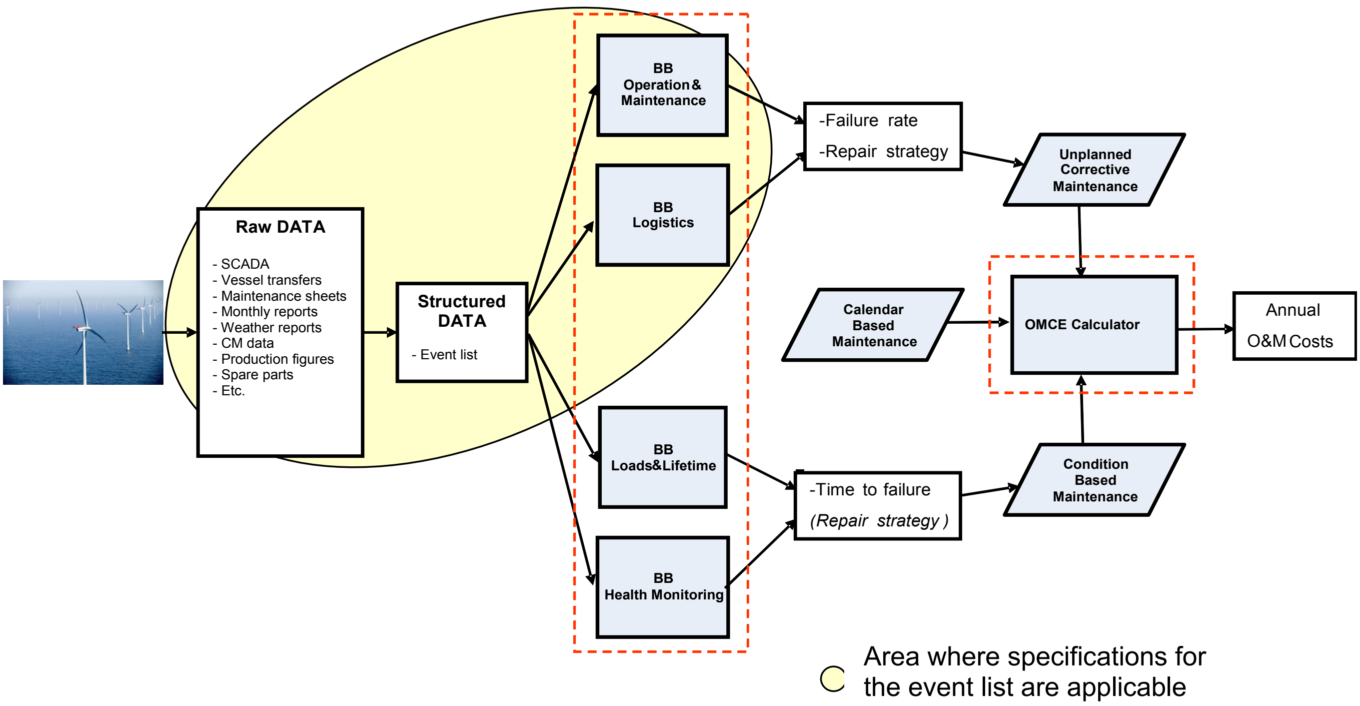


Figure 3-1: *OMCE concept including the process of structuring the raw data into an event list*

3.2.2 Event List

Originally it was assumed that the different data sources would provide enough information to execute the different BB's. However, from previous studies it was concluded that especially the O&M data and the logistics data were **not** available in a format suitable for straightforward further processing. The main reasons for this are:

[1] In fact a 5th Building Block called "Meteo" should be considered to assess the influence of the actual weather conditions on the O&M aspects as compared to the weather conditions assumed in the development phase of a wind farm. However, the further development of this 5th BB is beyond the scope of the OMCE developments within the We@Sea and DOWES framework.

- During the first few years of operation, operators are not in charge of the maintenance. Although they do receive copies of worksheets, SCADA data, and information on the use of equipment and spare parts, it is in most cases not traceable why certain activities are carried out and how some activities are linked to e.g. alarms or other activities.
- For those operators that are not in charge of the maintenance, there is not really a need to analyse the O&M data in large detail and to determine the cost drivers. In most cases long term contracts are signed with a service provider (usually the turbine supplier). The operator is not forced to analyse the data and thus to set up a structured format for data collection.
- The data are stored in different sources and in different formats, sometimes even handwritten. This makes it difficult to automate the processing, especially because the different data sources are generally not well correlated.

It was concluded that the acquisition of raw data generated by an offshore wind farm should be structured such that the data stored in various data sources are correlated uniquely. Based on the workflow controlled by the maintenance manager of a wind farm, a possible method is outlined for O&M related data. According to this method all O&M related data stored in the different data sources are correlated be means of the “initiating event” for a certain maintenance activity. In case data are collected in such a structured manner it should be possible to extract the so called “event list” from these data sources. Per turbine the event list contains an overview of the different maintenance events that have occurred in chronological order. Per event, relevant issues like the failed component, the trigger for a repair action, the equipment and labour used need to be stored. The event list is meant to structure and classify the raw data in such a way that it can be processed by the OMCE BB’s “Operation and Maintenance” and “Logistics”. For further development of the OMCE it is assumed that raw data can be imported in a relational database and that the event list can be extracted from this database. The structure of the event list is described in detail in Chapter 11.

3.2.3 Interface between Building Blocks and Calculator

As shown in Figure 3-1 the OMCE consists of 4 building blocks to process a specific data set each. The objective of processing the operational data is in fact twofold.

1. To provide information to determine or to update the input values needed for the calculation of the expected O&M effort.
2. To provide information that gives insight in the health of the wind turbines, for example by means of trend analyses.

In this report special attention will be given to the first objective in order to specify in more detail what kind of output is expected from the different building blocks in order to generate input for the OMCE-Calculator. It is not expected that the input needed for the calculations can be generated automatically in all cases. The opposite might be true, namely that experts are needed to make the correct interpretations. It is important to realise that there is a difference between the output of the different Building Blocks and the input needed for the OMCE-Calculator. The input needed for the OMCE-Calculator should represent the expected values for the coming period. The various BB’s describe the historical situation. If the future situation is expected to be similar to the historical situation, the information of the BB’s can be used to generate input data for the OMCE-Calculator. If the new situation has changed, the information of the BB’s should be used with care or maybe not used at all. Examples of changes are given below.

- The BB’s “Operation & Maintenance”, “Health Monitoring”, and “Loads & Lifetime” generate data (failure rates and expected times to failure) at the level of main systems, components or even (and most preferred) at the level of failure modes. If for instance certain components have been replaced (or will be replaced soon) in all turbines (e.g. by components from different suppliers), the data determined by the various BB’s do not necessarily represent the new situation. In the case of failure rates, new estimates need to be made for these components, e.g. by using data from generic databases, or by means of engineering judgement.

- Costs of personnel, equipment, spares, etc are very important input for the OMCE-Calculator to determine the (near) future O&M costs. Most of the cost items are very dependent on the type of contract between operator and e.g. component supplier or maintenance contractor. Such contracts, and thus the prices of spare parts or for renting equipment will change over time. The input for the OMCE should represent the contracts for the next coming period. Analysing the historical costs to generate input data only makes sense if the new situation with new contracts is similar to the historical situation.

So in general it can be said that it is not always necessary to extract all input data from historical data. It is important that the new cost estimates are based on values that represent the future developments best. This means that not all output of the BB's can and will be used as input data for the OMCE-Calculator. The BB's can be used later on to assess if the new situation indeed is an improvement as compared to the historical situation. E.g. the BB "Operation & Maintenance" can be used to verify if the failure rate of a new component indeed is less than the failure rate of the original component. Furthermore it is important to realise that the BB's "Operation & Maintenance", "Health Monitoring", and "Loads & Lifetime" generate data at the level of components or even at the level of failure modes whereas the OMCE-Calculator requires input data at the level of Fault Type Classes (FTC's).

3.3 Integral monitoring and control system

Although the OMCE is being developed as a standalone system it is expected that in the future the OMCE will become part of integral information and decision support systems, f.i. an IT-system as being developed by Dutch Offshore Wind Energy Services DOWES [Ref. 15, Ref. 16]. DOWES is a 4 year research project, which started in May 2009, and will stretch until the end of 2013 and does focus on the development of an integral monitoring and control system for various offshore wind farms at the North Sea. The development of the DOWES system is twofold. On one hand the development focuses on the raw data. The envisioned system is a platform which supports and enables the monitoring and control functionalities of (offshore) wind turbines, regardless of the type, manufacturer or capacity of the turbine. On the other hand the development is focused on the integration of data and information obtained and provided by parties in the value chain. This requires current insights and inclusion of detailed processes and information down to the individual users whereas information and decision support on strategic level requires overviews and extensive prognoses on the mid- and long-term.

The position of the OMCE BB's and the OMCE-Calculator within the DOWES portal is schematically depicted in Figure 3-2. The BB's will be integrated within the IT-system. However, the OMCE-Calculator is positioned as an add-in to the system. The input for the OMCE-Calculator is provided by the system and the results obtained with the OMCE-Calculator are stored in the integral system. In this way both the results of the BB's and the results generated by the OMCE-Calculator can be made available for long-term decision support. For instance when optimisation of the O&M strategy has to be considered, several scenarios can be analysed by means of the calculator using data originating from the BB's and other data sources available. After the results of these analyses are stored in the system they can be approached by the user in connection with all kind of other data to decide upon possible improvements in the O&M strategy.

In case the OMCE has to be integrated in a client specific information and decision support system a system similar to Figure 3-2 can be set up such that the client specific requirements are fulfilled.

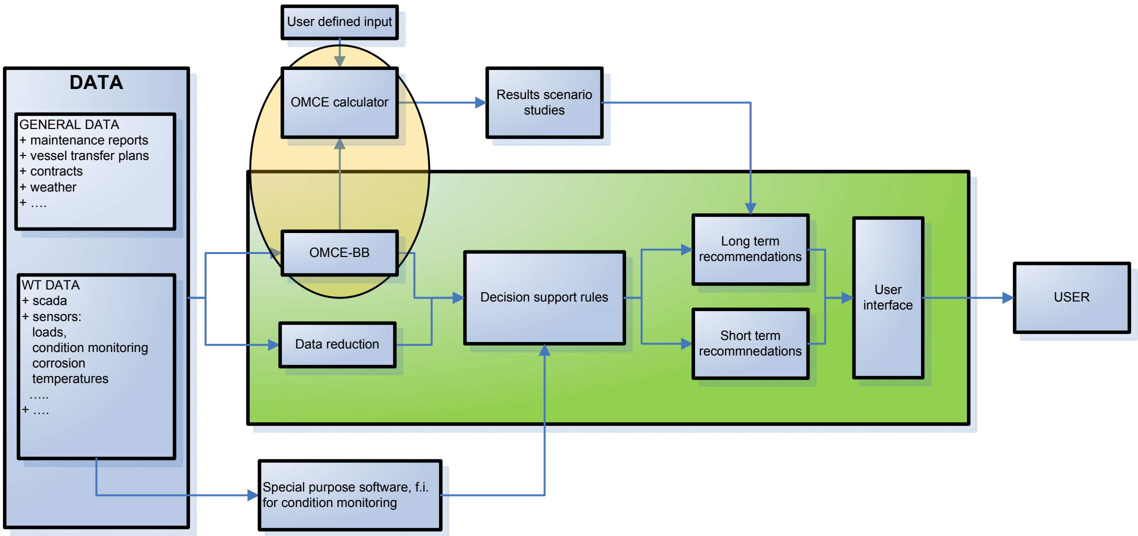


Figure 3-2: *Structure of the D OWES system for optimising O&M of offshore wind farms in the long and short term making use of wind farm data. The green rectangle represents the portal from which all data sources and models can be approached. The orange oval represents the OMCE concept. The OMCE-Calculator uses the data processed by the OMCE BB's as input.*

Part II:
OMCE Calculator

4. Specifications of the OMCE Calculator

The OMCE Calculator in fact is the tool to calculate the O&M aspects (among others in terms of downtime, costs, and revenue losses) as indicated in the left part of Figure 3-1, see also details in The OMCE Calculator has been designed to model the following types of maintenance:

- unplanned corrective maintenance
- condition based maintenance, and
- calendar based (preventive) maintenance.

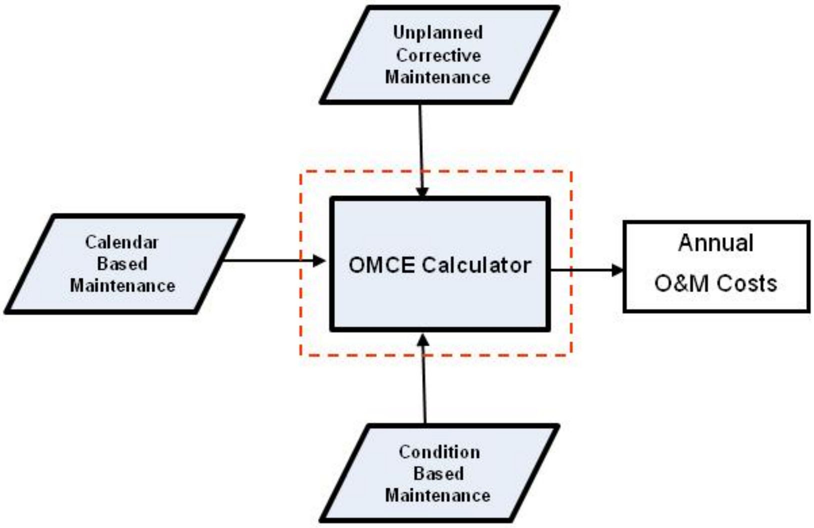


Figure 4-1: *OMCE Calculator to model 3 types of maintenance and estimate O&M aspects*

In this chapter, the specifications of the OMCE Calculator will be discussed briefly. In the following sections the general specifications of the software are given, followed by specifications of the different input modules, the actual calculation part, and the output module. In some cases it is mentioned how certain aspects have been modelled and implemented, but most of the details on the modelling solutions and the implementation in the Matlab software can be found in the Chapters 5 through 8.

4.1 General

The OMCE is a time simulation program designed to assist operators of wind farms to determine the optimal O&M strategy during the operational phase of a wind farm. The OMCE Calculator uses actual wind farm data as input and is able to estimate the future O&M costs for a period that is typically 1 to 5 years[2]. The estimate of the future O&M costs also includes the quantification of uncertainties in costs and downtime. Once the O&M aspects have been analysed for the "as-is" situation, the operator may analyse different O&M scenarios (by changing the input of the OMCE Calculator) and select the most cost effective one.

[2] Longer periods can also be analysed but it is then questionable if the acquired wind farm data are representative for the longer period.

4.2 Input module

4.2.1 Wind farm, wind turbine and Balance of Plant (BOP) data

The OMCE Calculator requires characteristic values of the wind farm as input, a.o. the number of turbines, the power performance curve, and the BOP items. For the turbines a breakdown needs to be made into maintainable items (main systems or components) preferably coded in accordance with the RDS-PP coding system [Ref. 19].

4.2.2 Unplanned corrective maintenance

The OMCE is able to take into account corrective maintenance as follows. To each maintainable item an annual failure frequency can be assigned. The annual failure frequency may consist of several failure modes with different severities and for each failure mode the required repair strategy can be defined. To consider the stochastic nature of the failures, the OMCE Calculator uses the Poisson process [Ref. 13] to generate random failures. The repair strategy comprises a.o. the required type of vessels, hoisting equipment, crew size, duration and number of repair visits.

4.2.3 Condition based maintenance

For condition based maintenance, the OMCE allows to select a certain amount of turbines (or components) that need to be maintained in a certain period of time. One is able to select the turbines (or components) and to define a maintenance activity. Such a maintenance activity consists of the same items as mentioned for unplanned corrective maintenance. A major difference between the two types of maintenance is that the OMCE assumes that the downtime of the condition based maintenance activities is equal to the actual repair time. Downtime due to logistic time of spare parts and vessels and due to bad weather is not relevant. The OMCE is among others able to determine if the resources dedicated to a condition based maintenance activity and/or the time period reserved for the activities are sufficient.

4.2.4 Calendar based maintenance

The input needed to model calendar based maintenance is more or less similar to the input needed for condition based maintenance. The difference however is that not a selection of turbines is chosen, but all turbines. The OMCE also returns with information whether the resources and chosen time period are sufficient.

4.2.5 Equipment

To model a certain maintenance or repair strategy it is necessary to define different types of equipment with its characteristic values. The characteristic values that can be defined are (if relevant) a.o.:

- the weather conditions during which the vessels (or helicopter) can be used,
- the (de)mobilisation time,
- travel time,
- time needed for positioning,
- the costs for long term renting,
- variable costs,
- hourly or day rates,
- (de)mobilisation costs, and
- costs during waiting.

4.2.6 Spare parts

In some cases when maintenance actions are carried out, spare parts are needed and the OMCE Calculator allows to consider the following aspects:

- spare part cost,

- whether or not on stock (including stock size and time needed for re-ordering),
- logistic time.

4.2.7 Weather conditions

The OMCE Calculator needs site specific weather data as input, preferably as time series with a sample rate of 3 hours. The model on the one hand needs the weather data to assess if maintenance can be carried out with certain vessels and given the restrictions for working offshore, and on the other hand to determine the revenue losses of the turbines during stand still.

4.2.8 Repair strategy and maintenance plans

The OMCE Calculator allows the user to define for each identified failure mode how a certain repair or maintenance action should be carried out. The user can define how many visits are needed, the sequence of the visits, how many technicians are needed per visit, which vessels will be used, the duration of each visit, whether or not spare parts are needed (on stock or not), and the time needed to organise each visit. The user can indicate if a visit can be interrupted (e.g. during the night) or if it needs to be one continuous avtivity.

4.3 Output module

The OMCE Calculator processes the input data (see Section 4.4) and generates output that can be used by the operator to determine the most cost efficient O&M strategy for the next coming years. Therefore the OMCE Calculator generates various graphs and tables. Especially the graphs are grouped in a way that they can be easily used for different purposes, e.g.

- "Summary of results" to inform the management about the optimal strategy,
- detailed information about the used "equipment" for "Optimisation" purposes (see Figure 4-2),
- or reflection of the input to be used by the analyst to quickly check the correctness of the input data.

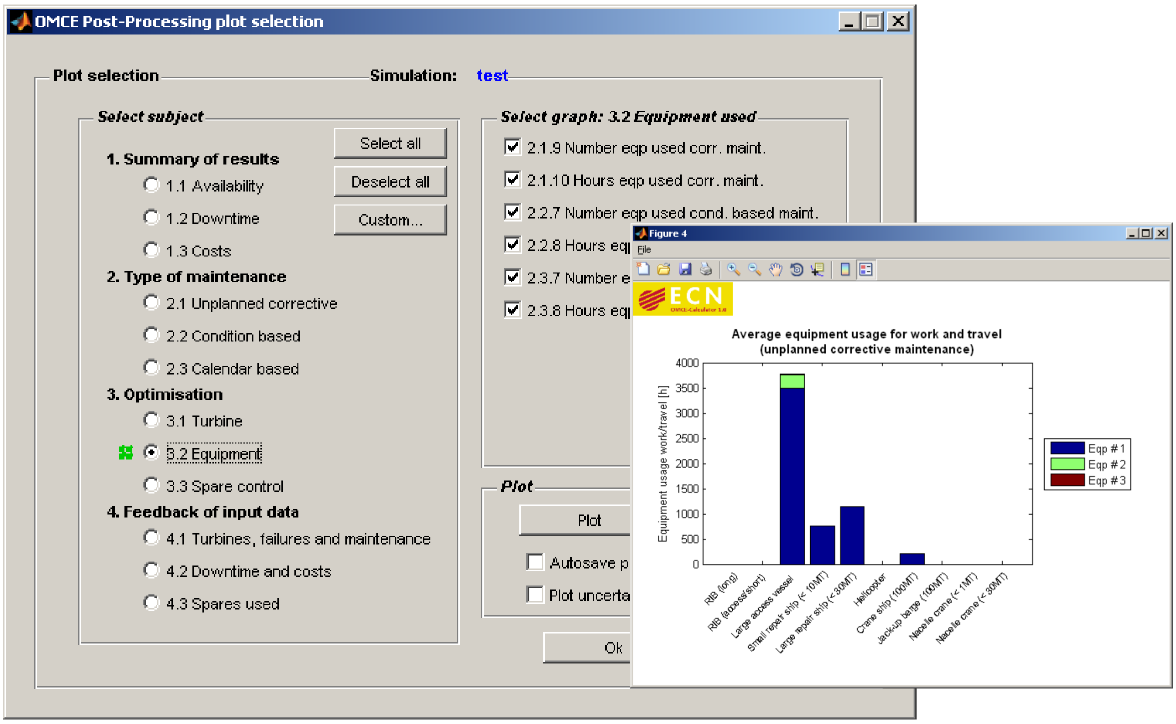


Figure 4-2: *Example of a plot to investigate and optimise the usage of equipment during corrective maintenance*

As can be seen in Figure 4-2, many output options are available from the OMCE as figures and/or as Cumulative Density Functions (CDF) to quantify average values and uncertainties. The output options provide among others information about:

- availability figures (for the wind farm, for each month, per turbine)
- downtime (for the wind farm, for each month, per turbine, per system, per maintenance activity)
- revenue losses and costs (per kWh, total costs, per type of maintenance)
- unplanned corrective maintenance (number of events, downtime, costs, spare parts used, equipment used)
- condition based maintenance (number of events, downtime, costs, number of events finished on time in selected period, spare parts used, equipment used)
- calendar maintenance (number of events, downtime, costs, number of events finished on time in selected period, spare parts used, equipment used)
- turbine (number of failures and downtime per system)
- equipment (number of times and hours equipment is need for the three types of maintenance activities)
- spare part control (number of spares for the three types of maintenance activities, probabilities of having no spares on stock and minimum stock size)

In addition to the graphs, the OMCE Calculator also generates an MS-Excel sheet with all data for further use, even the results per simulation.

4.4 Calculation module

The OMCE Calculator is designed in such a way that it treats the following aspects.

- The software generates an integral maintenance plan that takes into account that certain maintenance activities have a higher priority than others. Depending on the actual occurrence of failures, the actual weather conditions, and the available resources at that time, the maintenance plan is continuously being updated.
- The software takes into account that the available resources (vessels, crew, and spares) are limited and quantifies the consequences of this.
- The software takes into account that in certain periods (e.g. spring and summer) more crews and vessels can be available to carry out preventive and condition based maintenance.
- Uncertainties in random failures and weather conditions[3] (see also Appendix B).
    - The number of failures in a certain year is a stochastic quantity and the OMCE Calculator, uses the Poisson process [Ref. 13] to generate random failures.
    - By carrying out multiple simulations uncertainties in the weather conditions and in the occurrence of random failures (both will differ from year to year!) can be taken into account.
- Because the OMCE-Calculator is meant to make estimations for a relatively short period (1 to 5 years) and because the random occurrence of failures in combination with the actual weather conditions has to be taken into account, it was obvious to develop the software as a time based simulation model and by carrying out a (large) number of simulations the uncertainties are quantified.
- Since the model is a real time simulation tool, it takes into account the effect that during standstill and periods of high wind speeds work cannot be executed, and thus the revenue losses are high.

[3] A third type of uncertainty is the statistical uncertainty of input parameters (e.g. the failure frequencies of components). This type of uncertainty cannot be modelled with the present version of the OMCE Calculator but will be implemented in future versions.

- After the OMCE Calculator has carried out the defined number of simulations, results are stored and the software provides post-processing options to provide the required output (data, pots, etc.) to the user of the tool.

Considering the above mentioned specifications it is clear that when analysing future O&M aspects one has to deal amongst others with the random occurrence of failures, the stochastic nature of the weather conditions and furthermore a number of input variables are not known accurately but show some uncertainty. In Appendix B these uncertainties are described in more detail.

To model the simulation process an integral maintenance plan will be elaborated as a function of time, taking into account the interaction between the different maintenance types, the simultaneous maintenance actions on different wind turbines, and the availability of resources. The principle of the integral maintenance plan is explained in Chapter 6.

5. Modelling Maintenance Types

In Chapter 4, the specifications of the OMCE-Calculator are described including a summary of the input data needed to define the three types of maintenance. In this chapter the three different maintenance types are described in large detail and all aspects relevant for cost modelling are discussed. It is outlined how the different aspects are modelled and parameterised. The description starts with unplanned corrective maintenance because this type of maintenance is the most complex to model. Subsequently condition based maintenance and calendar based maintenance are discussed. For modelling the different types of maintenance, a uniform approach is proposed for all three types. In the sections on condition based maintenance and calendar based maintenance especially the differences with unplanned corrective maintenance are highlighted. In case of similarities, reference is made to descriptions under unplanned corrective maintenance. If relevant, the different approaches are illustrated with examples.

5.1 Unplanned Corrective Maintenance

To model the O&M aspects of unplanned corrective maintenance it is relevant to consider "the smallest maintainable items", and to quantify the associated maintenance effort. Therefore a turbine design needs to be broken down into these items. Also it is relevant to consider for each item the different failure modes in order to develop adequate maintenance schemes, including resources to be assigned to the individual maintenance actions.

However, if all items and failure modes will be dealt with one by one, the approach may lead to a very extensive list of maintenance actions of which many of them are nearly the same. To limit the number of maintenance actions that needs to be modelled and of which the costs needs to be determined, a proposal is made in this chapter to limit the number of maintainable items and to categorise the maintenance actions.

5.1.1 Turbine breakdown and definition of "Fault Type Classes"

The maintenance action that should be carried out after a failure strongly depends on the failed component and the corresponding failure mode. The complete breakdown of an offshore wind farm can be generally described by the following scheme:

Wind farm
- ↳ Wind Turbines and/or Balance of Plant (BOP)
  - ↳ Main Systems
    - ↳ Components
      - ↳ Failure Modes ⇒ Repair

The offshore wind farm consists of a number of turbines. In each turbine a number of main systems can be distinguished, where each main system can be subdivided in a number of components. For each component one or more failure modes are possible and to each failure mode a certain repair action is linked. The same holds for BOP.

It is desirable to group all possible maintenance activities into a limited number of manageable categories similar to the Fault Type Classes (FTC) in the ECN O&M Tool, see Figure 5-1.

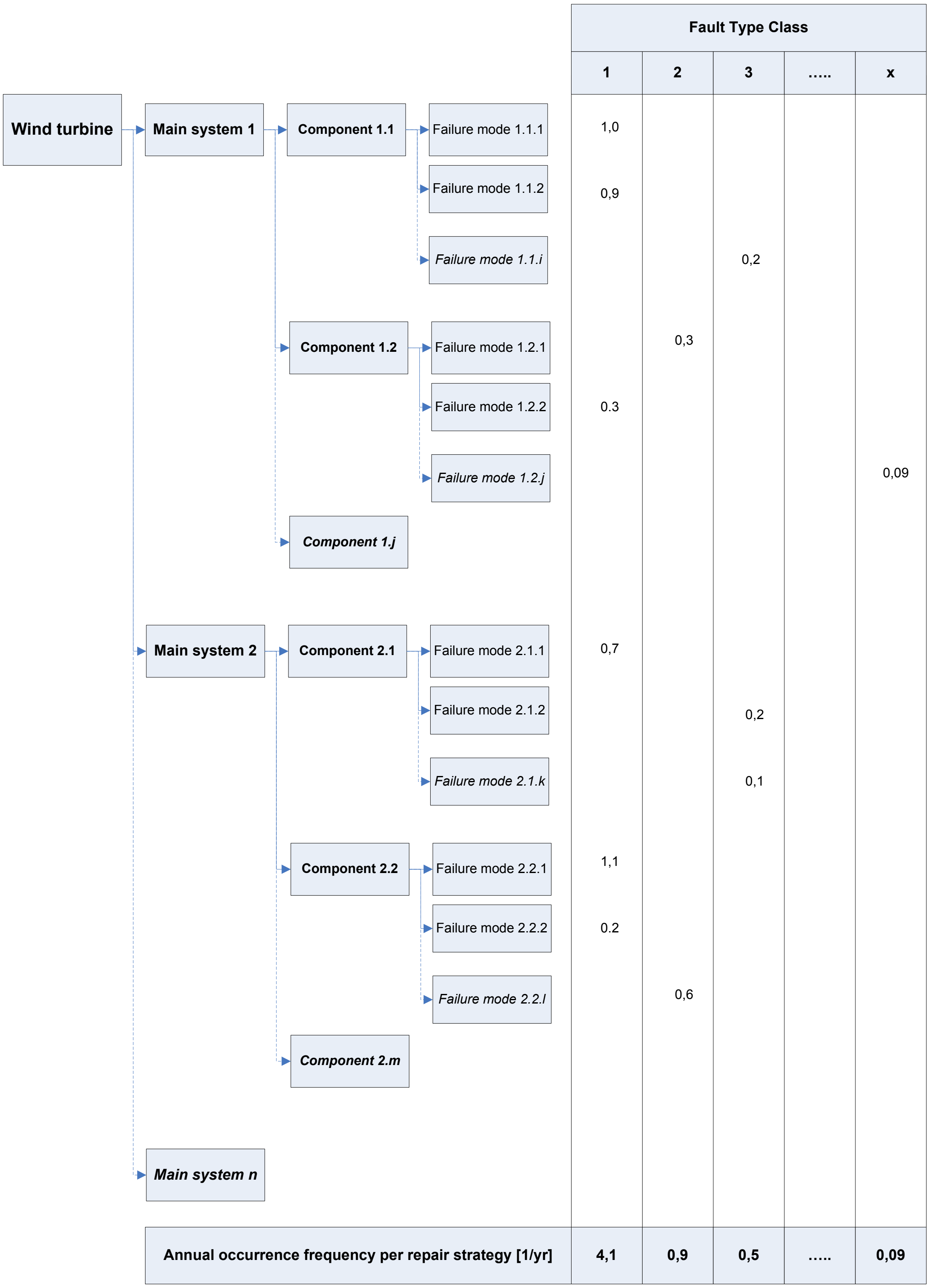


Figure 5-1: *Example of grouping failure modes into manageable set of fault type classes*

To determine at what level the maintenance actions are grouped for the OMCE Calculator the following points were of interest:

- availability of failure frequency data;
- feedback of maintenance data;
- implementation of stock control;
- level of detail desired by the user of OMCE-Calculator.

To estimate the expected failure behaviour generic reliability data are generally used, especially when no or limited operational data are available. The latter is applicable in the initial phase of a new wind farm. It is the author's experience that generic failure and reliability data only contains information of failure frequencies at the level of turbines or main systems. Occurrence frequencies of failure modes are hardly reported and published. This implies that it is not feasible to specify a failure frequency at a more detailed level in the breakdown of the wind farm (e.g. component or failure mode), since these data simply are not available.

When analyzing the maintenance data of a specific wind farm, it is expected that in the initial phase only a very small amount of maintenance actions are recorded for each defined failure mode. Therefore it is not possible to perform reliable trend analyses at this level and in this phase a sound quantification of the failure rates can be done at the level of main systems or in some situations on the level of components only. Based on the information derived from maintenance reports together with engineering judgement it should be possible to split up the maintenance activities for a main system into groups of similar severity with respect to the way the work is carried out, the costs of components and the logistic aspects[4]. In fact the groups are the FTC's. To assign failure rates to these FTC's it is obvious to specify the relative contribution of the FTC's to the total amount of failures of a certain system, because this is a logical approach when dealing with the results of engineering judgement and the interpretation of the maintenance reports when only a limited amount of data is available. It should be noted that during the lifetime more and more data become available, so that the quantification of the occurrence of the different FTC's will improve with time.

Another requirement for the O&M Cost Estimator is the implementation of stock control. To implement stock control it is necessary, when grouping maintenance activities, that the failure modes which lead to a replacement of a component for which stock control is applicable are treated as separate FTC's.

The level of detail of the results of the OMCE-Calculator is mainly determined by the level of detail of the input data. However, also the requirements of the user of the OMCE-Calculator have been considered. Hence the OMCE-Calculator is flexible with respect to the definition of the breakdown of the turbine and the grouping of maintenance actions into FTC's.

In order to accommodate all requirements listed above it is decided that in the OMCE-Calculator a turbine breakdown can be specified up to the level of main systems. The number of main systems can be specified by the user, in accordance with the level of detail required. To uniquely code the main components and systems of a wind power plant it is suggested to follow the recommendations as stated in [Ref. 19]. In [Ref. 19] a reference designation system for power plants (RDS-PP) is presented for wind turbine purposes based on the long term experiences gained in the power industry.

For each defined main system the annual failure rate, λ_{SYST}, should be specified. Next for each system a number of FTC's can be specified, where all failures within a FTC are similar with respect to the way the repair is carried out (equipment to be used, duration of repair, etc.) and the logistics and costs of the materials (consumables, spares, etc.) to be used. The number of FTC's per system is variable and has to be specified by the user. The distribution of all failures of the main system over the defined FTC's is specified by the relative failure rate, f_{FTC}, and the annual failure frequency per FTC, λ_{FTC}, is defined as:

$$\lambda_{FTC} = f_{FTC} \cdot \lambda_{SYST}$$

In addition to the relative failure rate, for each FTC the following has to be specified:

- Repair Class: the way the failure will be repaired;
- Spare Control Strategy: if spares are needed and how spare control is done;

[4] To determine the different failure modes of components and the associated repair actions, it is recommended to use a structured approach like an FMECA (Failure Modes, Effects, and Criticality Analysis).

- Priority Level: needed to determine which repair is carried out first in case simultaneous repairs are not possible due to lack of resources.

The way the failure will be repaired determines among others the usage of equipment (access, hoisting, and transportation vessels), the crew size, the duration of repair, etc. For modelling purposes, a limited number of so-called Repair Classes (RC) can be defined. To each FTC, a Repair Class needs to be assigned which can be selected from a predefined library. This library with RC's has to be set up first, as will be described in section 5.1.2.

Also for the spare control holds that first a number of Spare Control Strategies (SCS) need to be specified in a predefined library (see section 5.1.3). During the specification of a FTC a selection can be made from this library. It is specified whether stock control is applied or not, and furthermore all relevant parameters like logistics of spares, costs, etc. are included in this library.

In case multiple failures occur, the repair actions need to be prioritised in case insufficient resources are available to carry out all repair actions simultaneously. The user can assign a so called Priority Level (PL) to each FTC. For instance, if four small failures occur and one failure that requires a long repair time, one has to decide which failure(s) is (are) going to be repaired first. If small failures do have the highest priority, all resources will be assigned to the four small failures first and the repair of the fifth probably has to be postponed. If the large failure gets the highest priority, the repair of the four small failures will be postponed.

The breakdown of the turbine and the grouping of maintenance activities, which are used for the OMCE-Calculator, are shown in Figure 5-2.

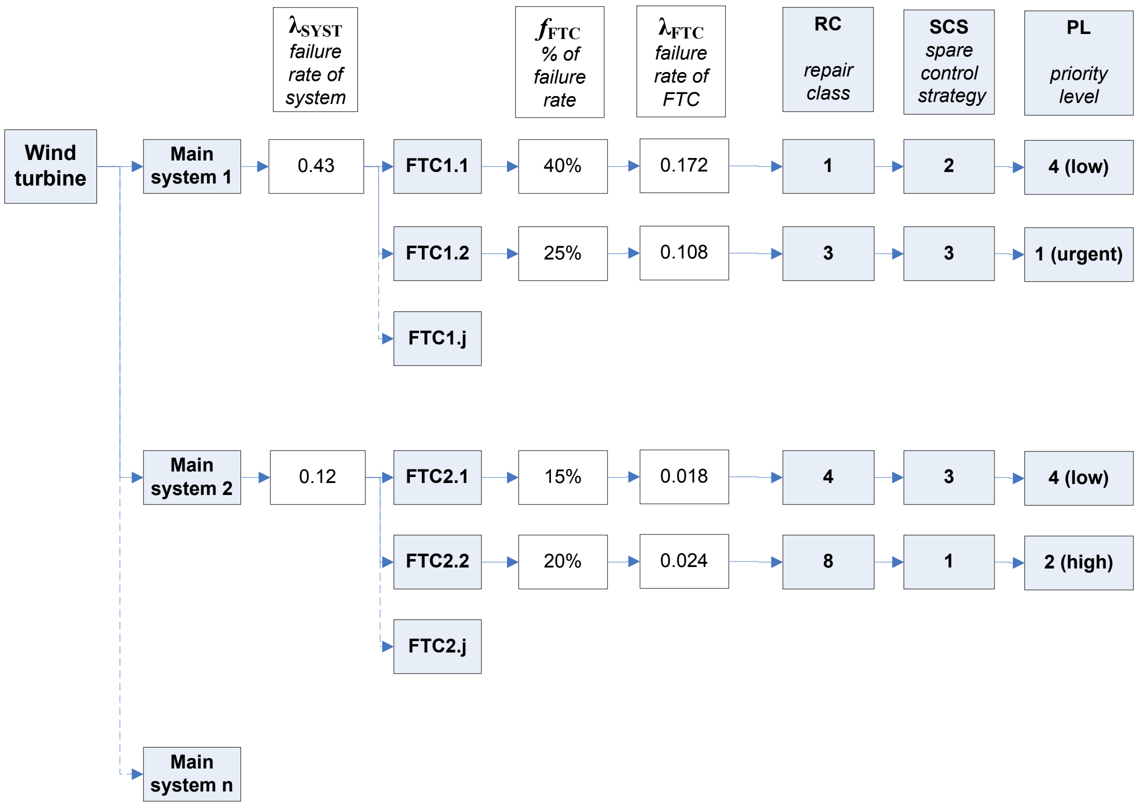


Figure 5-2: *Breakdown of the turbine and grouping of maintenance activities for the O&M Calculator.*

5.1.2 Repair Classes (RC)

In the previous section it was described that for each main system a certain number of Fault Type Classes can be specified. To each of these Fault Type Classes a relative failure rate, λ_{FTC}, a Repair Class (RC), a Spare Control Strategy (SCS), and a Priority Level (PL) needs to be assigned. In this section details are provided about the library structure, which contains pre-defined Repair Classes used for the modelling in the OMCE-Calculator.

Before defining a Repair Class, it will be described which phases have to be carried out during a maintenance action. Next it will be described how the different maintenance phases can be characterised and by which parameters. Finally, special attention will be given to the fact that some maintenance actions need to be split up into two or more periods. This has significant impact on the modelling process.

5.1.2.1 Maintenance phases

In section 2.4.1 the overall process for unplanned corrective maintenance is presented and it is outlined that after a failure a sequence of maintenance phases, each more or less similar to the process depicted in Figure 2-9, may be required before the turbine can be restarted again, which is depicted in Figure 5-3.

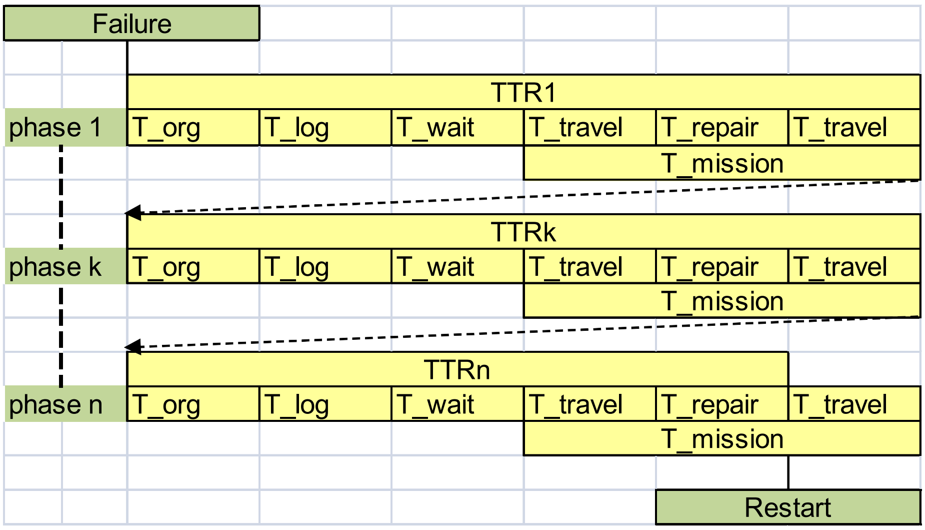


Figure 5-3: *Sequence of maintenance phases*

F.i. after two inspections (phase 1 and phase 2) it is decided that the generator has to be exchanged. Hence during phase 3 the electric cabling is disconnected and next during phase 4 the actual exchange will take place. Finally in phase 5 the electric cabling is installed again and the turbine is commissioned in phase 6. For this purpose in the OMCE-Calculator three types of maintenance phases are distinguished, viz.:

- Inspection
- Repair
- Replacement

Inspection
In some cases it is necessary that a small crew travels to the turbine and performs an inspection to determine the actual damage in the turbine so that it can be decided what kind of maintenance is required. Occasionally, it may be necessary to carry out more than one inspection, for instance if the damage is too complex to detect in detail or to determine the (root) cause. The inspection results need to be analysed and assessed and some time may be needed to organise a second (or third) inspection, e.g. with a representative of the component supplier. After the inspection(s) has been completed and the inspection results have been assessed the maintenance process can be continued by the organisation of the actual repair or replacement.

It is assumed that an inspection does not have to be completed during one continuous operation. For instance an inspection requiring two working days can be carried out during three non successive days. If the weather conditions change suddenly, the turbine will not be damaged. Inspections can thus be split over multiple periods with each a shorter duration. Furthermore it is assumed that for an inspection only one device is used, of either an access vessel, support vessel, or helicopter type.

Repair
The repair phase is used to model all (especially small) maintenance actions on the turbine for which no external hoisting is required. It can also be applied in combination with a large maintenance actions which require external hoisting, (see replacement below), f.i. to carry out pre-operational work (disconnecting electrical cabling in case of generator exchange). Similar to an inspection a repair does not have to be completed during one continuous operation and also for a repair only one type of equipment is used. In fact at the moment the phases inspection and repair are modelled identical.

Replacement
This phase represents the part of the maintenance where a (large) component is replaced. Within this phase four sub-phases can be distinguished, see Figure 5-4.

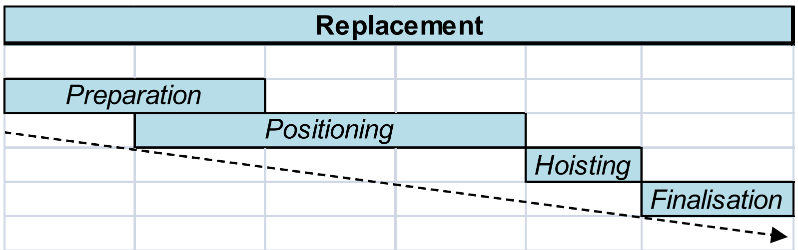


Figure 5-4: *Schematic representation of the possible sub phases for replacement*

The first step is the preparation for the replacement, f.i. by dismounting the failed component. After the preparation has been finished the actual replacement of the component can start. However, in case a jack-up type crane ship is used first a period is required for lifting the ship (partially) out of the water. This period is represented by the sub-phase ‘Positioning’. In reality the preparation and positioning can be performed (partly) simultaneously. Next, the failed component is hoisted from the turbine to the crane ship and subsequently the spare component is hoisted from the crane ship to the turbine. This period is represented by the phase ‘Hoisting’. After the hoisting activities are completed a period might be required to finalize the replacement, f.i. to (crudely) mount the new component. This is represented by the phase ‘Finalisation’. At the end of the Finalisation, the turbine can be left behind safely, however it does not necessarily mean that the entire maintenance action is completed. In this situation, the completion of the replacement and commissioning of the turbine should be modelled under a subsequent phase “Repair”.

It is assumed that the Replacement phase has to be performed during one continuous period. This is done, like in reality, to avoid unwanted situations where, for instance, the failed component is dismounted but the subsequent hoisting cannot be performed due to bad weather windows. Obviously the situation can occur where the total duration of the Replacement phase takes longer than the working hours allow. For this situation the Replacement phase activities need to be split over two or more days. Within the OMCE-Calculator it will be assumed that e.g. during the night the weather conditions shall be more benign than the weather limits specified for the maintenance equipment. So the reason for not splitting up this replacement phase is that the turbine cannot be left half way the replacement because bad weather may damage the turbine. For some replacements it may happen that not all four sub-phases are performed. E.g. not all crane ships require a certain period for positioning and therefore the replacement phase could also consist of the sub-phases Preparation-Hoisting-Finalisation only.

For a replacement more types of equipment can be specified, in addition to an access ship which is required during the whole replacement for each sub-phase three additional types of equipment can be assigned.

5.1.2.2 Parameter definition

For each of the three types of maintenance, at least the following aspects need to be defined:

1. the time needed to organise the required activities;
2. the duration;
3. equipment to be used; and
4. the crew size.

The logistic time is determined during the simulation process, because of its dependence on the availability and the lead time of spares, and its dependency on the availability and mobilisation time of equipment. Also the waiting time is determined during the simulation process, because of its dependence on weather conditions and the capabilities of the equipment.

Below, some information is provided on the aspects needed to characterise the different maintenance phases and Repair Classes.

1. Time to organise [hrs]

Prior to the actual work carried out, time is needed to organise the activity. E.g., if a wind turbine generates an alarm this alarm needs to be assessed. If a remote restart is not possible, the wind farm operator needs time to organise the crew and equipment (and possibly materials) to carry out a first inspection (or repair). After the first inspection, the results need to be evaluated which takes some time and it might be that a specialist needs to be hired for a second inspection. The time to evaluate the results of the first inspection and to time needed to organise the second inspection with a specialist can be defined as the "Time to organise" for inspection number 2. If, after a certain inspection it is concluded that a replacement or repair is needed, time is needed again to organise these maintenance phases.

2. Duration [hrs]

The time needed to complete each phase (and sub-phase) should be specified. As mentioned before, a replacement does not necessarily consist of all four sub-phases. In case Positioning starts while Preparation is not finished, the duration of Preparation is defined as the period before Positioning.

3. Equipment

The equipment required to perform each phase of the maintenance action should be specified. It may be clear that different types of equipment can be used, f.i an access ship for transfer of technicians, a supply ship to deliver the spare or a large crane ship to hoist large components an different approach may be required to model the availability and the usage of these different types. For this reason five categories of equipment are distinguished.

Access vessel

An access vessel is used for transportation of technicians between the base-station and the wind turbines. An access vessel can bring along a number of crews, which can be transferred to different turbines. It is assumed that this type of equipment does not require mobilisation.

Helicopter

A helicopter is used for transportation of technicians also, but contrary to an access vessel it is assumed that it can serve only 1 turbine. After the technicians have been transferred to a certain turbine the helicopter return to its base.

Support vessel

A support vessel can have two functions

1. Transportation of personnel, possibly together with the transportation of spares. Furthermore it may be equipped with a crane for hoisting of spare parts. In contrary to an access vessel it is assumed that it can serve only 1 wind turbine at the time. Hence it

can be used for inspection or repair but also for a replacement, where it is primarily used for transfer of technicians and besides possibly for support.

2. Support for replacement. In this situation it is used for support only, the technicians are transported by another vessel.

Vessel for replacement
Generally the large equipment necessary for a replacement, such as crane ships. This type of equipment cannot bring along technicians and may stay in the wind farm during the night.

Internal crane
An internal crane is included in the equipment list because the use may be limited due to the weather conditions. Hence, for an internal crane only the weather limits during hoisting can be specified.

Depending on the category one or more of the following parameters are of importance for the definition of equipment:

- Number of devices available. For smaller equipment like an access vessel used for transfer of the technicians, it might be that more than one vessel is permanently available for the wind farm. For larger of equipment like crane a ship it may the number of vessels available on the market.
- Maximum number of technicians to be transported. Transportation of technicians can be done only by the categories access vessel, support vessel and helicopter. An access vessel can serve more turbines, while a helicopter and a support vessel only can serve 1 wind turbine at the time. So for the latter two categories it is important that they can bring along the number of technicians required. An access vessel travels around in the vicinity of the wind farm to drop off the technicians at different turbines and to pick them up later on.
- Maximum allowable weather conditions. The use of the specified equipment is limited if the wind and wave conditions exceed certain limits, usually defined by the maximum significant wave height, H_{s_max} and the maximum allowable wind speed, V_{w_max}. A distinction has to be made for the different maintenance (sub-)phases like travelling, positioning, hoisting, repair, etc.
- Mobilisation time. This is defined as the time needed to make the device ready for takeoff, after a request has been made to use it for a certain repair. For example, certain adaptations need to be made on a deck of a supply vessel to transport gearboxes and a crane should be mounted on the deck to hoist these gearboxes from the vessel on the turbine platform. The mobilisation time also includes waiting time if a vessel is being used elsewhere and not immediately available.
- De-mobilisation time. This is defined as the time needed to make the vessel available for a next request, e.g. by removing certain adaptations.
- Costs. The costs of equipment should be split up into:
  - Fixed costs for a certain period of time, e.g. an annual contract for fast response, or a contract for only a certain period, f.i. for the period during which preventive or condition based maintenance is scheduled.
  - Costs per unit of time (hour, day, week, ...), for the various phases (waiting, travelling, actual operation)
  - Mobilisation and demobilisation costs.
- Travel time. For equipment used for transportation of technicians the travelling should be done during the period characterised as “working day”. So these types of equipment will not depart from harbour (or hotel boat, or mother vessel) before the start of working day, which is an input parameter for the model. If a large crane ship is based in a certain harbour and needs to travel to the wind farm it will depart in due time, so that it is present in the wind farm at the moment needed.
- Staying in the wind farm. It should be indicated if a vessel is travelling back to the harbour (or hotel boat) every evening like the small vessels for personnel transfer, or if the vessel stays within the wind farm during the night like for example a Jack-up barge.

4. Crew size [-]
The crew size needed to complete each phase should be specified. This value is not necessarily equal for all phases. For instance the inspection(s) preceding the replacement of a component can be performed by two mechanics, whereas for the actual replacement a much larger crew might be required.

5.1.2.3 Maintenance phases which can be split up

The maintenance phases “Inspection” and “Repair” can be split up, meaning that it is not necessary to carry them out as one continuous action. The maintenance actions can be interrupted if bad weather occurs, or if no resources are available. For the OMCE-Calculator this means that it should look for periods with suitable weather conditions shorter than the actual duration of the maintenance phase. An illustration of a typical “Inspection” (or “Repair”) is given in Figure 5-5. A WindCat leaves at 6.00 in the morning, travels to the turbine in 1 hr, the crew carries out the inspection, returns at 15.00 to the harbour where it arrives at 16.00. In the left hand part of Figure 5-5, it is assumed that the inspection can be carried out as one continuous action. The two lower graphs show the maximum allowable wave height and wind speed during the inspection and travel. For these maintenance phases it is assumed that the equipment stays in the wind farm during the period the technicians are working in the turbine and the weather limits during travelling and during the stay in the wind farm are assumed to be identical. It is also possible to split up the action if bad weather occurs, but only if at least an inspection of 2 hours (input variable) can be carried out. This is shown in the right hand part of Figure 5-5.

During the modelling process, the OMCE-Calculator will look for suitable weather conditions with a duration that is shorter than the total inspection time. In fact small parts of the repair can be performed as long as the weather window is large enough to allow a working time on the turbine that is equal to or larger than the defined minimum working time on the turbine (2 hrs in the example).

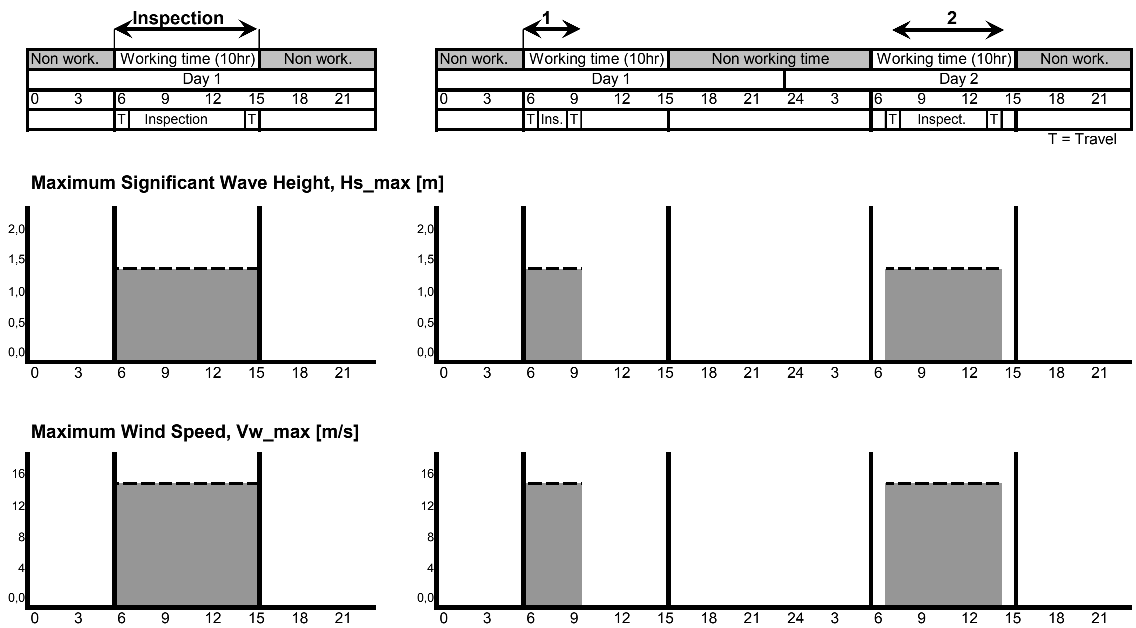


Figure 5-5: "*Inspection" of 8 hrs with 1 hour travelling to and from the turbine*
- continuous action (left), or
- split up (right)

5.1.2.4 Maintenance phases which cannot be split up

The maintenance phase “Replacement” (for which external hoisting is needed!) on the contrary needs to be carried out as one continuous action and interruptions due to bad weather are not allowed. The duration of suitable weather conditions should at least be as long as the duration of the “Replacement” phase. An example of a "Replacement" which includes Preparation, Positioning, Hoisting and Finalization and for which different vessels are needed is given below. The total “Replacement” action and the maximum allowable weather conditions are presented in a graphical manner in Figure 5-6.

Example: Replacement of Gearbox

> An inspection has shown that a complete failure of the gearbox has occurred and subsequently the gearbox needs to be replaced.
>
> First the failed gearbox is dismounted. The dismounting (8 hours) is performed by a small crew which travels (1 hour) to the failed turbine using a WindCat (V_w < 16 m/s and H_s < 1.5 m).
>
> Prior to the hoisting the jack-up vessel needs to position itself (4 hours, V_w < 12 m/s and H_s < 1.0 m). This can be done parallel to dismounting of the gearbox. During positioning, a WindCat with a crew needs to be present to escort the operation.
>
> After the jack-up vessel is positioned and has lifted itself out of the water, the failed gearbox can be hoisted from the nacelle onto the vessel and the replacement component can be hoisted from the jack-up vessel to the nacelle; this takes 6 hours (V_w < 8 m/s and H_s < 2.0 m). During hoisting, again a crew transported with a WindCat is present on the turbine to escort the operation.
>
> Finally, after the hoisting activities have been completed a period of 4 hours is required for mounting the new component. Similar as for the dismounting, the mounting is performed by a small crew using a WindCat.
>
> The total time necessary to perform the preparation, positioning, hoisting and finalization equals 18 hours. 10 working hours are available per day. Working during the night is not allowed.

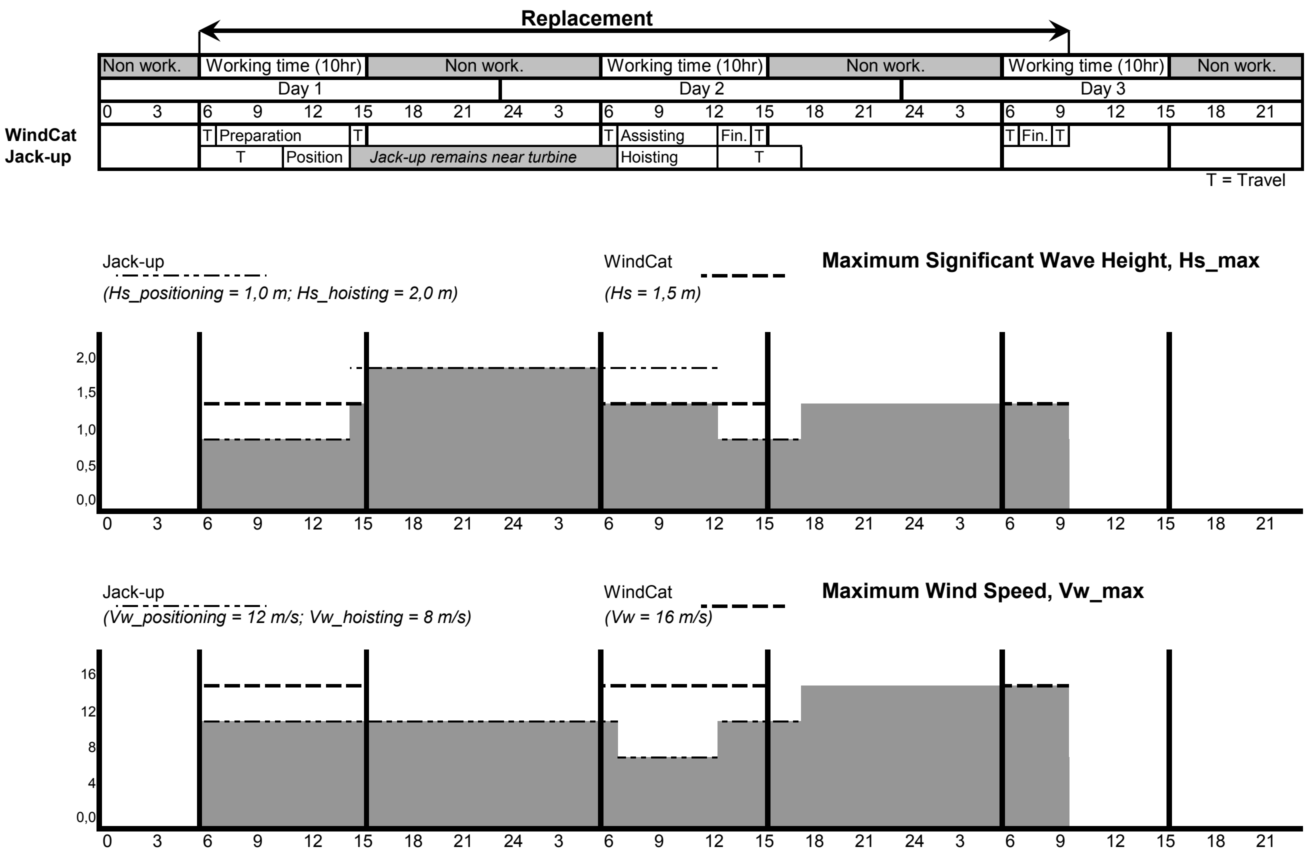


Figure 5-6: *"Replacement" of gearbox; maximum allowable weather conditions indicated as grey areas*

As can be seen in Figure 5-6, the Jack-up and WindCat, each have different maximum weather limits. The maximum weather limits the OMCE-Calculator should look for are the gray shaded areas. During the first night, when the turbine is unattended and the Jack-up is positioned, the wind and wave conditions should not exceed the maximum wind and wave conditions of the Jack-up. During the second night, the Jack-up is back in the harbour and the maximum allowable wind and wave conditions of the WindCat are decisive.

In general it can be said that during the period of "Non working time" (e.g. during the night) if more than one device is used, the most stringent weather limits should be chosen:

$$V_{w,\max} = \min_i \left(V_{w\max,i} \right) \quad and \quad H_{s,\max} = \min_i \left(H_{s\max,i} \right)$$

where $V_{w,max,i}$ and $H_{s,max,i}$ denote the maximum allowable wind speed and significant wave height of the ith device, $i = 1, \ldots, N_E$, where N_E is the total number of devices used to perform the maintenance.

As described above, several assumptions have been made in order to model maintenance actions that have to be performed during one continuous operation. For clarity these assumption are summarized below:

- The crew does not stay in the vicinity of an offshore wind farm during night and therefore has to travel back to the harbour (or hotel boat);
- For other equipment (support vessel, crane ship, etc.) it has to be specified in the input whether they stay in the wind farm or travel back to the base station during night.
- The maintenance action is assumed to always commence at the start of a working day in order to prevent the calculation of numerous weather windows;
- Outside working hours the weather limits of the equipment remaining on site should not be exceeded.
- The OMCE-Calculator should look for maximum wind and wave conditions that are a (complex) combination of all maintenance phases and different vessels used. The minimum weather limits for the different equipment become decisive.
- The length of a working day may be different, e.g. during summer or winter.

5.1.3 Spare Control Strategy (SCS)

Besides the failure frequency and Repair Class, for each Fault Type Class also the Spare Control Strategy should be specified. The Spare Control Strategy specifies the costs and the logistic aspects to arrange spare-parts or consumables necessary for a repair or replacement. Stock control has been incorporated in the OMCE-Calculator. Where the costs of consumables or spare-parts do not depend on whether stock control is applied, the time to arrange a spare-part might depend largely on whether stock control is applied or not, especially when a spare is required while no spare is in stock anymore. Therefore, the modelling of the Spare Control Strategy will make a distinction between maintenance actions where no stock control is applied and maintenance actions where stock control is applied. In the following subsections more details are provided.

5.1.3.1 No stock control

For consumables and spare parts where no stock control is applied, the costs of the item and the logistic time to arrange it have to be specified. Both values are assumed to be constant, even if several failures occur during a short period.

In principle it is possible to specify a Spare Control Strategy for each individual consumable, small part, or large component. However to improve the manageability of the model, it is advised to use only a limited number of SCS's.

5.1.3.2 Stock control

For the replacement of certain components the wind farm operator might want to investigate whether it is beneficial to apply stock control. Keeping one or more spare components in stock significantly reduces the logistic time required to arrange a spare-part in case of a failure. This could possibly lower the downtime and consequently revenue losses. On the other hand, investment in a storage facility is necessary and in addition to this costs are also associated with maintaining the spare-parts in stock.

In case the spare-part is in stock the time to transport the spare to the harbour (logistic time) is very short. The time required to re-order a spare-part to the storage facility is also of importance. In case no spare-parts are in stock the time to arrange a spare-part to the harbour is equal to the time to the next deliverance added to the logistic time (*it is assumed that ordered spares will be delivered at the storage facility and a spare is ordered immediately after a spare is taken from the ware house!*). Furthermore it should be specified what number of spare-parts should be kept in stock in order to control the re-ordering process. Finally, also the costs associated with keeping spare components in stock should be specified.

5.1.3.3 Summary

Similar as for the Repair Classes, an almost infinite number of Spare Control Strategies can be defined by varying the parameters discussed above. However, the objective is to define a library containing a limited set of Stock Control Strategies, which are diverse enough to model the logistic time and material costs associated with repairs and replacements with sufficient accuracy. Subsequently, for each Fault Type Class an appropriate Stock Control Strategy can be selected.

For each defined SCS first it is specified whether stock control is applied. If not, only the logistic time and material costs are relevant. If yes, the material costs, fixed costs, stock size, logistic time, and re-ordering time need to be specified. Summarising:

For spares <u>without</u> stock control it is sufficient to only specify
- the costs of the spare part;
- logistic time (from component supplier to harbour).

For spares <u>with</u> stock control the following aspects need to be specified:
- costs of the spare part;
- (annual) costs for stock control;
- stock size (default number of spares in stock);
- logistic time (from stock to harbour);
- re-ordering time (from component supplier to stock).

An example of a possible layout of a library containing several Spare Control Strategies is shown in Figure 5-7.

	Stock control	Logistic time [hrs]	Re-ordering time [hrs]	Stock size [-]	Fixed costs [kEuro]	Material costs [€]
SCS 1		48				1000
SCS 2		168				5000
SCS 3	x	24	336	5	250	25000
SCS *i*						

Figure 5-7: *Possible layout of a library containing Spare Control Strategies.*

5.2 Condition based maintenance

When analysing the aspects of condition based maintenance, the authors foresee that at a certain point in time information is available that one or more components need to be repaired in some wind turbines. For instance: inspection results show that pitch systems need to be repaired of those turbines that run the most at full load. Turbines in the middle of the wind farm run much more at partial load so the degradation of the pitch system is much less. When defining the input for the OMCE-Calculator, condition based maintenance actions can be planned for the most heavily loaded turbines in the next year; for the remaining turbines in the middle of the wind farm condition based maintenance is foreseen for instance between now and year 5. Because condition based maintenance can be planned in advance and for more turbines at the time, several costs like for instance MOB and DEMOB costs of large crane ships, have to be paid for only once for the total maintenance action. For unplanned corrective maintenance such costs will probably be charged per failed turbine, or in case of clustering, per clustered action but in those cases long downtimes should be taken into account for most of the failed turbines.

Condition based maintenance is initiated on the basis of the observed status or degradation of a certain component. The condition of the component has been determined for instance from alarms, SCADA data, inspections, measurements, or condition monitoring systems. The typical maintenance process for condition based maintenance is in general quite similar to the corrective maintenance process see Figure 2-9. Condition based maintenance generally will be carried out for a group of turbines during a certain period. So the organisational phase and the logistic phase are not repeated for each turbine but done once for all turbines involved.

The major difference between condition based maintenance and unplanned corrective maintenance is the length of the downtime which is shorter for condition based maintenance, because for condition based maintenance the turbine is shut down only during the period that turbine is being maintained. Since maintenance can only be carried out at low wind speeds, it is expected that the revenue losses are relatively low. The parameter *TTR* (Time To Repair) as illustrated in Figure 2-9 equals T_repair and is not relevant for condition based maintenance (see also 2.4.2).

5.2.1 Modelling assumptions

To model condition based maintenance within the OMCE, it is assumed that the condition of the component prior to the actual repair is such that the turbine can continue running. The turbine only needs to be shut down during the actual repair. This means that even when long times are needed to organise crew, equipment, spares, etc. and even if the waiting time due to bad weather is long, the turbine continues running.

Furthermore, for modelling condition based maintenance the assumption is made that condition based maintenance will be done at wind farm level, and not for each individual turbine. By making this assumption the interaction between condition based maintenance and unplanned corrective maintenance cannot be taken into account. It is expected that this assumption will have a limited effect on the outcome of the calculations, but by eliminating the interaction between the different types of maintenance, the complexity of the modelling is significantly reduced.

5.2.2 Fault Type Classes (FTC)

To define the maintenance actions for condition based maintenance, Fault Type Classes will be defined at the level of main systems, similar to unplanned corrective maintenance in Section 5.1.1. Now the number of wind turbines for which a certain type of condition based maintenance has to be carried out during a certain period has to be specified. For each type of condition based maintenance the following is specified per FTC, see also Figure 5-8:

- the number of turbines involved;
- the repair class RC;
- Spare Control Strategy (cost of spares);

- the priority; especially when more types have to be dealt with during the same period a priority can be assigned to each type of condition based maintenance.
- the date at which the work can be started the earliest together with the date before the work has to be finished.

At the start date all spares are available and the equipment is mobilised. During the period (start date – end date) equipment is available for carrying out the work. In case the work cannot be completed within this period, f.i. due bad weather conditions or shortage of equipment a message will be given by the program. Depending on the number of times the maintenance cannot be finished within the prescribed period, it can be considered to allocate more equipment or to lengthen the period.

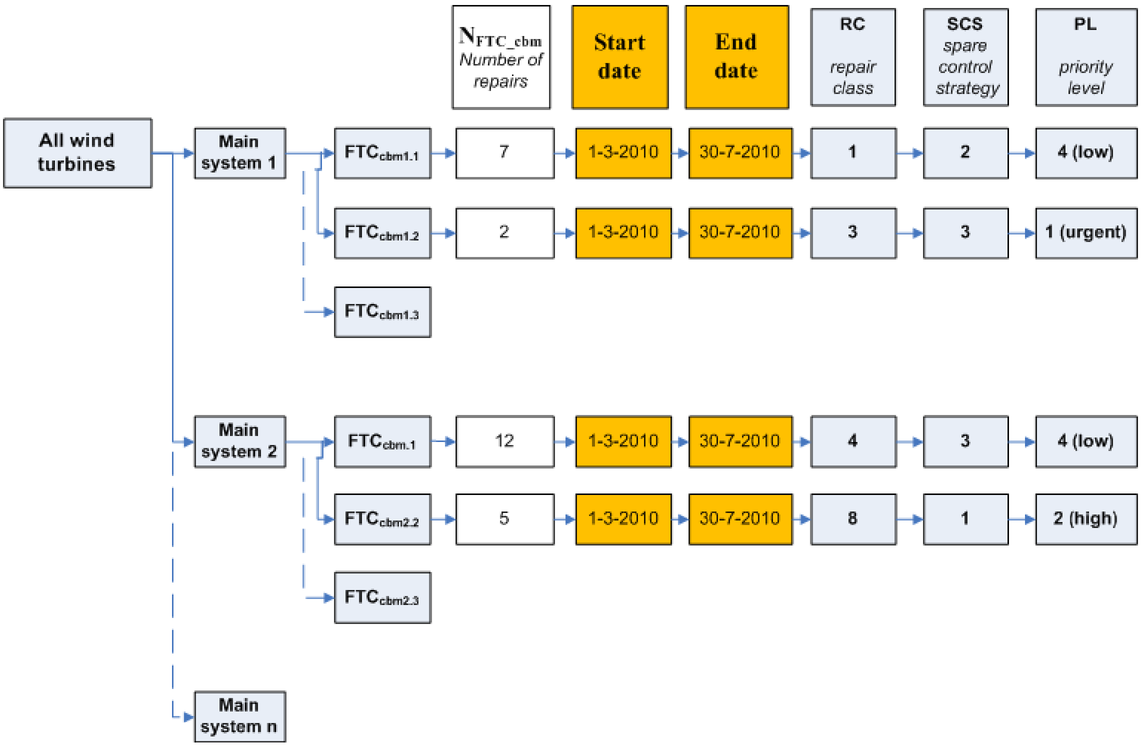


Figure 5-8: *Definition of FTC's for condition based maintenance (subscript "cbm" = condition based maintenance)*

5.2.3 Repair Classes (RC)

The Repair Classes for condition based maintenance are similar to those for unplanned corrective maintenance as presented in paragraph 5.1.2. When defining input parameters it is unlikely that maintenance phase "Inspection" will be used because inspections have been carried out already. RC's for condition based maintenance in fact only apply to the maintenance phase "Replacement".

Next, it is not necessary to use the parameter "Time to organise" prior to the Replacement or Repair for downtime calculations. For each type of RC only the following needs to be defined:

- the duration,
- type of equipment, and
- crew size.

The structure for modelling RC's for condition based maintenance is kept the same as for unplanned corrective maintenance, but less input parameters are needed.

5.2.4 Spare Control Strategy (SCS)

A spare control strategy in fact is not necessary to model within the OMCE. It is assumed that all equipment will be ordered especially for condition based maintenance, irrespective of the spare parts needed for unplanned maintenance. Aspects like logistic time, re-ordering time and stock size are not of importance. Only the costs for spare parts are relevant.

The structure for defining the different SCS's is kept the same as for unplanned corrective maintenance (see for instance Figure 5-7) but only the column "Material costs" is of importance.

5.3 Calendar based maintenance

Calendar Based Maintenance requires more or less the same modelling approach as condition based maintenance. The maintenance actions can be planned in advance and the turbines will only be shut down during the actual repair.

A opposed to condition based maintenance and unplanned corrective maintenance however, calendar based maintenance does not focus on only one component or failure mode. A calendar based maintenance action usually deals with the entire turbine. For instance once per year two technicians travel to a turbine to carry out repair as described in the preventive maintenance plan. This usually takes more than one visit. The costs for spares in fact apply to costs for consumables (lubricants, nuts, bolts, and other minor items). It should be possible to define different types of preventive maintenance, e.g. with different crew sizes, different equipment and different duration.

If for instance once per 5 or 6 years more intensive preventive maintenance is foreseen, e.g. replacement of gearbox oil, changing pitch batteries, etc., and such actions are related to certain components, it might be considered to model these actions as "condition based maintenance" actions.

5.3.1 Fault Type Classes (FTC)

The fault type classes for calendar based maintenance can be modelled more or less in the same way as for condition based maintenance, see also 5.2.2, but with some differences. It is not necessary to specify the number of turbines because calendar based maintenance applies to all turbines. There is not really a start and end date, but a period should be specified during which the maintenance actions should be carried out, e.g. every two years during spring and summer only. Finally it is not necessary to specify priorities; all turbines are equally important.

For each type of calendar based maintenance the following is specified per FTC, see also Figure 5-9:

- the frequency of maintenance (once per year, once per three years, etc.);
- the repair class RC;
- costs of spares;
- the period during which the work should be carried out (e.g. during spring and summer only).

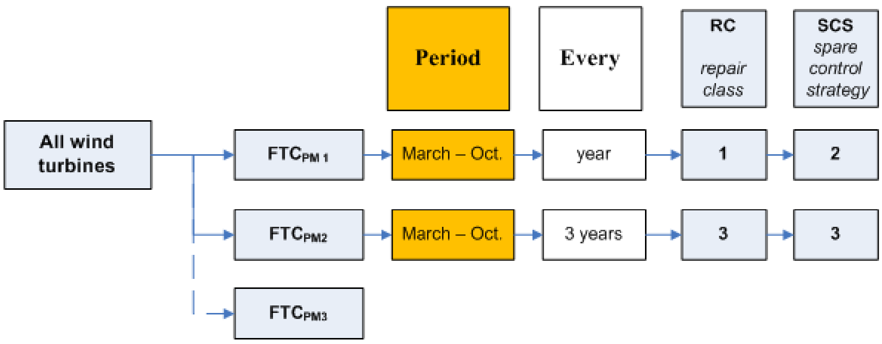


Figure 5-9: *Definition of FTC's for calendar based maintenance (subscript "pm" = preventive maintenance)*

Similar to condition based maintenance, at the start date all spares are available and the equipment is mobilised. During the specified period additional equipment might be available for carrying out the work. The OMCE-Calculator determines if all the work can be completed in the defined period and if this is not the case, f.i. due bad weather conditions or shortage of equipment a message will be given by the program. Depending on the number of times the maintenance cannot be finished within the prescribed period, one can consider to allocate more equipment or to lengthen the period. New simulations will then provide information if the work can be completed (and at what costs).

5.3.2 Repair Classes (RC)

The Repair Classes for calendar based maintenance are similar to those for condition based maintenance as presented in paragraph 5.2.3. When defining input parameters it is unlikely that maintenance phase "Replacement" will be used because these types of planned maintenance would be part of condition based maintenance. RC's for calendar based maintenance in fact only apply to the maintenance phases "Inspection" and "Repair".

5.3.3 Spare Control Strategy (SCS)

The structure for defining the different SCS's can be kept the same as for condition based maintenance.

6. Elaboration of the integral maintenance plan

6.1 General description of an integral maintenance plan

The way the integral maintenance plan is set up can be understood by considering the following very simplified case. During a certain period two vessels (Equip 1 and Equip 2) are available and both vessels can transfer two crews of technicians. The 1st vessel is especially hired for a limited period and is used for preventive maintenance only. The 2nd vessel is initially meant for corrective maintenance but will be employed for preventive maintenance during the time no corrective maintenance is required.

The development of an integrated maintenance plan is illustrated in Figure 6-1. In this figure it assumed that the work is carried out during the day time and that it is not allowed to work during the night. The work starts at the beginning of the day and that moment the plan is updated.

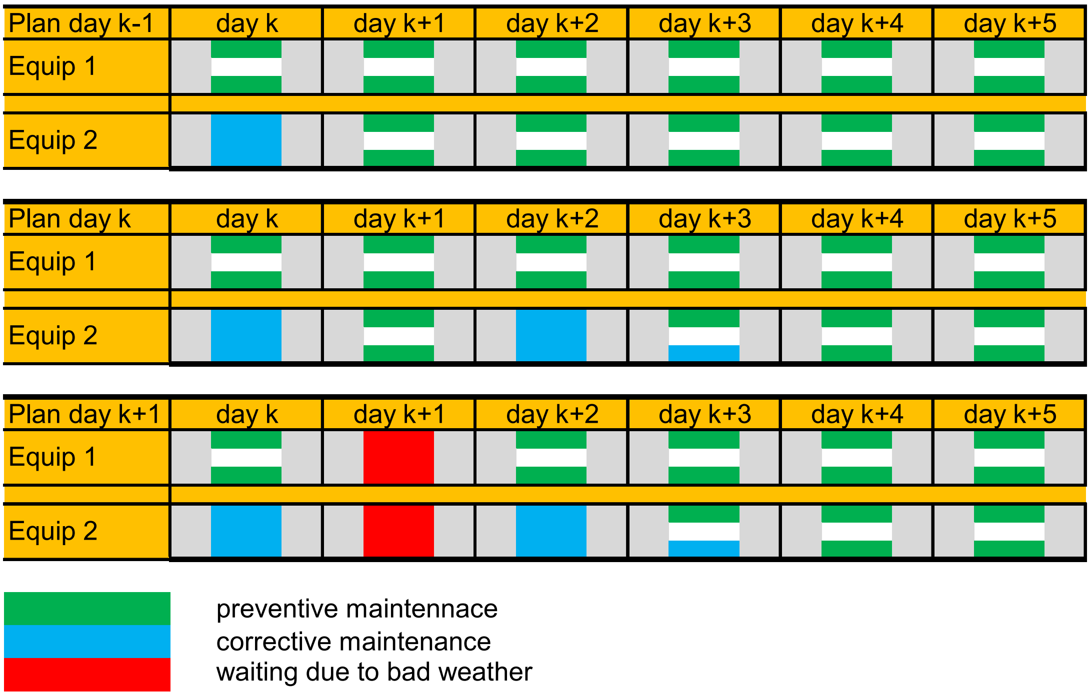


Figure 6-1: *Schematic overview for development of an integral maintenance plan*

After day *k-1* the integral maintenance plan is depicted in the upper part of Figure 6-1, and vessel 1 will transfer every day technicians to two turbines to carry out preventive maintenance. Vessel 2 will be used on day *k* to transfer 2 crews to finish the corrective maintenance started before. After day *k* vessel 2 will be employed for preventive maintenance.

At the morning of day *k* it appears that 2 turbines have failed, in fact these failures are predicted to occur following the Poisson process described in Appendix B.1. One turbine requires maintenance during one day with two crews of technicians. The other turbine also requires one day maintenance with only 1 crew. For both failures the spares can be available at day *k+2*. So both failure could be fixed on day *k+2*, in case three crews could be transferred simultaneously. However vessel 2 can bring along only two crews, and therefore one repairs has to postponed. As illustrated in the middle part of Figure 6-1, the failure requiring two crews is planned on day *k+2* and the other failure on day *k+3.* The previously scheduled preventive maintenance for vessel 2 has to be postponed.

On day *k+2* the weather conditions are such that the vessels are not allowed to leave the harbour, hence the preventive maintenance scheduled has to be postponed as depicted in the lower part of Figure 6-1.

In fact for the elaboration of the integral maintenance plan the following aspects are considered.

- The initial planning for calendar based maintenance and for condition based maintenance.
- The occurrence of random failures, i.e. time and type of failure. For each type of failure it is determined how the repair has to be carried out, and which resources are required (spares, technicians, vessels, etc.). Furthermore the weather windows for the equipment or the envelope for the whole operations has to be established.
- Checking of availability of resources.
- Checking weather windows.

Finally the simulation process results in an integral maintenance plan from which it can be derived during which periods the turbines were down for preventive maintenance. For corrective maintenance not only the downtime is captured, but also the fault type class, so that all information concerning spares etc. can be retrieved. Furthermore it can be derived which vessel was used at any time and also the application of these vessels (travel, stand by, hoisting, waiting due to bad weather, etc.). After the integral maintenance plan has been set up during a time simulation, all results on costs, downtime, usage of equipment and spares, etc. are derived straightforwardly from this plan.

6.2 General description of the simulation process

The main objective of the simulation process is to set up an integral maintenance plan for the coming period of 1, 2 or 5 years. This integral maintenance plan is set up based on the overall process depicted in Figure 2-9, which is in general applicable to model all three types of maintenance. The aim of this integral maintenance plan is that it reflects in detail during which period what maintenance is carried out, where the following aspects are taken into account:

- repair strategy;
- accessibility due to the weather conditions;
- availability of resources.

In the light of this objective the three maintenance types are interpreted as follows.

<u>Calendar based maintenance</u> is preventive maintenance that should be carried out at predefined moments in time, according to the existing guidelines. So at the start of the coming period of 1, 2 or 5 years the amount and type of the required calendar based maintenance is well known, such that the effort in terms of resources required (technicians and equipment) can be determined and an initial plan for the whole period to be considered can be developed without uncertainty worth mentioning. This plan specifies in detail which maintenance is carried out during what period. However, due to limited accessibility due to the weather conditions adjustment of the time schedule may be required.

<u>Condition based maintenance</u>, which either can be condition based preventive maintenance or condition based corrective maintenance, will be initiated based on the observed status or degradation of the wind turbines. Another reason might be that the quality of a component is not good enough to obtain the required lifetime and that an improvement program is foreseen to replace these components by better ones. For the model this means that at the start of the coming period of 1, 2 and 5 years, the information available (a.o. provided by the building block “Health Monitoring” and “Loads & Lifetime”) is analysed to make an assessment of the remaining lifetime of the selected critical components. Based on this assessment and the estimation of the time to failure the required maintenance for the coming period of 1, 2 and 5 years has to be determined. So at the beginning of the period to be analysed an assessment of the amount and type of condition based maintenance is known, so the required effort in terms of resources required (technicians and equipment) can be determined and an initial plan for the whole period to be considered can be developed. Also this plan specifies in detail which

maintenance is carried out during what period, where the accessibility due to the weather conditions is taken into account. Probably for the coming year the assessment can be done quite accurate, but for the coming 2 years and especially for a longer period (f.i. a period of years), the predictions will be uncertain; at least more uncertain than for calendar based maintenance. In the model this uncertainty is considered.

Unplanned corrective maintenance is due to random failures of wind turbine components, which can be modelled by means of the Poisson process [Ref. 13]. To model a simulation it should be noted that the occurrence of the next failure in a wind turbine is dependent on the moment the turbine was ready again for operation after the previous failure. The latter is dependent on a lot of operational aspects, such as the availability of resources (crew, equipment and spare parts) in connection with the simultaneous occurrence of failures in other wind turbines. Hence, in principle it is not possible to predict on beforehand the occurrence of these failures and to set up the accompanying plan for the whole period. The plan of the maintenance effort for random failures has to be built up step by step, where the accessibility due to the weather conditions and the availability of resources should be taken into account.

However, when modelling the O&M for a wind farm taking into account the three defined types of maintenance it is important to consider the interaction between these types. The overall structure of the model for the OMCE-Calculator is an integral maintenance plan which combines the three maintenance types and which combines simultaneous maintenance actions on different wind turbines. Because of the stochastic nature of the weather conditions and random occurrence of failures, this integral maintenance plan is elaborated by means of a number of simulations in the time domain. Once the integral maintenance plan for the specified simulation period has been elaborated, the associated downtime and costs can be determined straightforwardly as outlined in Section 6.1.

When devising such an integral maintenance plan it is essential to take into account the priorities of the three types of maintenance. For the OMCE-Calculator it is assumed that for each type of maintenance resources are allocated especially for that type of maintenance. Condition based maintenance and calendar based maintenance generally will be scheduled during special selected periods and for these types of maintenance it is assumed that resources are allocated during these periods only. During the planning of these types of maintenance the number of workable days is taken into account, so it is expected that the work can be completed within the scheduled periods. However, it may occur that due to bad weather conditions it was not possible to complete all work within the scheduled period, and it should be determined how often this does occur. Spares both for condition based and calendar based maintenance are assumed to be ready for shipping at the moment required. It is expected that condition based maintenance, like major overhauls, generally will be treated as a separate activity with its own logistic organisations and therefore it is assumed that condition based maintenance will be carried out without interaction with calendar based or unplanned corrective maintenance.

Meanwhile the work for calendar based maintenance will be combined with unplanned corrective maintenance. When equipment allocated for unplanned corrective maintenance is still available but not required for corrective maintenance it will be employed for calendar based maintenance, as illustrated in the example given in the previous section.

For modelling in the OMCE-Calculator the planning process as occurring in reality will not be simulated, but an integral plan of all maintenance activities during the period to be considered will be developed. For this purpose first a plan of the corrective maintenance will be made for the whole desired simulation period. After this plan is completed the calendar based maintenance and, subsequently, condition based maintenance is incorporated in this plan. It should be noted that additional equipment can be allocated especially for condition based maintenance and for calendar based maintenance, but it may occur that not all the work scheduled can be carried out due to bad weather conditions.

Obviously, this method seems to contradict common sense, since in reality first a planning for the calendar based maintenance is made, which probably is adjusted every time an unexpected failure occurs. However, for modelling purposes the order in which the three types of maintenance are considered does not have an effect on the outcome of the calculations, but the speed of the modelling is significantly improved. The process to develop such an integral maintenance plan can be done according to Figure 6-2. Each iteration results in an overview with the logistic aspects, such as the number of times equipment is used and the duration, the hours of standstill of the turbines, the number of spare parts used, the number of times no spares were available in the warehouse, and so on. The logistic aspects will be combined with costs for e.g. the use of equipment, revenue losses, or spare parts to determine the total O&M costs. After the iterations are finished, the intermediate results will be processed to determine the required output in terms of statistical values e.g. downtime, waiting time, costs of vessels, costs of spares, or use of crew.

The variability of the weather condition is taken into account by the determination of the point in time at which a simulation is started. It is assumed that the weather data cover a range of compete years starting at January 1st in year 1 and ending at December 31st in year n. A certain simulation starts at January 1st in the year k, where k is randomly chosen from the range 1,..,n.

Further details about the way the different types of maintenance are modelled, the elaboration of the integral maintenance plan, and assignment of the costs are given in the following Chapters and Chapter 7 respectively.

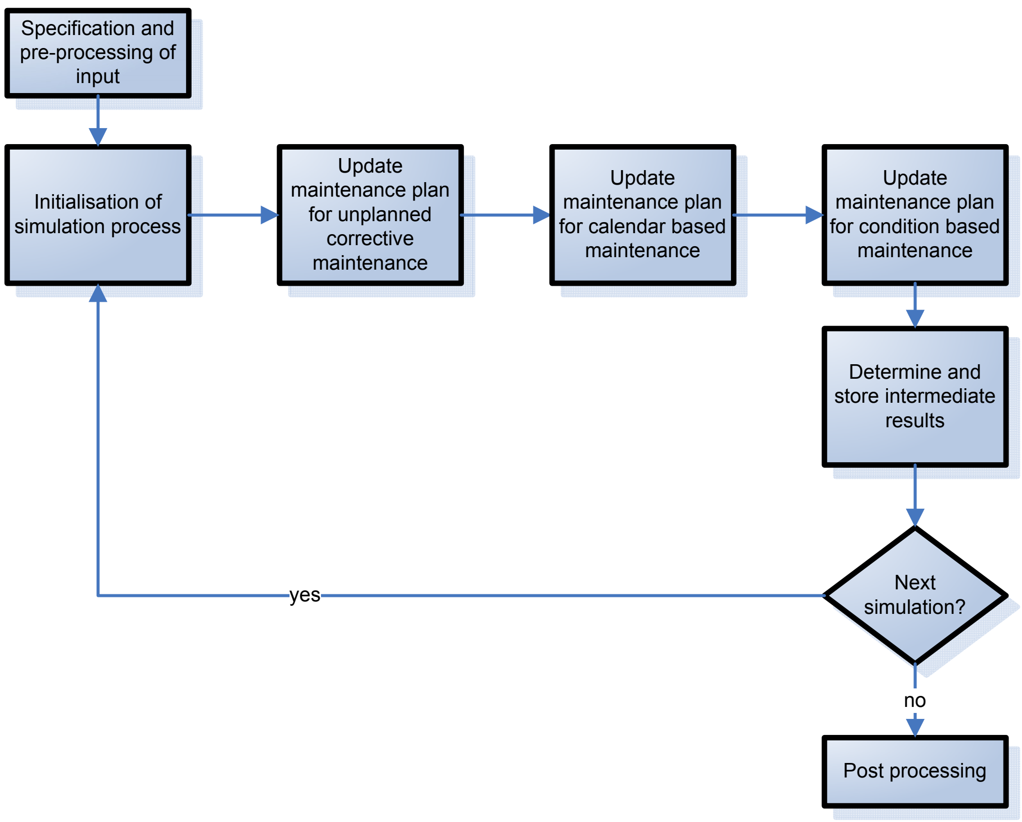


Figure 6-2: *Basic schematic overview of the modelling process of the different types of maintenance.*

6.3 General description of the overall process

Because of the statistical constraints (the inherent variability of the weather conditions, the random occurrence of failures, and the statistical uncertainty in the input variables, see also Appendix B) the OMCE-Calculator is based on a time simulation process and to quantify the uncertainties a (large) number of simulations have to be carried out. Within each simulation an integral maintenance plan is set up as a function of time such that the following information can be determined from the simulation history.

- For each type of maintenance (random failure, calendar based, or condition based) initiated up to time *t** the associated FTC (repair and spare part information) and the downtime are specified. For random failures the downtime is subdivided as follows:
  - the downtime due to the fact that the maintenance is being carried out;
  - waiting time due to logistics, i.e. lead time of equipment and spares;
  - waiting time due to bad weather conditions;
  - waiting time due to lack of equipment or technicians.

  It should be noted that the three categories of waiting time are applicable only for random failures; for calendar based and condition based maintenance the WT is shut down only during the period the maintenance is being carried out.
- With the specification of the FTC it is known which type of equipment is required and for each equipment it is specified when it has been used for what kind of work. For this purpose the following types of work are defined:
  - Travel and transfer of technicians;
  - Working, i.e. equipment is stationed near certain turbine to support work being carried out for that turbine;
  - Overnight stay (break during night);
  - Stand by (f.i. equipment used for transfer of personnel is stand by and waiting until the technicians can be picked up for transfer again);
  - Mobilisation or demobilisation;
  - Waiting due to bad weather or lack of resources.

  In this way costs can be assigned depending on the type of work the equipment is used for.
- The number of technicians that have been employed as a function of time.

When looking at the future ($t > t^*$) the following information can be determined.
- The time at which the next failure will occur.
- The time a turbine which has been shut down will be restarted after the maintenance due to a random failure has been completed.
- The allocation of equipment for previously initiated maintenance.

For random failures the integral maintenance plan is updated at the moment of occurrence of a failure.

In the following subsections the actual planning process for corrective maintenance is outlined, after which the definition and the process to include both condition and calendar maintenance is described.

6.4 Unplanned corrective maintenance

Before describing the actual planning process of corrective maintenance, first the definition of the unplanned corrective maintenance and, secondly, the description of a typical (corrective) maintenance process, as has been discussed before in this report, will be summarized.

For each possible failure the required maintenance is defined by the indicated Fault Type Class (FTC). For each FTC a Repair Class (RC) and Spare Control Strategy (SCS) are specified. The Repair Class defines the sequence of maintenance phases to be carried out (see Figure 5-3) and for each phase the type (inspection and/or repair and/or replacement), the duration of the maintenance, the type of equipment to be used and the number of technicians required to perform the maintenance are specified. The indicated Spare Control Strategy defines the time to arrange the required consumables or spare-parts. Furthermore the associated costs of equipment, spares and labour are defined by the FTC.

The typical maintenance process, which has been shown in Figure 2-9 in section 2.4.1 consists of three steps:

1. Organisation time; the period required to analyse the cause and details of a failure or to analyse the results of a previous phase and subsequently to decide how to continue;
2. Logistic time: the period necessary to deliver the required equipment and spares;
3. Waiting time: the period during which the maintenance cannot start due to (1) bad weather conditions (denoted as T_wewi), or (2) the waiting time due to lack of equipment or technicians (denoted as T_nores);
4. Mission time; the period during which the actual maintenance is performed.

When planning the corrective maintenance, for each defined maintenance phase, the three stages (logistic, waiting and mission), as discussed above, have to be performed. However, it is important to take the following aspects into account:

- At the end of a previous phase the follow-up activities are decided upon, i.e. the organisation of the next phase starts.
- In case both phases Replacement and Repair are specified for a certain Repair Class, it is assumed that the spare-parts will have to be arranged for the phase Replacement. If no replacement is included it is assumed that spare parts are required during the 1st phase of the type “Repair”.
- The time a certain phase is initiated is determined by the time the device used for transfer of personnel leaves the base station. It is assumed that at the start of a phase the access equipment leaves the base station at the start of the working day.

The procedure to process the sequence of phases is depicted in Figure 6-3.

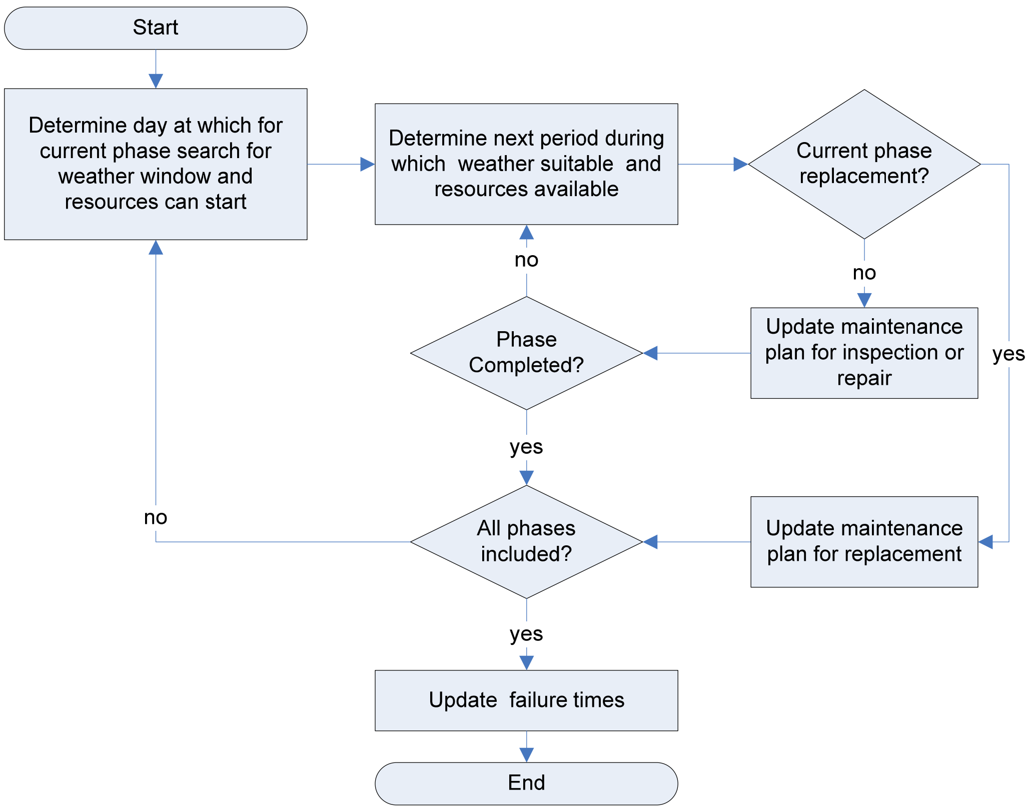


Figure 6-3: *Flowchart describing the general approach for processing corrective maintenance.*

It can be seen in this figure that a maintenance phase of the type “Replacement” has to be completed during one dense period, while phases of the type “Repair” or “Inspection” can be split up.

6.4.1 Start search for suitable weather window and resources

The occurrence of random failures in wind turbine components is described by the Poisson process and the occurrence of random failures is modelled on the level of Fault Type Classes (FTC). Hence the day can be determined at which the next failure will occur and in what FTC the failure can be categorized. In case more failures do occur on the same day they are processed in order of decreasing priority level. To determine the start of the organisational period the following rules are applied:

- Failures which do occur after 12:00 hrs. are processed the next day.
- Failures which have occurred before the start of the working day are processed at the start of the working day;
- Failures which do occur between the start of the working day and 12:00 hrs are processed at 12:00 hrs;
- The organisation of a subsequent phase starts immediately after the finish of the previous phase.

Once it is known when a failure does occur it can be determined when the work at sea can start the earliest, taking into account the time required for the organisational period, the lead time for the spares, and the mobilization time for the equipment. At this moment the search for a suitable period during which a certain phase can be carried is started. Summarising, the time at which the repair of these turbines could start the earliest is determined by the aspects described below.

1. Arranging spare-parts:
   In case spare-parts are required to perform the maintenance a certain time might be required to arrange these spare-parts to the harbour. The time required to arrange spare-parts is determined by the Stock Control process, which will be described in Section 6.7.1. In case more maintenance phases have to be modelled one should take care that the ordering of the spares will not start before the last Inspection phase has been fully concluded. The reason for this is that in reality the results of the inspection are the starting point to decide how to proceed.
2. Arranging equipment:
   The time required to mobilise equipment is specified in the Repair Class, see section 6.7.2.
3. Arranging technicians:
   The availability of technicians is linked to the availability of equipment to transfer (access vessels) the technicians, see section 6.7.2.

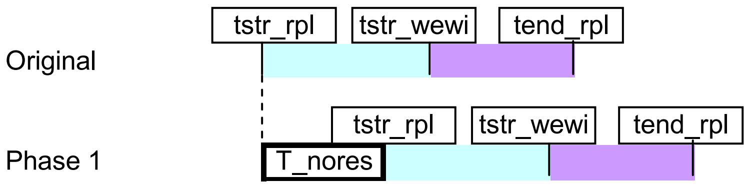
To include the subsequent maintenance phases following a failure in the integral maintenance plan, for each phase a period in time has to be found during which the weather conditions are suitable and during which the required equipment and is available. As outlined in section 5.1.2 two types of maintenance phases can be distinguished, viz. maintenance phases that cannot be split up ("Replacement") and maintenance phases that can be split up ("Inspection" or "Repair").

6.4.1.1 Replacement

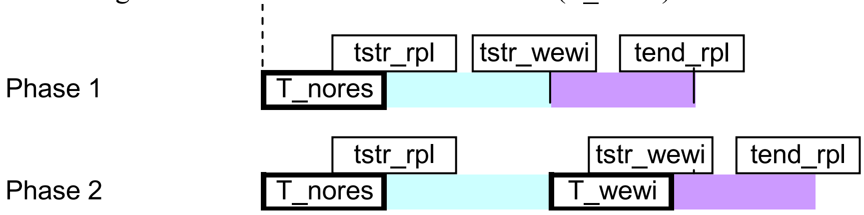
To illustrate the processing of a maintenance phase of the type "Replacement" the example depicted in Figure 6-5 is used. According to the schematic overview a replacement can be split up in two main periods, viz. the period before the 1st depart (tstr_rpl≤ t < tstr_wewi), and the period after the 1st depart (tstr_wewi ≤ t < tend_rpl). Once the resources have been ordered and mobilised it may occur at tstr_wewi that the weather conditions are not suitable and the equipment has to stay in the harbour. The main part of this function deals with finding the point in time where the replacement can be included, i.e. resources are available and weather conditions are suitable. It should be noted that the time tstr_wewi at which the activities actually could start, might not be the starting time to be used in the computer model. As stated before a certain maintenance phase will start at the beginning of a working day and for this reason the start time will be will be postponed to the beginning of a working day. This delay is is characterised as logistic time.

To find the actual points in time at which the 1st mobilisation starts (tstr_rpl) and at which the 1st depart takes place (tstr_wewi) three phases can be distinguished, where it should be noted that the availability of technicians is linked to the availability of access vessels, see section 6.7.2.

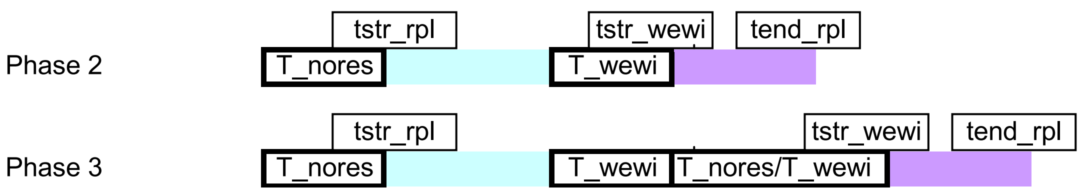
1. Waiting time due to lack of equipment.
Starting with the original scheme based on Figure 6-5 it may occur that during the period (tstr_rpl, tend_rpl) not all required equipment are available for the current maintenance phase. This may bring about that the start of the replacement is delayed w.r.t. the original plan. This delay is added to the waiting time due to lack of resources (T_nores).



2. 1st delay due to bad weather conditions
Next it is checked whether the weather conditions are suitable at the start of the 2nd phase (tstr_wewi in phase 1). In case this is true the replacement can be included in the provisional plan. Otherwise the part of the scheme starting at tstr_wewi is shifted to a point in time at which a suitable weather window is present. This delay caused by the weather conditions is added to the waiting time due to bad weather conditions (T_wewi).



3. Further delays due to lack of resources or bad weather
After the previous phase it is **not** clear whether the replacement can be carried out according the scheme resulting from phase 2, because at the start of the suitable weather window the availability of equipment has to be checked again first. However now only the part of the scheme starting at the 1st depart (tstr_wewi) has to be considered, because mobilisation has been initiated already before. After finding a period with resources available, the weather conditions have to be checked again and this process is continued until a period is found during which the resources are available and the weather conditions are suitable. Depending on the course of this further delay the T_nores or T_wewi is increased.



The overall process to find such a suitable period is depicted in Figure 6-4.

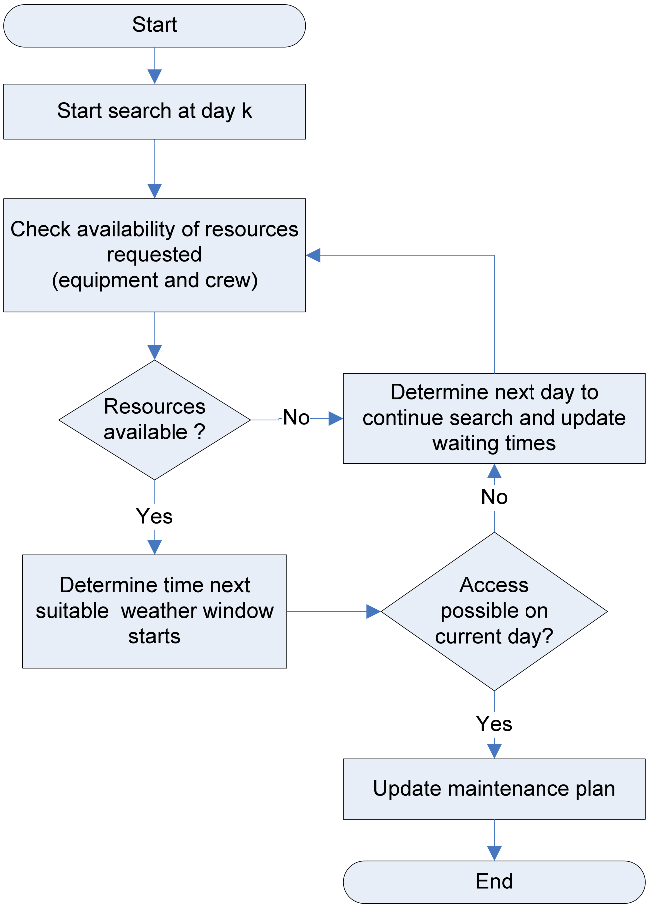


Figure 6-4: *Process flow of insertion of replacement*

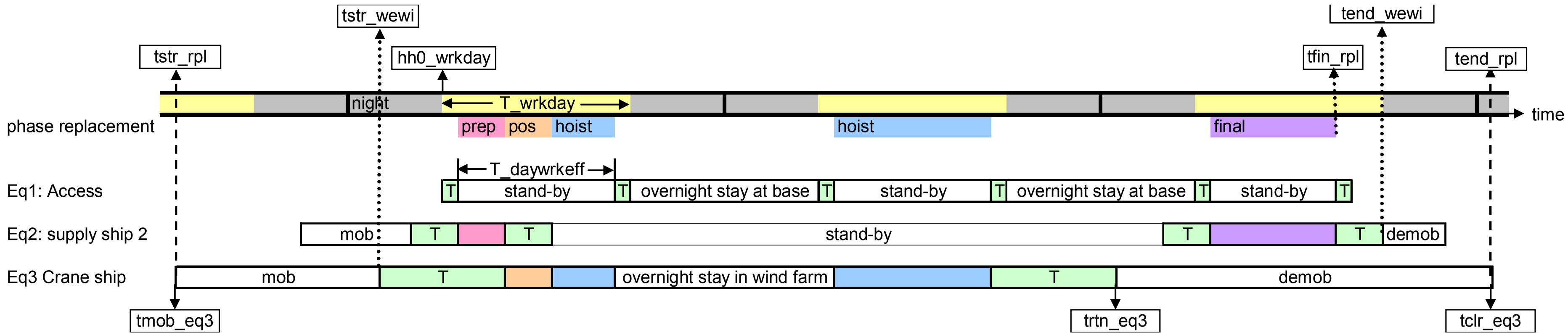


Figure 6-5: *Schematic overview of replacement*

Explanation of variables:

T_wrkdayeff: effective length of working day, i.e. period during which maintenance can be carried out, so travel time is excluded
tmob_eqn: time at which mobilisation of equipment n starts (can be equal to departure time)
tdep_eqn: time at which equipment n leaves base for 1st time
trtn_eqn: time at which equipment n is back at base the latest
tclr_eqn: time at which de-mobilisation of equipment n is finished (can be equal to trtn_eqn)
tstr_rpl: time at which 1st activity of replacement starts; $tstr\_rpl = \min_{i\_eq}\left(tmob(i\_eq)\right)$
tstr_wewi: time at which weather data become important (1s equipment leaves base); $tstr\_wewi = \min_{i\_eq}\left(tdep(i\_eq)\right)$
tend_wewi: end of period for which weather data are important (all equipment back at base); $tend\_wewi = \max_{i\_eq}\left(trtn(i\_eq)\right)$
tend_rpl: time at which replacement is completed; $tend\_rpl = \max_{i\_eq}\left(tclr(i\_eq)\right)$
hh0_wrkday: start of working day, i.e. the time technicians depart the earliest
T_wrkday: length of working day

6.4.1.2 Inspection and Repair

The organisational period for a maintenance phase that can be split up ends at the point in time denoted as tstr_splt. At this point in time the required equipment can be ordered.

In connection with finding periods during which work can be carried out, the waiting time due to the weather conditions or the waiting time due to lack of equipment is being assigned as outlined below, where it should be noted that availability of technicians is linked to availability of access ships, see section 6.7.2. Assuming that at day k the next suitable weather window is found the following four situations can be distinguished (see picture below).

1. The length of weather window at day k is shorter than the minimum specified value. If tN_win – t1_win < T_repmin + 2*T_travel, the period during which the work actually can be carried out is too short. In this situation the search for the next day with a suitable weather window is continued the next day and the waiting time due to bad weather is increased with 24 hours.

2. The length of workable period at day k is too short. If tN_res – t1_res < T_repmin + 2*T_travel ≤ tN_win – t1_win, the period within the weather window during which the work actually can be carried out is too short. In this situation the search for the next day with a suitable weather window is continued the next day and the waiting time due to lack of resources is increased with 24 hours.

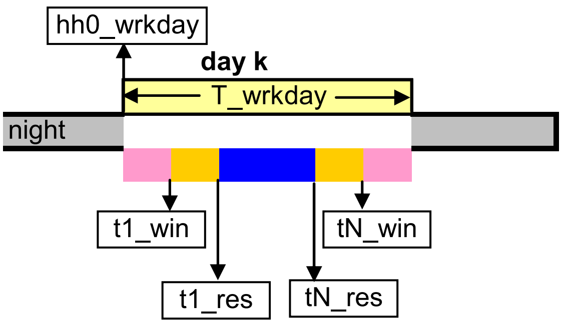
3. Part of the work can actually being carried out (T_repmin + 2*T_travel ≤ tN_res – t1_res). In this situation the waiting time due to bad weather is increased with

   T_wrkday – (tN_win - t1_win),

   and the waiting time due to lack of resources is increased with

   (t1_res - t1_win) + (tN_win - tN_res).

   The search for the next day day with a suitable window is continued the next day, but in this case the break during the night is not included in the waiting times.



   After day k has been processed and the work is not completed yet, the process is continued by finding the next day with a suitable weather window, and this search starts at day k+1. When the next suitable weather window is not found on the next day (day k+1) but on on day k+n (with n>1) the waiting time due to the weather conditions is raised with (n-1)*24 hours.

4. The work can be completed (T_repmin + 2*T_travel ≤ tN_res – t1_res) and the length of the remaining work is less than (tN_res – t1_res - 2*T_travel). In this situation the waiting time due to bad weather is increased with

   t1_win – t_{hho_wrkday},

   and the waiting time due to lack of resources is increased with

   (t1_res - t1_win) .

The overall process is depicted in Figure 6-6.

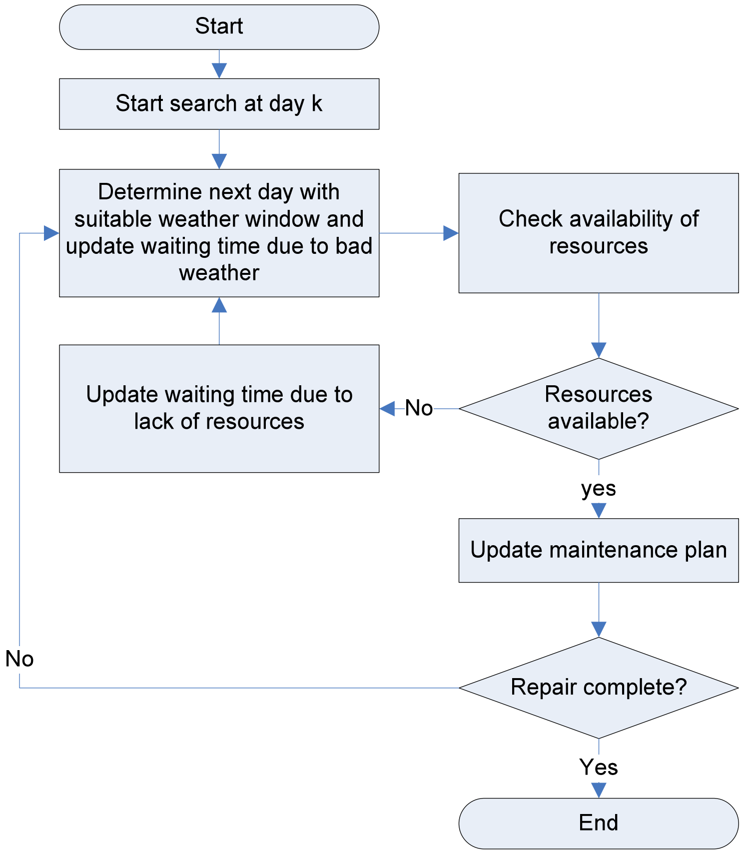


Figure 6-6: *Process flow of insertion of inspection or repair*

6.4.2 Update time next failure

After all maintenance phases are included the time at which the turbine is restarted is known and it can be determined when this failure will occur again. It is assumed that a turbine will be repaired only once during a day, hence if a wind turbine fails again after it has been restarted a failure it will not be repaired before the next day.

6.5 Calendar based maintenance

In the flowchart depicted in Figure 6-2 it is shown that after the plan for all unplanned corrective maintenance has been concluded, the next step is to add calendar based maintenance to this plan. Calendar based maintenance is modelled at wind farm level. Therefore certain occurrences of interaction between calendar based maintenance and corrective maintenance are not taken into account in the model. This assumption is not expected to have a large effect on the outcome of the calculations, but results in a less complex and, most probably, faster model.

The process for updating the plan for corrective maintenance with calendar based maintenance starts with:

- the definitive maintenance plan for corrective maintenance;
- a provisional plan for the calendar based maintenance.

In the provisional plan for calendar based maintenance the type of calendar based maintenance to be carried out is specified by means of predefined FTC’s, see section 5.3. These FTC's are specially defined for calendar based maintenance and can only contain either an inspection or a repair phase, see section 5.3. Therefore, the modelling process is kept very similar to the process for adding an inspection/repair for corrective maintenance as described in section 6.4.

6.6 Condition based maintenance

The final step in the planning process is the planning of condition based maintenance, see Figure 6-2. As discussed in Section 2.4.2, condition based maintenance is initiated on the basis of the observed status or degradation of a certain component. The process for updating the definitive plan with condition based maintenance starts with:

- the definitive maintenance plan for corrective and calendar based maintenance;
- a provisional plan for the condition based maintenance.

Now the approach for condition based maintenance is similar to the approach for calendar based maintenance.

6.7 Availability of spares, equipment and technicians

As part of the process to set up a plan for unplanned corrective maintenance it has to be determined when the spare parts if required, are available for shipping. This will be described in Section 6.7.1. It should be clear that this aspect is of importance only for unplanned corrective maintenance, because for condition based and calendar based maintenance it is assumed that all materials needed are available on the date at which the work can be started the earliest.

In the setting up of the maintenance plan for corrective maintenance and also later on when including the maintenance plans for condition based and calendar based maintenance, it has to be checked whether the required equipment and technicians are available to carry out the provisional plan. This part of the process is described in detail in Section 6.7.2.

6.7.1 Stock control

In the following it is assumed that a request for a spare is made at $t = t_0$ and it has to be determined when the spare is available for shipping, which will be denoted as t_{spare}.

Following section 5.1.3 a distinction will be made between a component for which stock control is applied and a component for which no stock control is applied.

No stock control
According to Figure 5-7 for each type of these components the following is specified:
T_{log}: Logistic time

and the time these components are ready for shipping read

$$t_{\text{spare}} = t_0 + T_{\text{log}}$$

Stock control
According to Figure 5-7 for each of this type of components the following is specified:
T_{log} : Logistic time
T_{order} : Re-ordering time
N_{stock} : Stock size

For each type of component the times at which the components have been or will be delivered to the warehouse are registered. These times are denoted as $t_{\text{stock},i}$, i =1, ..,N_{stock}.

At the moment a spare is needed it is determined whether a spare is available in stock which is true if

$$\min_i(t_{\text{stock},i}) < t_0$$

and the time the component is ready for shipping now reads

$$t_{\text{spare}} = t_0 + T_{\text{log}}$$

In case no component is in stock available anymore the time the component is ready for shipping becomes

$$t_{\text{spare}} = \min_i(t_{\text{stock},i}) + T_{\text{log}}$$

As soon as spare *k* is allocated a new spare will be ordered and the time at which this pare will be delivered has to be updated as follows

$$t_{\text{stock},k} = t_0 + T_{\text{order}}$$

The process described so far is sufficient to determine the time at which a component is available for shipping. To decide whether the stock size is too small or too big the following two parameters are stored for each spare stored in the warehouse.

- The minimum number of spares available in the warehouse. In case this number is greater than zero it should be considered whether the default number of spares available can be decreased.
- The number of time a spare was requested while no spare was available. In case this number is greater than zero it should be considered whether the default number of spares available should be increased.

6.7.2 Equipment and technicians

The availability of technicians is linked to the availability of equipment to transfer technicians and it is assumed that in case technicians can be transferred these technicians are available. This is explained by the example below. Say two Windcats are available for transferring technicians, and each Windcat is allowed to bring along maximally 12 technicians. So in total 24 technicians can be transferred at the same time. In case at a certain point in time 18 technicians are allocated already, it is assumed that still 6 technicians can be deployed at that moment.

The availability of equipment not used for transfer of technicians depends on the type of work the equipment has to carry out for the new repair and the type of work already scheduled for that equipment. Of course also the number of equipment of a certain type is of importance. This is illustrated by the following examples.

If a supply ship is scheduled to support a replacement of a main component and has to stay near that turbine, it cannot be used for support at other wind turbines.

If a crane ship has been mobilised and is positioned near a wind turbine, it cannot be used for another wind turbine at that same moment. However, it can be deployed for another turbine after completion of the current repair without mobilisation. So repairs are clustered and the ship is mobilized- demobilized only once, while it has been used for several repairs.

6.8 Balance of Plant (BOP)

The modelling of maintenance of BOP is done similar as for a wind turbine and the approach described above is being applied. However, a shutdown of the BOP may involve that that all or a group of turbines will be shut down also. This additional downtime is stored and can be retrieved during post-processing, and is denoted as “downtime due to BOP”. It should be noted that a BOP shutdown will not always lead to additional downtime for a wind turbine, f.i. in case the wind turbine was already shutdown due to a failure.

7. Determination of Downtime and Costs

Once the integral maintenance plan has been elaborated the following information is available.

- For each structure within the wind farm (wind turbine or balance of plant) it is specified during which periods the WT or the BOP has been shut down and for what reason, so that the downtime and availability can be determined straightforwardly. The downtime can be split up into:
  - repair time
  - waiting time due to logistic, due to bad weather conditions, due to lack of resources, and due to BOP (only for wind turbines).
- The usage of spares.
- For each equipment it is specified how it has been used as function of time, where the following types of work are distinguished: transfer of technicians, working inside wind farm, travelling, stand-by, waiting, and (de-)mobilisation.

To calculate the costs the information extracted from the integral maintenance plan has to be combined with the specification of the costs (input), where the following four categories are distinguished:

1. *Energy production and revenue losses*:
   a. Energy price [€/kWh]
2. *Labour*
   Cost of technicians are given by:
   a. Cost per hour per person [€/hour]
   b. A fixed yearly cost for all personnel (lump sum) [€/year]

3. *Equipment*
   The cost for *equipment*, viz.: helicopters, access vessels, support vessels, and crane ships, can be specified in sub categories, viz.:
   a. Work time per vessel per hour/day/mission [€/hour, €/day, €/year]
   b. Waiting time per vessel per hour/day/mission [€/hour, €/day, €/year]
   c. Fuel surcharge per vessel per trip (one trip includes return to base) [€/trip]
   d. Mobilisation and demobilisation cost per vessel per mission [€/mission]
   e. Annual fixed cost per vessel [€/year]

4. *Spare parts*:
   a. Material cost per spare part [€]
   b. Annual cost per spare type for stock control [€/year]

Energy production and revenue losses
To determine the revenue losses the total amount of energy [kWh] which could have been produced during production during the periods of downtime has to be determined. For this purpose the PV-curve, which has to be specified as part of the input, is combined with the wind speed. The wind speed at hub height is derived from the pre-processed meteo data by applying a logarithmic law[5] as noted in Ref. 3 :

[5] The formula is based on a mixing length type analysis by Wortman, assumes so-called neutral atmospheric stability conditions, and is generally used in wind energy analysis

$$v_{hh} = v_{ref} \cdot \log\left(\frac{h}{z_0}\right) \Big/ \log\left(\frac{h_{ref}}{z_0}\right)$$

In this function, a default surface roughness length parameter for a calm open sea is suggested: $z_0 = 2 \cdot 10^{-4}\ m$ (Ref. 3). However, the end user is able to define this parameter as input in the OMCE input module.

Labour
To determine the labour costs only the hours are considered during which a technician is active within the wind farm or during which a technician is travelling.

Equipment
The costs of equipment can be calculated more or less straightforwardly by determining the number of hours, days or years applicable for the whole simulation period. The same holds for the number of trips, and the number of missions, but special attention is needed in case a mission does not fall completely within the simulation period, f.i. when a turbine fails within the simulation period but the repair cannot be completed for the end of the simulations period, see Figure 7-1.

Missions
Only mobilisations started within the simulation period interval (*ts_sim, te_sim*) are counted. Considering Figure 7-1, this means that mobilisation for failure #2 is not counted.
In case, the type of equipment defined is an "access vessel", it is assumed that each available vessel is mobilised and demobilised only *once* during the simulation period, resulting in 1 mission per simulation.
For additional equipment specifically deployed for preventive or condition based maintenance one mobilisation - demobilisation is assumed per period.

Trips
Only return-trips started within the simulation interval (*ts_sim, te_sim*) are counted.

Spares
The cost of spares are assigned at the moment a turbine or the BOP is re-started. So in case a re-start cannot be done before the end of the simulation period the cost are not taken into account. However, in case a start-up period has been included (see situation 2 in Figure 7-1) it may also occur that a turbine fails before the actual start of the simulation period and is re-started just after the start of the simulation.

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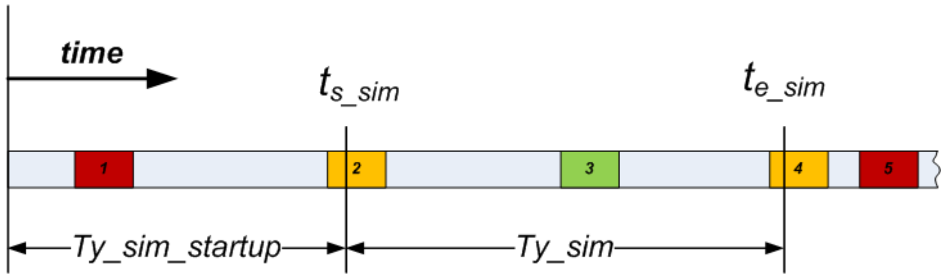

Figure 7-1: *Simulation period and possible repairs due to simulation period selection; ts_sim and te_sim are the start time and the end time of a certain simulation period (i.e. the next 1, 2, .., 5 years), and Ty_sim_startup is the start-up period*

Part II: OMCE Calculator

8. OMCE-Calculator structure and examples

As outlined before the OMCE-Calculator can be used to estimate the required O&M effort and associated uncertainties for the coming period taking into account operational experiences from the wind farm processed by the OMCE Building Blocks, see Figure 3-1. The OMCE-Calculator tool is developed with the MATLAB technical computing software. The modelling assumptions, specifications and requirements are already discussed in chapters 4, 5, 6 and 7.

The present chapter will provide some of the details of the structure and interface of the OMCE-Calculator software and will also illustrate some of the capabilities by means of a number of examples.

8.1 Modules

The OMCE-calculator consists of 4 separate modules:

1. OMCE input module
   In this module the maintenance models are set up and the required input data is imported by the user. The maintenance model and the corresponding input data are stored in a number of so called libraries, i.e. MAT-files, in such a way that the other three modules can extract all required information from these libraries straightforwardly.
2. OMCE pre-processor module
   To facilitate the simulation process a number of MAT-files are generated, which can be loaded in the simulator module. An important part is the processing of the weather data to assess the accessibility for various equipment with respect to their weather limits.
3. OMCE simulator module
   The simulation process is part of this module. At the start of a simulation a number of control parameters have to be specified by the user, such as the number of simulations and length of the simulation period. The results of the simulations are stored in a number of MAT-files which should be loaded in the post processing module.
4. OMCE post-processor module
   After the simulations are finished, the results can be processed to obtain the required output in tables and graphs. At the start of the post-processing a number of control parameters has to be specified by the user to define the required output.

The execution of these four modules is organised by the OMCE-Calculator Graphical User Interface (GUI), where it should be noted that these modules can be executed independent of each other. However, this can be done only if all MAT-files generated by foregoing modules are present already. This is notably of interest for the simulator module and the post-processor module as these modules can be executed again with another set of user defined control parameters.

8.2 Demo interface and relation to modules

After starting the software the main menu of the OMCE-Calculator is opened. The main menu of the OMCE-Calculator software is presented in Figure 8-1. Within the main menu the user can access each of the OMCE-Calculator's modules.

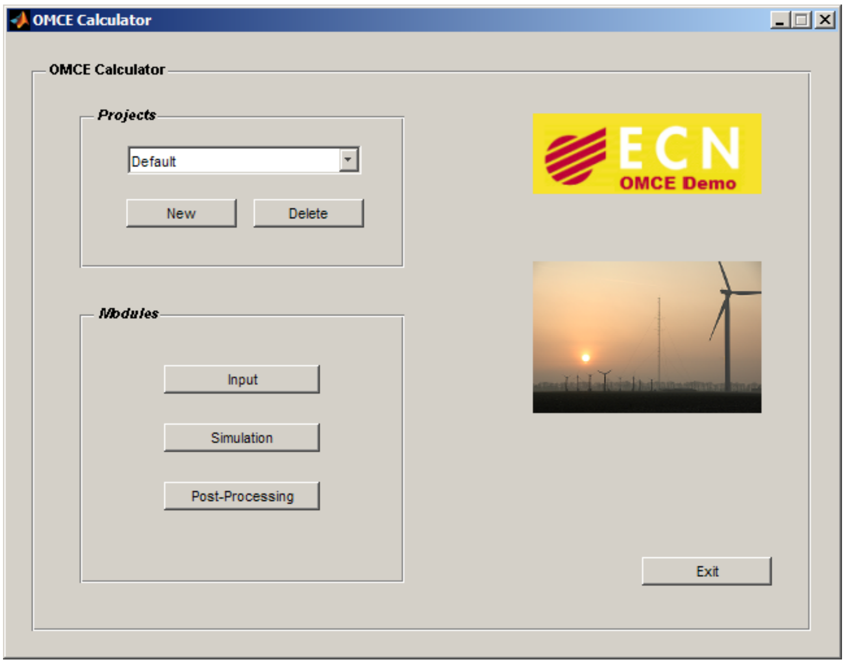

Figure 8-1: *OMCE-Calculator main menu*

In the main menu, an existing project can be selected or a new project may be defined. Once a project has been selected (either existing or new) one can continue with one of the menus: "*Input*", "*Simulation*" or "*Post-Processing*" via the corresponding buttons. The menus link to the corresponding OMCE-Calculator modules, where the *Input* menu includes both the input and the pre-processing modules.

Initially these modules have to be settled in order, so first the input has to be specified, next the simulations can be carried out and finally the results can be processed. For an existing project one can continue in each of these modules. However, it should be noted that in case the input is adjusted existing simulation and post-processing results will be deleted in order to keep the input data and the obtained results mutually consistent. Hence in this case simulations have to be carried out again before one can start with the post-processing.

8.2.1 Input and pre-processor modules

As an example the *input* menu and its links to the input and pre-processor modules are depicted in Figure 8-2. In the input module the maintenance models are set up and the required input data is imported by the user. Basically the input module consist of 5 data blocks which generate 5 binary MAT-file libraries on the hard disk, each corresponding to one of the following 5 buttons:

1. General: General wind farm operation & maintenance data and technician cost
2. Equipment: Data for different types of equipment available for maintenance which includes travel times, weather limits and cost
3. Spare Control Information on the number of spare parts to be applied for each type of maintenance, including stock control, logistic time and cost
4. Repair Class: Definition of maintenance repair classes, mission phases, work hours, number of technicians required and equipment to be applied
5. Wind Turbine: Definition of number and type of wind turbine or BOP, P-V data, breakdown of systems, definition of Fault Type Classes and selection corresponding Repair Classes and Spares

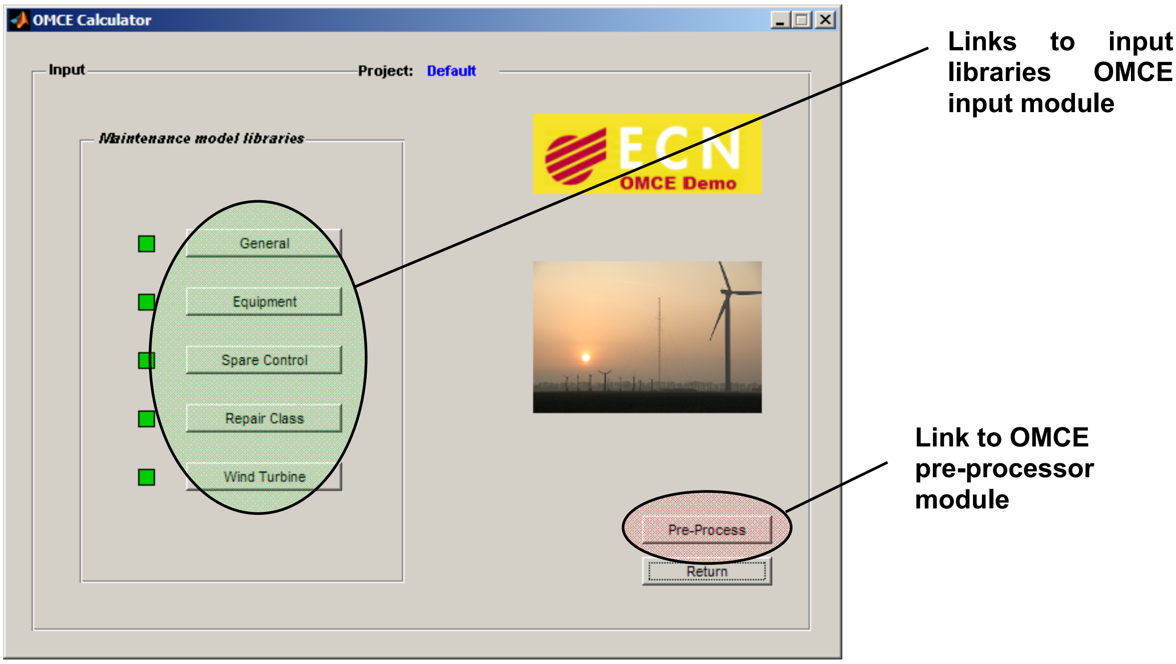

Figure 8-2: *OMCE-Calculator input menu*

Data structures have been set-up to store the required data in the MAT-file libraries. The data structures are filled automatically when a user is editing fields in one of the above data blocks in the input module GUI. To illustrate the design of such input fields for each data block, an example is given in Figure 8-3 of the General data block.

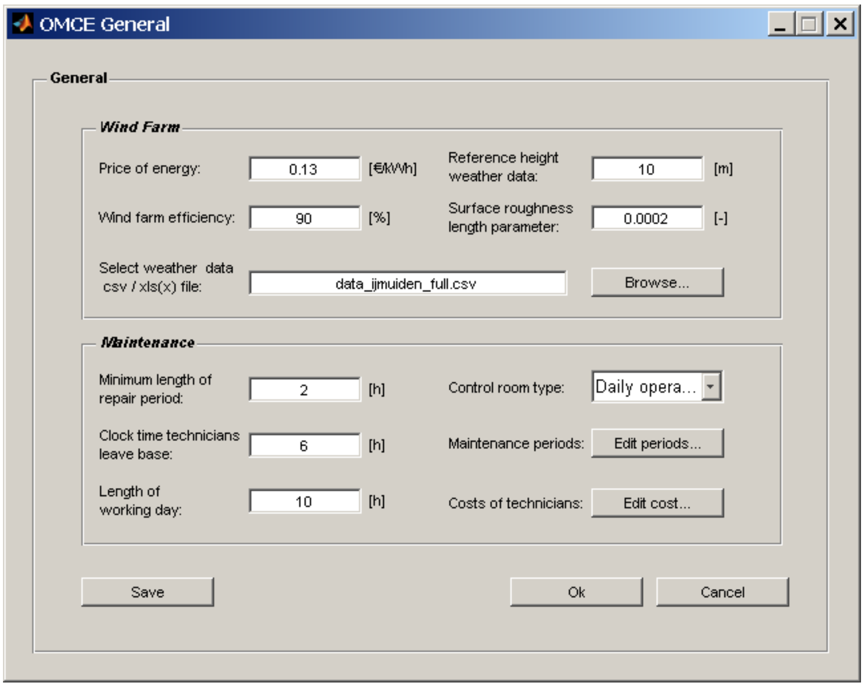

Figure 8-3: *OMCE-Calculator General data block*

As mentioned before it is beyond the scope of this report to specify and describe all required input and functionality for all data blocks. This will be part of the user manual for the OMCE-Calculator.

The structure of the OMCE-Calculator is such that especially the simulation module and the post processing module can be executed with different control parameters without adjusting the model or the input data. For this reason the pre-processing, which is identical for each simulation, is done within the pre-processing module. Hence the main objective of this module is to generate a number of MAT-files required for the simulation process. The pre-processing does not require additional user input and the module can be executed by the *Pre-Process* button once all input data blocks are fully defined (see Figure 8-2).

8.2.2 Simulator module

The simulator module is accessed from the *Simulation* button in Figure 8-1. The button opens the *simulation* menu shown in Figure 8-4 below. Within this menu either a new simulation can be defined or an existing simulation can be selected. The module can be executed independently with different control parameters. The following control parameters can be set for each simulation performed:

- Simulation period — duration [years] of actual simulation period; the actual simulation period is determinative for the post-processing.
- Start-up period — duration [years] of start-up period preceding the actual simulation period; this start-up period in included to make that at the start of the actual simulation period the status of the wind farm is representative for a wind farm in operation for a while.
- Number of simulations — needed to incorporate the uncertainties in failure frequencies and weather conditions.

After these parameters have been specified the simulation can be started by means of the button *Simulate* in Figure 8-4. This will also activate the progress bars, which indicate the remaining time and a *stop* button which allows the user to interrupt the simulation process.

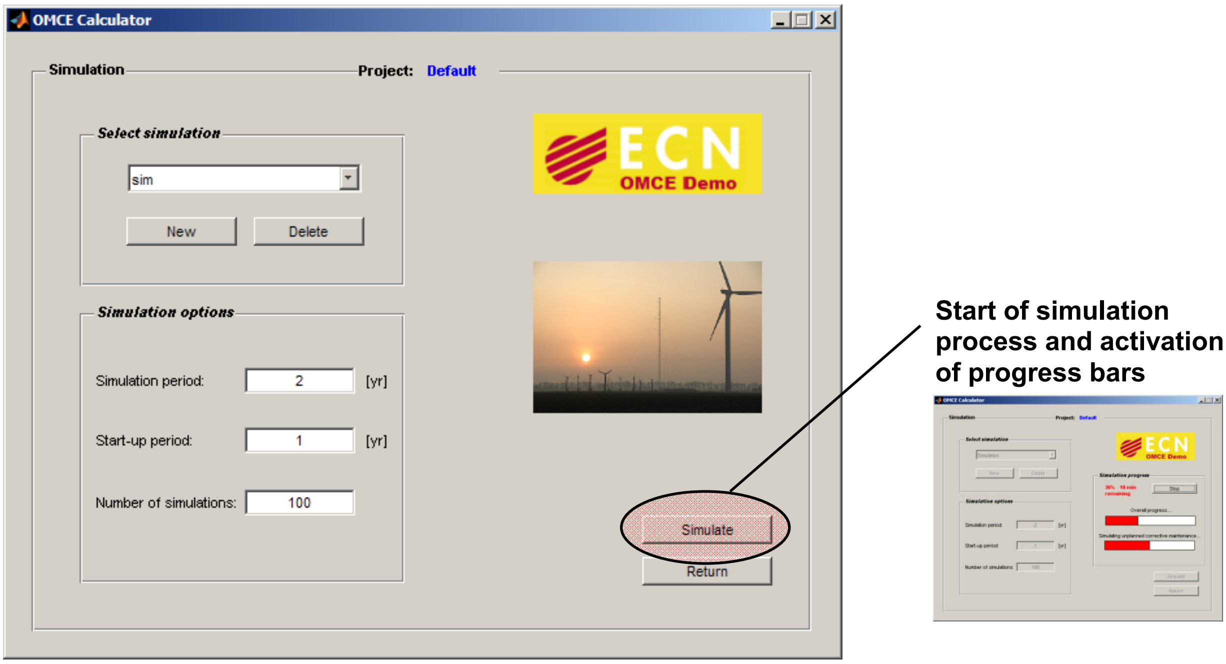

Figure 8-4: *OMCE-Calculator simulation menu*

8.2.3 Post-processor module

The post-processor module is accessed from the *Post-processing* button in Figure 8-1. The button opens the *post-processor* menu shown in Figure 8-5 below. Within this menu an existing simulation can be selected. A report in MS Excel can be created and opened by means of the button *Create/Open report* in Figure 8-4. With the button *Create plots* the end user is able to plot the results graphically.

Figure 8-5: *OMCE-Calculator demo post-processor menu*

The report output contains matrices which are automatically exported to MS Excel. The Excel document contains a total of 8 worksheets, which were specified during development of the post-processor module:

1. *Overview_results*: This sheet presents an overview of important cost drivers and the total Operation & Maintenance cost as average, standard-deviation, minimum and maximum values over the number of simulations performed. The sheet also displays a general summary of the simulation control parameters.
2. *Logistic_results*: This sheet contains an overview of man-hours per defined access equipment, usage of spare parts (incl. stock control information), and usage per available vessel for each defined equipment type. All values are presented as average, standard-deviation, minimum and maximum values over the number of simulations performed.
3. *Sim_results_operational*: This sheet returns an overview of operational results (such as downtime, number of repairs, production and production losses) per simulation performed
4. *GEN_input* Reflection of stored input in the GEN library (General)
5. *EQP_input* Reflection of stored input in the EQP library (Equipment)
6. *SCS_input* Reflection of stored input in the SCS library (Spare Control Strategy)
7. *RPC_input* Reflection of stored input in the RPC library (Repair Class)
8. *WTG_input* Reflection of stored input in the WTG library (Wind Turbine data)

Many of the results of the simulator module have a variable length due to a variable length input (e.g. no. of equipment defined, no. of spares, no. of wind turbine systems, no. of fault type classes etc.). To facilitate these output of variable length, the MS Excel document is based on a template which contains pre-formatted worksheets with respect to layout, colour and significant digits displayed. As an example of the reporting output a part of the sheet *Overview_results* is displayed in Figure 8-6.

Summary of costs		
Project	Default	
Simulation	Simulation	
Type of wind turbine	Demo Wind Turbine	
Number of wind turbines in farm	33	
Simulation period	2	yr
Start-up period	1	yr
Number of simulations	100	

Wind farm averaged per year			Unit	Average of simulations	Standard deviation	Minimum	Maximum
Number of repairs per year							
	Unplanned corrective		-	146,88	7,98	124,50	170,00
	Condition based		-	3,50	0,00	3,50	3,50
	Calendar based		-	1,50	0,00	1,50	1,50
Downtime per year							
	Unplanned corrective	Logistics	h	6498,2	385,7	5357,9	7548,1
		Weather	h	10791,6	3090,2	4912,0	29049,3
		Resources	h	643,3	252,1	246,9	1459,0
		Repair	h	14310,6	1504,2	11223,4	18283,5
		TOTAL unplanned corrective	h	32243,6	4137,3	24671,5	51687,5
	Condition based	**TOTAL condition based**	h	350,0	0,0	350,0	350,0
	Calendar based	**TOTAL calendar based**	h	198,0	0,0	198,0	198,0
		TOTAL	h	**32791,6**	**4137,3**	**25219,5**	**52235,5**
Loss of production per year			kWh	36.757.871	5.623.861	25.662.131	56.429.946
Energy production per year			kWh	260.726.719	13.886.848	229.554.827	292.113.192
Availability			%	88,66	1,43	81,93	91,29
Capacity factor			%	32,21	1,72	28,36	36,09

Figure 8-6: *OMCE-Calculator Excel report output in data blocks 'Summary of costs' and 'Wind farm averaged per year' in sheet Overview_results*

Based on specifications drawn up during development of the post-processor, various graphs can be exported from the OMCE-Calculator. These graphs are functionally divided in 4 main categories:

1. Summary of results
2. Type of maintenance
3. Optimisation
4. Feedback of input data

The graphs can be selected via the GUI which refers to these categories as well, see Figure 8-7. The post-processed simulation output is presented for these categories in one of the following three types of graphs:

1. CDF plots (cumulative distribution function)
2. Bar charts
3. Pie charts

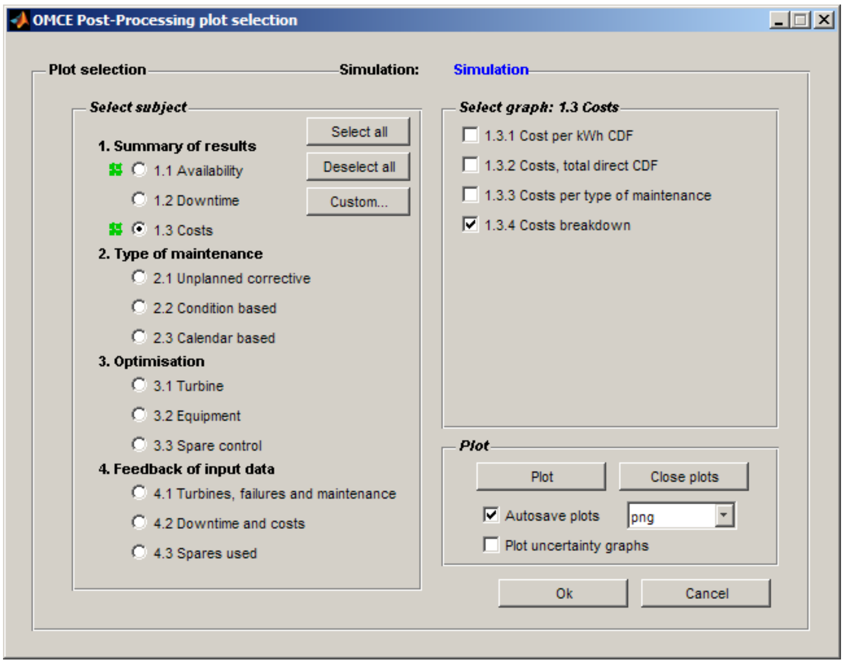

Figure 8-7: *OMCE-Calculator post-processor plot selection menu*

It is beyond the scope of this document to specify and show each of the 51 graphs which are presently implemented in the post-processor module. However, as an example two of the graphs are presented in Figure 8-8.

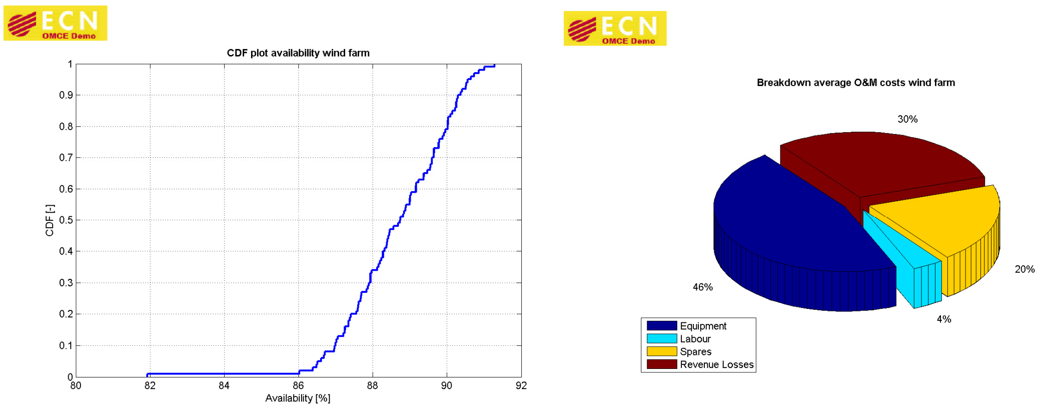

Figure 8-8: *OMCE-Calculator post-processor plot output, CDF availability wind farm (left) and breakdown of O&M costs wind farm (right)*

The left figure shows a CDF plot of the availability of the wind farm. The CDF plot y-axis represents the fraction of simulations where the corresponding x-axis value (availability %) is below a certain value. So in this example 100% of the simulations result in a wind farm availability below 91,3 % (see also Figure 8-6). The right-handed pie-chart represents the a breakdown of the average O&M costs of the modelled offshore wind farm in terms of equipment, material, labour and revenue losses due to standstill of the turbines.

8.3 OMCE-Calculator demo examples

To illustrate the capabilities of the OMCE-Calculator software a number of examples are presented. These examples are not representative for an entire wind farm, but are specifically defined to show how the OMCE-Calculator output can be used to optimise O&M on an operational wind farm. This paragraph will focus on the following 4 examples:

1. Consider limitations in stock control of spare parts for unplanned corrective maintenance and use this information to optimise the number of components on stock with respect to downtime of the turbines in the wind farm.
2. Consider limitations in vessels available for unplanned corrective maintenance and determine the optimal number of vessels to buy or hire with respect to total O&M costs of the wind farm.
3. Investigate the cost advantages of clustering maintenance events at different wind turbines. A reserved crane ship for a replacement is assumed to stay in the wind farm if multiple repairs coincide and continue with the following repair rather than being released for lease/rent by another party.
4. Perform condition based maintenance in the wind farm with different amounts of dedicated equipment and show the advantage of having multiple vessels with respect to the maintenance planning period.

8.3.1 Stock size optimisation

To illustrate how the limitations in the number of spare parts available influence the downtime of the turbines in the wind farm, a simplified example is analysed. The objective of this example is to investigate the relation between the number of spare parts in stock, the total downtime, and to determine the optimal stock size. This example has the following significant inputs:

- 12 wind turbines
- Failure rate per turbine $\lambda_{wt,i} = 2\, y^{-1}$
- Historical wind en wave data at the 'Munitiestortplaats IJmuiden' is used to determine site accessibility and revenues
- A work day has a length of 10 hours and starts at 6:00 am.
- 1 system with 1 fault type class for unplanned corrective maintenance, 1 corresponding repair class and 1 corresponding spare part
- The repair class will contain a maintenance event with 1 mission phase (repair) which can be split up in time.
- The reordering time of the spare part is set at 720 h (approximately 1 month), which is much longer than the logistic time to transport the spare part from the warehouse to the harbour at 2 h.
- The simulation was executed for a simulation period of 1 year with a start-up period of 1 year. The number of simulations performed is set at 100 to obtain statistically significant results with respect to the downtime.

If the failure distribution were to be uniform in time, then logically the number of failures will require 2 spare parts per month. With a reordering time of 1 month, a stock size of 2 spares would be sufficient. However, the failure distribution is a Poisson distribution. Now by varying the stock size from 1 to 12 the relation between the stock size and the total downtime of turbines in the wind farm can be set-up. A stock size of 0 spare parts is simulated by disabling stock control and increasing the logistic time to 722 h, while similarly an infinite stock size is simulated by simply disabling stock control and setting only the logistic time at 2 h. The simulation results are depicted in Figure 8-9.

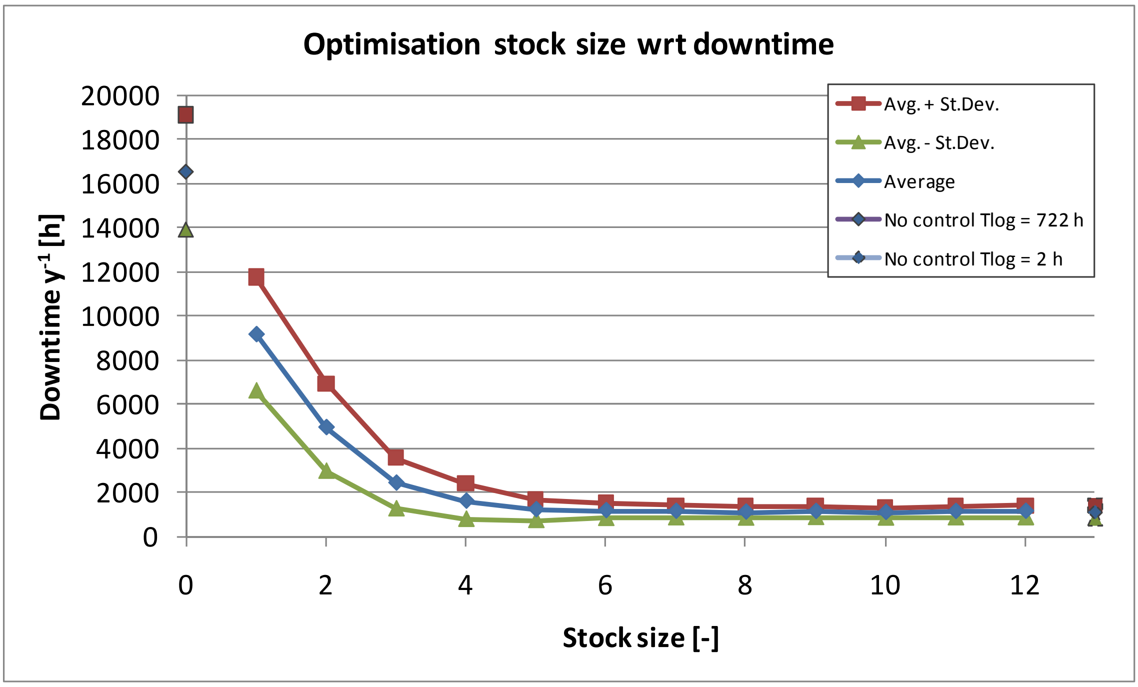

Figure 8-9: *Results of stock size variation vs. total downtime of wind turbines*

In the graph it can now be seen that for this example when 6 or more spares are kept in stock, both the average downtime and the standard deviation in the results seem to converge to the static value obtained without stock control (the data points for 'no control T_{log} = 2 h'). The remainder of the downtime at this point is a combination of remaining logistic downtime, waiting time for a suitable weather window and repair time (the applied vessel for maintenance does not have mobilisation time).

Based on these observations the advantages of having spare parts (with high reordering time) in stock for components which fail frequently become very clear and can be quantified with the output of the OMCE-Calculator.

8.3.2 Equipment optimisation

To illustrate how the limitations in the number of vessels available for unplanned corrective maintenance influence the downtime of the turbines in the wind farm, a second simplified example is programmed in the OMCE-Calculator. Now the objective of this second example is to investigate the relation between the number of vessels available and the total downtime. This example has the following significant inputs:

- 50 wind turbines
- Failure rate per turbine $\lambda_{wt,i} = 5\,y^{-1}$
- Historical wind en wave data at the 'Munitiestortplaats IJmuiden' is used to determine site accessibility and revenues
- A work day has a length of 10 hours and starts at 6:00 am.
- 1 system with 1 fault type class for unplanned corrective maintenance, 1 corresponding repair class and 1 corresponding spare part
- The repair class will contain a maintenance event with 1 mission phase 'Repair', where 6 hours of work with 2 technicians are required.
- The vessel used for the repair will be of the 'support vessel' type, which can only apply maintenance on a single wind turbine with a single crew when it travels to and from the wind farm. The travelling time of this equipment is set at 1 hour. The mobilisation time of this vessel will be set at 0 hours. In addition to hourly cost and fuel surcharges, fixed yearly cost of 250 k€ are assigned to each vessel.

- The simulation will be run for a simulation period of 1 year with a start-up period of 1 year. The number of simulations performed is set at 100 to obtain statistically significant results with respect to downtime and energy production.

The input details for the equipment defined are also shown in Table 8-1.

Table 8-1: *Reflection of equipment input optimisation project (1 equipment available)*

Project:	Equipment 1											
Equipment no.	*Type*	*Name*										
1	**Support vessel**	**Support 1**								**Unplanned corrective**	**Condition based**	**Calendar based**
	Logistics & availability	**Unit**	**Input**	**Weather limits**		**Unit**	**Input**	**Cost**	**Unit**	**Input**	**Input**	**Input**
	Mobilisation time	h	0	Wave height	Travel	m	2	Work	Euro/h	300	300	0
	Demobilisation time	h	0		Transfer	m	2		Euro/day	0	0	0
	Travel time	h	1		Positioning	m	2		Euro/mission	0	0	0
	Max. technicians	-	6		Hoisting	m	2	Wait	Euro/h	0	0	0
	Transfer category	-	single crew	Wind speed	Travel	m/s	12		Euro/day	0	0	0
	Travel category	-	daily		Transfer	m/s	12		Euro/mission	0	0	0
	Vessels available corrective	-	1		Positioning	m/s	12	Fuel surcharge per trip	Euro/trip	300	300	0
	Vessels reserved condition	-	0		Hoisting	m/s	12	Mob/Demob	Euro/mission	0	30000	0
	Vessels reserved calendar	-	0					Fixed yearly	Euro/day	250000	0	0

Although the example objective is similar to the example as discussed in section 8.3.1, the results are assumed to be different. The example inputs are set such that the average amount of failures will approximate to 250 per simulation. If these 250 failures were to occur independently on days where the defined support vessels' weather limits are sufficient to carry out all of the work, it would theoretically be possible to service the entire wind farm with 1 vessel. However, the failures follow the Poisson distribution and the weather limits set for this vessel are relatively strict with respect to the measured wave heights and wind velocities. This is expected to lead to a large increase in resource-related downtime if only 1 vessel were to be available to perform maintenance.

Now, by varying the number of available support vessels from 1 to 6, the relation between the number of vessels available and the total downtime of wind turbines can be set-up. The simulation results are depicted in Figure 8-10. We see that if only one vessel is available, than the average total downtime is more than doubled compared to the case when there are 2 vessels available. From 4 vessels onward, the decrease in downtime due to a lack of resources becomes smaller.

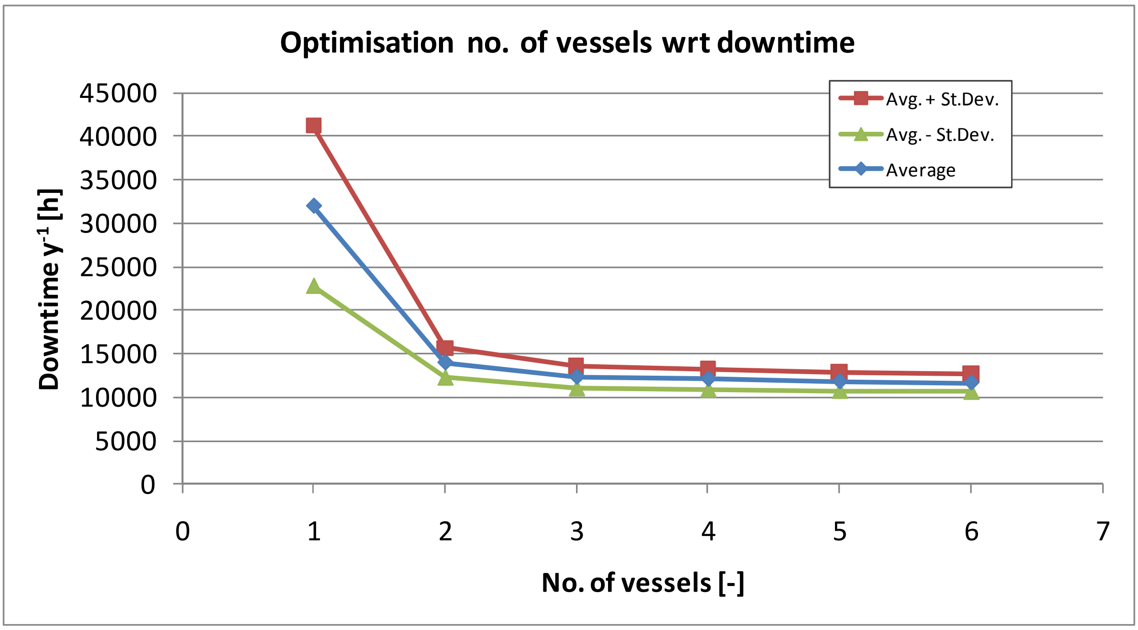

Figure 8-10: *Results of variation of no. of available vessels vs. total downtime of wind turbines*

Although the number of available vessels with respect to downtime should be as high as possible to prevent revenue losses due to a lack of resources, additional vessels will require additional O&M investments. The optimum number of vessels available for a wind farm should be related to the increase in repair costs and the decrease in revenue losses. The number of available vessels with respect to repair costs and revenue losses is now plotted in Figure 8-11.

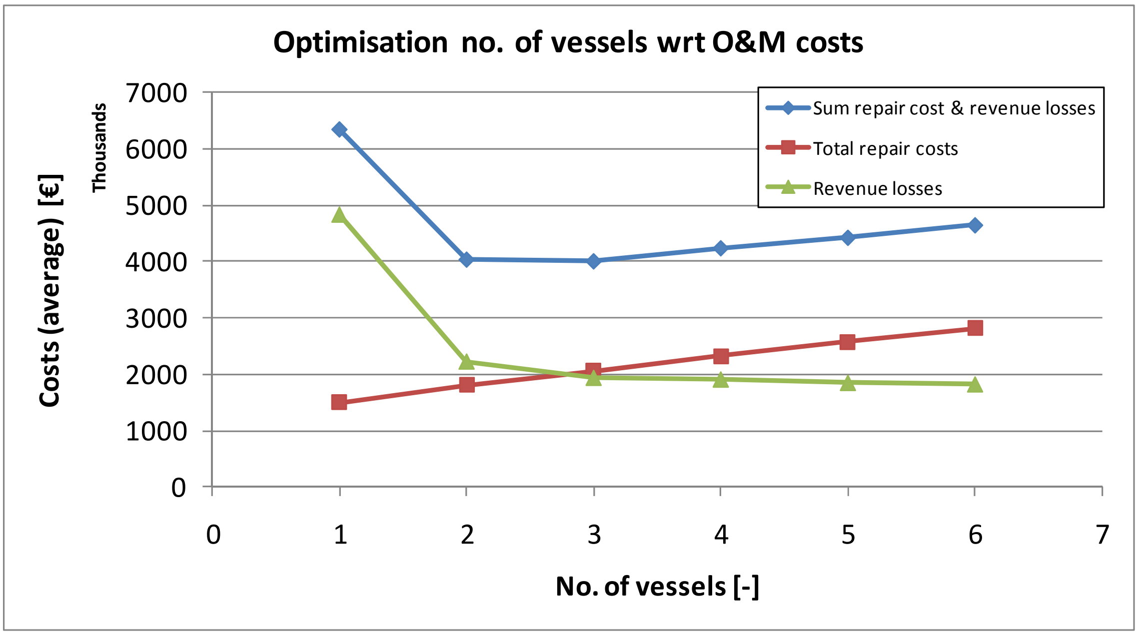

Figure 8-11: *Sum of total O&M cost and revenue losses as a function of no. of available vessels*

In Figure 8-11 the trend of the revenue losses versus the number of available vessels is decreasing, which naturally resembles the trend in downtime of wind turbines in the wind farm. At the same time, the total repair cost is increasing almost linearly with respect to the number of vessels. To plot the total O&M cost, both the repair cost and the revenue losses are super-positioned leading to the blue line in the graph. Based on the sum of these repair cost and revenue losses, the optimum number of vessels for the proposed example is seen to be 3 support vessels, since the effect of having more than 3 vessels on the overall downtime (and thus revenue losses) is negligible and the cost of having those vessels available increases.

Based on the above observations we can conclude that with the output of the OMCE-Calculator demo it is possible to quantify the effect on downtime & costs and to optimise the number of vessels available to perform corrective maintenance.

8.3.3 Clustering of maintenance

The advantages of clustering of maintenance events will be demonstrated in this 3rd example which is programmed in the OMCE-Calculator demo. Clustering of maintenance events for multiple failures will help save equipment mobilisation/demobilisation cost. Clustering is defined as the case where a vessel reserved for a certain failure is assumed to stay in the wind farm and if possible continue with the following repair rather than being released for lease/rent by another party. This form of clustering is implemented in the OMCE-Calculator demo. Now the objective of this 3rd example is to investigate the relation between the number of failures and the effect of clustering of maintenance events. This example has the following significant inputs:

- 100 wind turbines
- Historical wind en wave data at the ‘Munitiestortplaats IJmuiden’ is used to determine site accessibility and revenues
- A work day has a length of 10 hours and starts at 6:00 am.
- 1 system with 1 fault type class for unplanned corrective maintenance, 1 corresponding repair class and 1 corresponding spare part.

- The repair class will contain a maintenance event with 1 mission phase 'Replacement, where 16 hours of work with 4 technicians are required.
- The vessels used for the replacement will be both of the 'access vessel' and 'vessel for replacement' types. The crane ship defined will obtain a mobilisation cost set at €250000,- to clearly indicate the effect of clustering on the O&M cost. The crane ship has a mobilisation time of 720 hours and a demobilisation time of 360 hours. Including the night break, where the crane ship will stay in the wind farm, a weather window length of 38 hours will be required to complete one replacement.
- The failure rate per turbine will be varied between $\lambda_{wt,i} = 0.005\ y^{-1}$ to $\lambda_{wt,i} = 0.5\,y^{-1}$, since the failures are modelled stochastically the failure frequency is increased in steps to a high value as to ensure that clustering will occur.
- The simulation will be run for a simulation period of 1 year with a start-up period of 1 year. The number of simulations performed is set at 1000 to obtain statistically significant results with respect to downtime and energy production.

The example inputs are set such that the average amount of failures will be varied by adjusting the turbine failure rates. For example the lower limit is set at $\lambda_{wt,i} = 0.005\ y^{-1}$, which will lead to an average number of failures of 0.5 for the 100 turbines defined. At average clustering is expected not to occur and the cost per repair are estimated to be at the maximum. However, if more of these same failures occur, clustering of the maintenance will be executed and the cost per repair performed are expected to be lower.

For further discussion of the results, the repair mission breakdown of the replacement is illustrated in more detail in Figure 8-12. Now if maintenance can be clustered (i.e. two or more failures occur within the timeframe of the mobilisation), the crane ship is assumed to stay near the wind farm and so eliminating the need for demobilisation of the current and mobilisation of the following repair. More information about the modelling details of the repair class is found in Section 5.1.2.

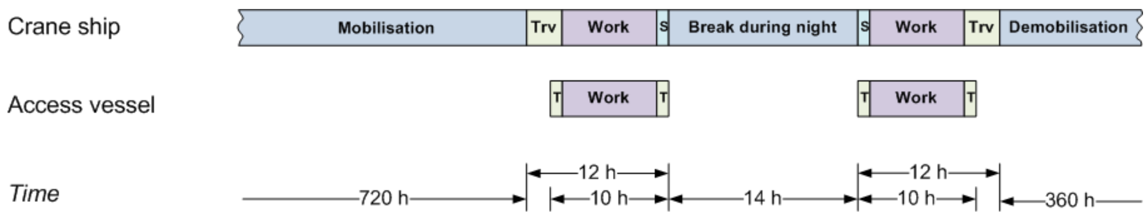

Figure 8-12: *Breakdown of repair mission for defined replacement with 16 hours of work performed by 2 vessels*

Now, by varying the failure rate per turbine from $\lambda_{wt,i} = 0.005\ y^{-1}$ to $\lambda_{wt,i} = 0.5\,y^{-1}$, the number of failures in the wind farm will vary accordingly. The OMCE-Calculator demo output is used to set-up the relation between the simulated number of failures, the average cost per repair and the total number of mobilisations performed by the crane ship. The result is given in Figure 8-13.

We see that if more failures occur, the repair cost made per failure drops. This is caused by the stochastic failure distribution, where some of the simulations contains one or more failures which are clustered. The clustering results in reduced mobilisation cost on average. With an increasing number of failures, first the number of mobilisations increases up to around 10 failures since more mobilisations are performed on average and then, as we may expect, the number of mobilisations starts to decrease as the number of mobilisations is reduced by continuous clustering of some of the repairs. When 47 failures per year occur on average, the average number of mobilisations is as low as 0.6 indicating that most of the maintenance is clustered by now. On average all maintenance is expected to be clustered, however also some of the simulations contain less failures which are also then less clustered.

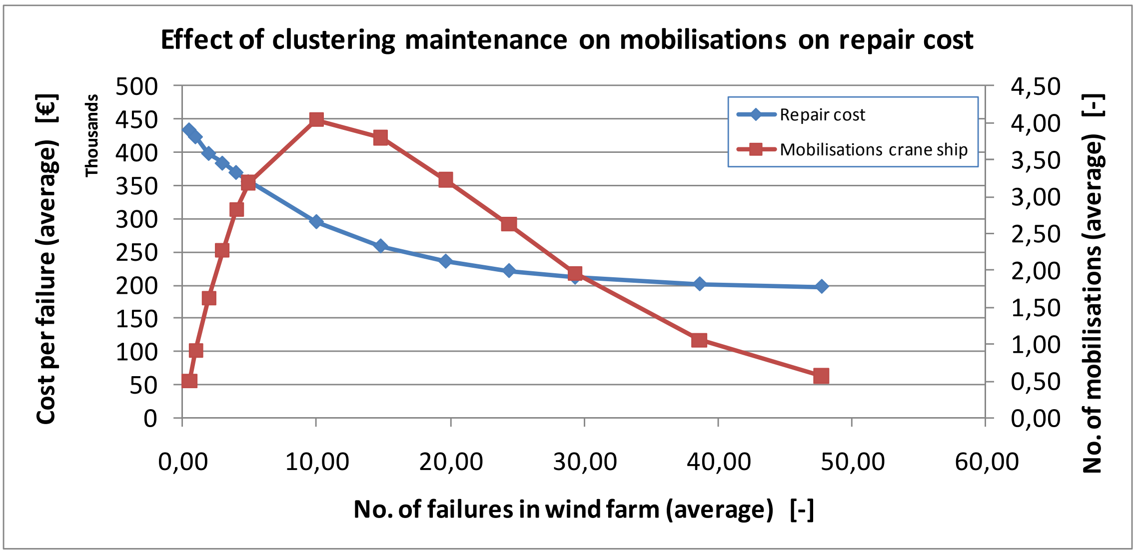

Figure 8-13: *Effect of clustering maintenance on number mobilisations and repair cost*

By using the cost inputs and the repair scheme in Figure 8-12, the repair cost can be estimated in the upper and lower limit states. The access vessel defined is rated at €300,-/hr with an additional fuel surcharge of €300,- per (return-)trip, while the crane ship is rated at €5000,-/hr with additional fuel surcharge of €10000,- per trip and a mobilisation/demobilisation cost of €250000,-. Spares cost are rated at €50000,- per part and the 4 technicians are rated at €100,-/hr each. Apart from the mobilisation cost all other costs will be charged per repair regardless of the number of mobilisations. No fixed cost are assigned to technicians, spares or equipment as to not bias the results. Considering Figure 8-12, a single repair without clustering would than cost:

$$\lim_{N_{cluster}\to 0} Cost_{repair} = 20\cdot 300 + 2\cdot 300 + 24\cdot 5000 + 10000 + \\ 250000 + 50000 + 4\cdot 100\cdot 20 = €444600,-$$

Now assuming that all repairs could be clustered this would result in:

$$\lim_{N_{cluster}\to \infty} Cost_{repair} = 20\cdot 300 + 2\cdot 300 + 24\cdot 5000 + 10000 + \\ 50000 + 4\cdot 100\cdot 20 = €196600,-$$

We see these upper and lower limits of the repair cost correspond to be observed output of the repair cost in Figure 8-13. Based on the above observations we can conclude that with the output of the OMCE-Calculator demo it is possible to quantify the effects of clustering corrective maintenance.

8.3.4 Implementing condition based maintenance

One of the additional features of the OMCE-Calculator is the ability to model condition based maintenance. One of the main modelling assumptions as noted in section 0, is that the maintenance events can be planned in advance and the turbines will only be shut down during the actual repairs made. A period can be specified during which equipment is available for condition based maintenance. In case the work cannot be completed within this period, e.g. due to bad weather conditions or shortage of equipment a message will be given by the program

(N.B. the number of repairs will be constant for each simulation, the random year chosen in the weather data will not). It can then be considered to allocate more equipment or to lengthen the period.

The current example will demonstrate the modelling of condition based maintenance in relation to the defined maintenance period and the number of equipment available. The objective is to model the same maintenance with 1 vessel available per equipment type and 2 vessels available per equipment type, after which the results can be compared with respect to the planned maintenance period. This example has the following significant inputs:

- 50 wind turbines
- Number of repairs to be made (no. of turbines) $N_{rep\,wt} = 10$
- Historical wind en wave data at the 'Munitiestortplaats IJmuiden' is used to determine site accessibility and revenues
- A work day has a length of 10 hours and starts at 6:00 am.
- 1 system with 1 fault type class for condition based maintenance and 1 corresponding spare control strategy
- The repair class will contain a maintenance event with the phase 'Replacement', where in total 16 hours of work with 4 technicians are required.
- The type of vessels used for the replacement are: 'Access vessel' and 'Vessel for replacement'. The travelling time of the access vessel is set at 1 hour, while the travelling time of the vessel for replacement is set at 4 hours. The vessel for replacement is assumed to have an overnight stay in the wind farm.
- The maintenance period window is set from 1st of July up to and including the 31st of July.
- The simulation will be run for a simulation period of 1 year with a start-up period of 1 year. The number of simulations performed is set at 100 to obtain statistically significant results with respect to downtime and energy production.

The equipment input parameters are also displayed in Table 8-2.

Table 8-2: *Reflection of equipment input condition based maintenance project*

Project:	Condition based maintenance 1											
Equipment no.	*Type*	*Name*										
1	**Access vessel**	**Swath workboat**								**Unplanned corrective**	**Condition based**	**Calendar based**
	Logistics & availability	**Unit**	**Input**	**Weather limits**		**Unit**	**Input**	**Cost**	**Unit**	**Input**	**Input**	**Input**
	Mobilisation time	h	0	Wave height	Travel	m	2	Work	Euro/h	0	300	300
	Demobilisation time	h	0		Transfer	m	2		Euro/day	0	0	0
	Travel time	h	1		Positioning	m			Euro/mission	0	0	0
	Max. technicians	-	5		Hoisting	m		Wait	Euro/h	0	0	0
	Transfer category	-	multiple crews	Wind speed	Travel	m/s	12		Euro/day	0	0	0
	Travel category	-	daily		Transfer	m/s	12		Euro/mission	0	0	0
	Vessels available corrective	-	1		Positioning	m/s		Fuel surcharge per trip	Euro/trip	0	300	300
	Vessels reserved condition	-	1		Hoisting	m/s		Mob/Demob	Euro/mission	0	25000	25000
	Vessels reserved calendar	-	0					Fixed yearly	Euro/day	0	0	0
2	**Vessel for replacement**	**Crane ship**								**Unplanned corrective**	**Condition based**	**Calendar based**
	Logistics & availability	**Unit**	**Input**	**Weather limits**		**Unit**	**Input**	**Cost**	**Unit**	**Input**	**Input**	**Input**
	Mobilisation time	h	16	Wave height	Travel	m	2	Work	Euro/h	0	10000	0
	Demobilisation time	h	8		Transfer	m	2		Euro/day	0	0	0
	Travel time	h	4		Positioning	m	2		Euro/mission	0	0	0
	Max. technicians	-	0		Hoisting	m	2	Wait	Euro/h	0	0	0
	Transfer category	-	single crew	Wind speed	Travel	m/s	8		Euro/day	0	0	0
	Travel category	-	stay		Transfer	m/s	8		Euro/mission	0	0	0
	Vessels available corrective	-	0		Positioning	m/s	8	Fuel surcharge per trip	Euro/trip	0	5000	0
	Vessels reserved condition	-	1		Hoisting	m/s	8	Mob/Demob	Euro/mission	0	250000	0
	Vessels reserved calendar	-	0					Fixed yearly	Euro/day	0	0	0

Based on the input parameters the minimum time required to fulfil 1 condition based maintenance repair is exactly 2 work days. If the weather conditions are calm, it should be possible to perform all condition based repairs within the given maintenance period. However, the weather window limits for hoisting are set fairly strict and the weather pattern in the North Sea is known to be variable even in the summer periods.

Two different simulation runs have now been performed; the first run has 1 vessel available for both equipment types, the 'access vessel' and the 'vessel for replacement', while the second run has 2 vessels available for each equipment type. To determine whether or not the maintenance could be performed within the given maintenance period, the graph output of the OMCE-Calculator is used. Two cumulative distribution function (CDF) plots are shown in Figure 8-14. The CDF plot y-axis represents the fraction of simulations where the corresponding x-axis value (no. of events outside period) is below a certain value. So in this example 13% of the simulations result in all maintenance events finishing within the simulation period when there is 1 vessel available of each equipment type (left CDF plot in Figure 8-14). We also see that when there are 2 vessels available, then 85% of the simulations do finish within the simulation period (right CDF plot in Figure 8-14).

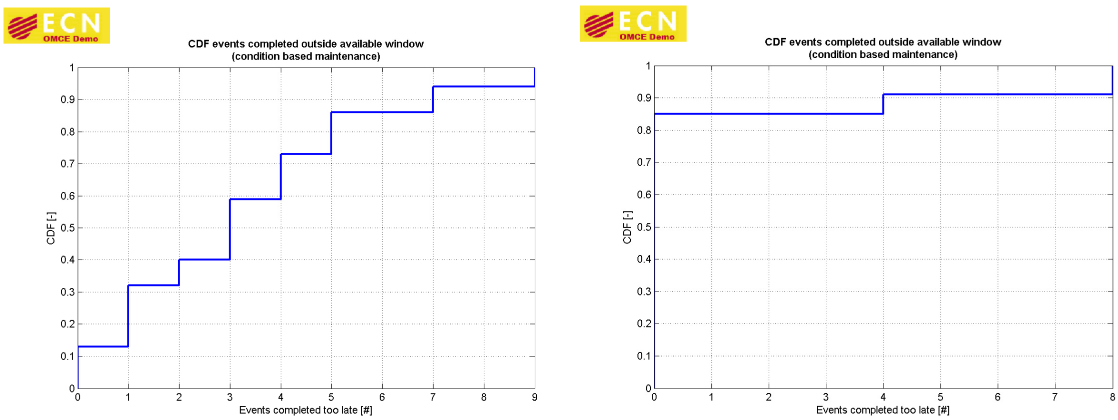

Figure 8-14: *CDF plot of number of maintenance events performed outside required maintenance period; Simulations with 1 vessel available (left) and simulations with 2 vessels available (right)*

However, having additional vessels will not decrease the revenue losses (turbines are only shut down during maintenance) and at the same time there may be an increase in equipment cost. Engineering judgement will be required to determine whether or not additional delays are allowable with respect to the remaining lifetime of the components which should be replaced, or if it is possible to extend the period.

Based on the above observations we can conclude that with the output of the OMCE-Calculator demo it is possible to quantify condition based maintenance replacements and to set a specific maintenance period when this maintenance should be performed. However, notice that the OMCE-Calculator demo is not intended to be used as a program to optimise maintenance planning in time. The output should rather be used by the maintenance engineer as a first indication whether or not a certain maintenance scenario is feasible to perform in a given time frame.

Part III:
Data Collection and Analysis
(OMCE Building Blocks)

9. Data Collection and Processing

In Part II of this report the OMCE Calculator, especially its specifications, the modelling solutions, and some examples, have been discussed. In order to make use of the OMCE-Calculator to estimate the O&M costs for the near future it is recommended to make use of the data generated by the wind farm. On the one hand it is necessary to collect the data in a structured way so that it can be analysed for reliability engineering and O&M modelling; on the other hand it is necessary to develop models, tools, and/or software with which it is possible to analyse the data and generate input data for e.g. the OMCE-Calculator.

In the past, the authors have been collecting and analysing data from onshore and offshore wind farms and concluded that the present procedures for collecting and storing field data should be improved if the data are going to be used for modelling the O&M aspects and reliability engineering. The collection of the data in a structured way in fact is the responsibility of the wind farm operator in close collaboration with the maintenance departments and the contractors. The experiences of the authors on the data sources available in a typical offshore wind farm are discussed in Chapter 10. To better structure the data collection, the OMCE project could not develop tools or software but only specifications and recommendations on how to do so. The specifications are called the "Event List" and will be discussed in Chapter 10.

Once the data is collected in a structured format, software and tools can be used to analyse the data and generate input for modelling purposes. Within the OMCE project the combination of analysis software with procedures are called the OMCE Building Blocks (BB). The OMCE BB's will be discussed in detail in the Chapters 12 through 15. The purpose of each Building Block will be discussed, its specifications and procedures will be explained and developed software will be highlighted. Furthermore, some examples will be presented on how to analyse operational data and generate input data for the OMCE-Calculator.

The relationship between the Event List and the OMCE BB's together with the expected results of the OMCE BB's is already briefly discussed in Section 3.2 and explained in Figure 9-1. Figure 9-1 also explains the scope of Part III of this report.

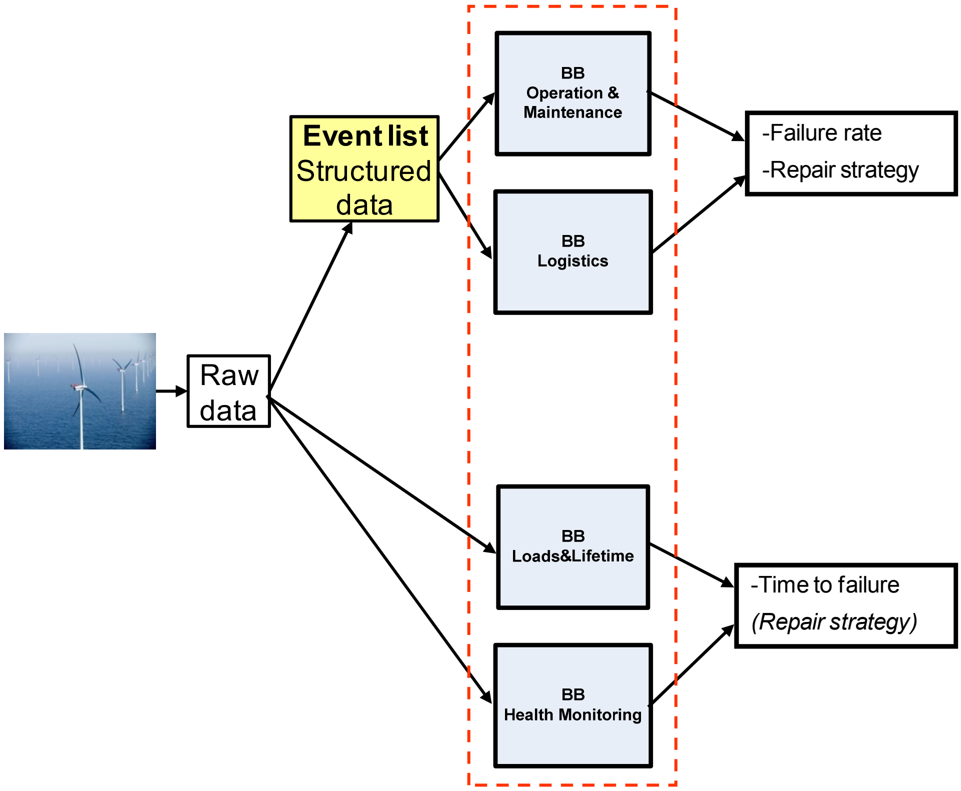

Figure 9-1: *Relationship between the raw wind farm data, the Event List and the OMCE BB's*

The Event List in fact only deals with structuring the raw wind farm data needed to derive information from the maintenance actions carried out, failure and repair data, the repair strategies applied, and the usage of vessels, labour, and spares in relation to the observed weather conditions. Next to these types of data, the wind farm also generates data that can be used for condition based maintenance, e.g. measured loads, degradation of components, inspection reports etc. The Event List developed in the OMCE project does not cover these data sets.

As is shown in Figure 9-1 (and also in Figure 3-1) the OMCE consist of four Building Blocks (BB) to process each a specific data set. Furthermore, it was also mentioned that the Building Blocks in fact have a two-fold purpose:

1. To provide information to determine input data for the OMCE-Calculator, or to update the input values used earlier on e.g. during the development phase.
2. To provide more general information on the wind farm performance and 'health' of the wind turbines.

In this report special attention will be given to the first objective in order to specify in more detail what kind of output is expected from the different Building Blocks in order to generate input for the OMCE-Calculator. It is not expected that the input needed for the calculations can be generated automatically in all cases. The opposite might be true, namely that experts are needed to make the correct interpretations. Furthermore it is also essential to keep in mind that the output of the Building Blocks (based on the analysis of 'historic' operational data) is not always equal to the input for the OMCE-Calculator (which aims at estimating the future O&M costs).

The Building Blocks 'Operation & Maintenance and 'Logistics' have the main goal of characterisation and providing general insight in the corrective maintenance effort that can be expected for the coming years. With respect to corrective maintenance important aspects are the failure frequencies of the wind turbine main systems, components, and failure modes. Furthermore, other parameters that are needed to describe the corrective maintenance effort are for instance the length of repair missions, delivery times of spare parts and mobilisation times of equipment. Within the OMCE project tools and software have been developed that can be used by operators to analyse their data sets and generate input data needed for O&M modelling but only if the data are collected in accordance with the Event List specifications!).

For estimating the expected future condition based maintenance work load the Building Blocks 'Loads & Lifetime' and 'Health Monitoring' have been developed. The main goal of these Building Blocks is to obtain insight in the condition or, even better, remaining lifetime of the main wind turbine systems or components. Within the OMCE project it was concluded that it was not possible to develop a software tool for analysing the data sets that apply to 'Loads & Lifetime' and 'Health Monitoring'. These data are often obtained from measurement systems from third parties and require experts to draw meaningful conclusions. The results need to be interpreted carefully and combined for instance with inspection results. Such procedures appeared to be too complicated to incorporate in software that can be used straightforwardly by wind farm operators. For the further development of the BB 'Loads & Lifetime' a separate project was initiated (*Flight Leader concept for Wind Farm Load Counting*) and the results are presented in Chapter 14. For the BB 'Health Monitoring' the description is limited to the lessons learned, some general procedures, and references to further reading.

The interface between the OMCE-BB's and the OMCE-Calculator (briefly discussed in Section 3.2.3) is schematically given in Figure 9-2. The red ovals indicate the output of the BB's that can be used firstly by the operator directly for O&M optimisation and secondly to determine input data for the Calculator.

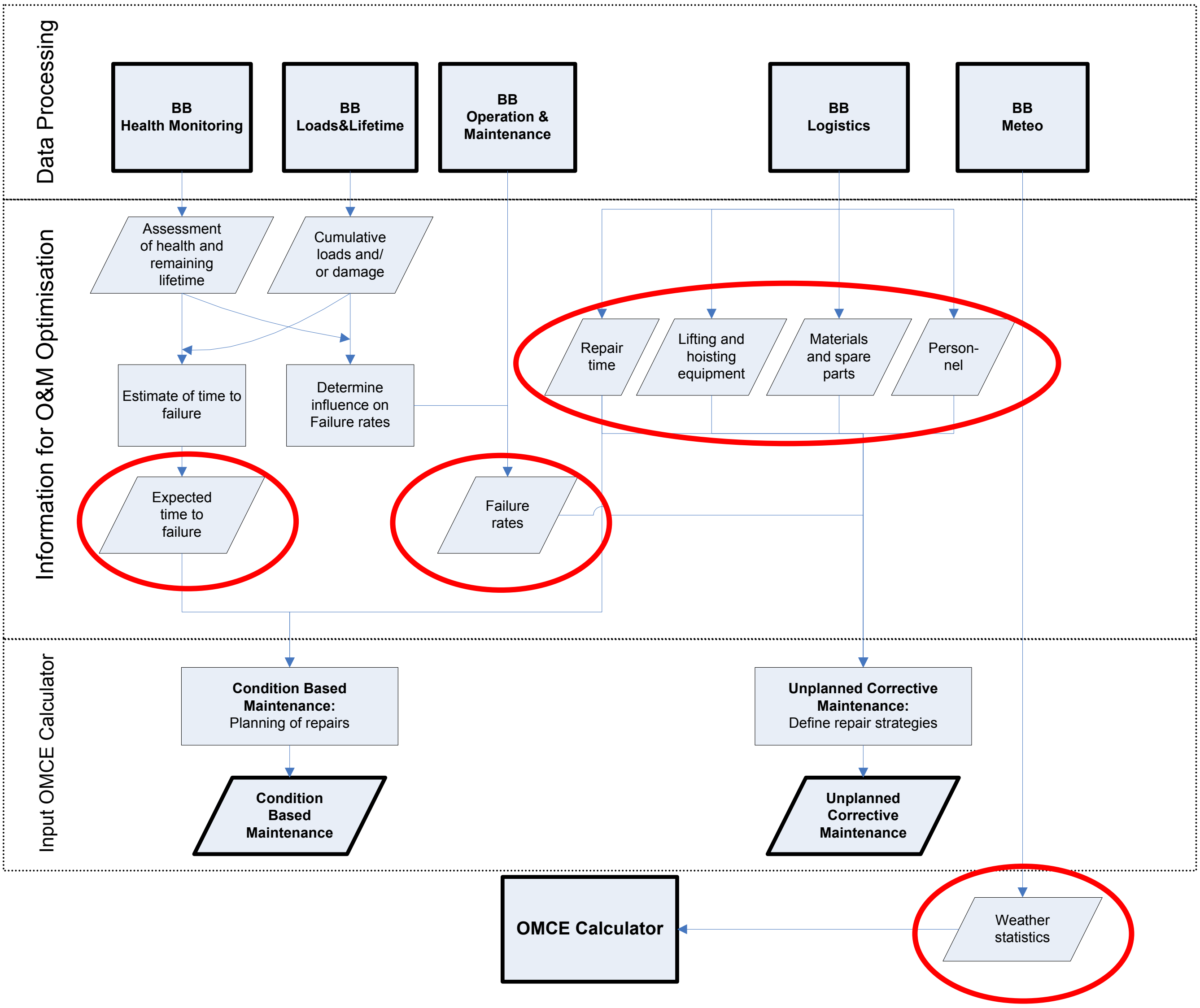

Figure 9-2: *Interfaces between the OMCE-BB's and OMCE-Calculator*

10. Available Data Sources

ECN has experiences with analysing different types of data, often stored in different sources. In this chapter mainly those types of data relevant for the OMCE BB's "Operation & Maintenance" and "Logistics" will be discussed.

10.1 Maintenance (or service) sheets

Maintenance or service sheets are often used by technicians to fill in the work they have carried out, the duration, some details about the failure or repair action, and the costs they have made for a.o. spares, consumables, or cranes. In the past, most of these sheets had to be filled in manually. Presently, more and more digital sheets are being used. The fields to be filled in in this service report are considered to be representative for most nowadays maintenance sheets used in the wind industry.

- Report nr.
- Type of maintenance (*erection, commissioning, warranty, service, errors, extension, control, or customer complaint*)
- Wind farm, wind turbine, customer
- Date of visit
- Operating hours and energy produced
- In case of error: "description of error"
- Work carried out (description)
- Date and time of stop and start
- Name(s) of technicians
- Working hours
- Vehicle used by technicians, travelling time, hotel visits
- Materials used (including cranes)

As mentioned in previous studies in which maintenance sheets for onshore wind turbines have been processed, e.g. Ref. 28, it was concluded that as long as the maintenance sheets are filled in manually and a free format is used for the description of the component, the failure mode, and the work carried out, it is too labour intensive to perform reliability analyses with the collected maintenance reports. It is preferred to set up an automated data collection system in which the individual components of the turbines, the description of errors and work carried are already pre-defined. Technicians can then select the failed component, the error, and the work carried out by means of pull down menus. This will lead to an unambiguous description of the items required for reliability analyses.

From analysing different data sets of on- and offshore wind farms the authors concluded that in most cases it is unclear from the individual reports what the trigger was for a certain visit or repair action. The trigger could be for instance an alarm leading to a shutdown, or the result of an inspection. The trigger was hardly reported on the service reports and therefore relations between more than one service action could not be made.

10.2 SCADA data and alarms

Data from SCADA systems usually contain statistical parameters (min, max, mean, stdev) of 10 minute time series (e.g. nacelle wind speed, energy produced, yaw angle, pitch angle, etc.). SCADA data can be assessed and analysed by the operator of a wind farm in various ways. The operator may for instance perform trend analyses and assess if certain parameters (e.g. temperatures) change over time and decide if maintenance is required in due time. In fact, these types of analyses should be part of the OMCE BB "Health monitoring" because they will lead to condition based maintenance. Therefore the 10 minutes statistical data from SCADA systems will no longer be considered in this report.

SCADA data may also include alarms with an immediate shutdown. Or: the operator may conclude after analysing 10 minute statistical that an immediate shutdown is required. These types of SCADA data, viz. alarms, require immediate manual intervention and are considered as unplanned corrective maintenance and thus relevant for the OMCE BB's "Operation & Maintenance" and "Logistics".

Lists of alarms usually contain the following fields.

- Turbine ID
- Alarm code (referring to the failed system or component, and/or the failure cause, and/or the external situation, and/or the operational mode)
- Date and time of alarm
- Date and time of re-start
- Duration of the alarm or shutdown, derived from the time of re-start and stop.
- Production losses

The alarm codes in some cases do not exactly determine what kind of component has failed or what the (root) cause of the alarm was. E.g. an alarm of a swarf sensor does mean that the gearbox oil is contaminated but the real cause of the alarm could be a failure of a bearing. Many of the alarms need to be combined with judgements of experts if reliability analyses are to be made. The alarm lists do not give any information on the repair actions carried out to fix the problem (e.g. reset, or repair), so the correlation with for instance resources used is difficult to make.

10.3 Transfer and hoisting equipment

The use of equipment for transferring personnel and parts and the equipment for hoisting large components have a large influence on both the cost of the maintenance actions and the downtime due to bad weather conditions. Often, the usage of equipment is reported in so called "vessel transfer plans" and "activities lists" but no reference is made to the actual trigger of the maintenance visit.

Vessel transfer plans are being prepared at the evening before the vessels will leave the harbour and describe which vessel with which personnel will sail to which turbine. If the weather conditions are not good enough, the planned activities will be postponed. From the vessel transfer plans it is hardly possible to exactly determine what kind of work was carried out and completed. Activities reports are meant to report the activities after the work is carried out.

By combining the vessel transfer plans, the activities reports, the weather data, the alarm lists, and the energy production figures the authors succeeded in re-constructing the usage of small and large vessels (but to a limited extend only). Information was obtained about the following fields.

- Vessel ID
- Turbines visited
- Technicians involved
- Maintenance activities planned (and/or carried out)
- Date and time leaving the harbour
- Date and time of return

It is likely that within the data sources of an offshore wind farm more information about vessel transfers is available. Most likely the vessels are equipped with a GPS which records all movements. Furthermore it is likely that all persons entering and leaving the vessels are reported in a kind of logbook, together with the spare parts and components that are transferred. The usage of the large crane ships can probably be derived from the contracts signed between the owner of the ship and the wind farm operator. Furthermore it is relevant to understand under what conditions the ship owners decide whether or not to sail out or to carry out a maintenance action. Therefore the weather conditions per day should also be reported.

10.4 Weather conditions

The weather conditions, especially wind and wave conditions, determine if repair and maintenance actions can be carried out. Usually the local weather conditions are acquired for most wind farms. The wind farms are equipped with a met mast and in some cases a wave buoy is present. If not, the weather conditions can be derived from a met office.

For O&M purposes three hourly average values of wind speed and significant wave height are needed (and acquired in most cases!).

10.5 Spare parts and consumables

The spare parts and consumables used are reported on e.g. the service reports. In addition, maintenance departments or the operations manager also have knowledge about the spare parts and consumables used for a certain wind farm. ECN has insufficient knowledge to assess what kind of information is being stored and if it is applicable for cost estimation purposes.

11. Event List for Structured Data Collection and Analyses

11.1 Types of events

Within the context of the OMCE, an event is considered as a maintenance action to prevent turbine malfunctioning, or a maintenance action following after malfunctioning of the turbine. An event may consist of a single maintenance action, or a series of actions with a total duration of several days or even weeks.

Within the OMCE-Calculator, the modelling of the following events is considered:
1. preventive maintenance;
2. unplanned corrective maintenance;
3. condition based maintenance (or “planned corrective”);
4. shutdown with automatic reset

To obtain the right level of detail for collecting and analysing the events, it is recommended to use an additional level of detail and to split up the two of the four event types.

1. Preventive maintenance
   - 1.1 small (e.g. once per year or half year, or 3 months after commissioning);
   - 1.2 large (e.g. once per two years);
   - 1.3 major overhaul (e.g. once per five years);

   (The three types of preventive maintenance should be considered as an example only; in reality more types could be relevant.) The description of the components to be serviced, the procedures to be followed, and the spare parts and consumables, and the equipment to be used during preventive maintenance are written in the work order of the technicians. By closing the work order, all relevant data needed for data processing by the BB “O&M” and “Logistics” should be available.

   The trigger for the execution of preventive maintenance is usually a calendar date. The downtime is more or less equal to the time the technicians actually spend on the maintenance action. In some cases a turbine shutdown is not necessary at all, e.g. in cases where a tower is inspected insight, steps at the tower bottom need to be maintained, inspection of cables and scour protection, or painting of the lower platform.

2. Unplanned corrective maintenance
   - 2.1 shutdown with remote reset;
   - 2.2 shutdown which requires a visit of a technician;

   The latter type of maintenance can be split up again into so called Fault Type Classes (FTC’s) with different Repair Classes and Stock Control Strategies. A first division could be for instance:
     - 2.2.1 personnel (with toolboxes) only making use of small boat
     - 2.2.2 replacement of intermediate parts making use of supply vessel
     - 2.2.3 replacement of large parts making use of a largecrane vessel

   The trigger for unplanned corrective maintenance can be: (1) an alarm with an immediate shutdown or (2) a decision of an operator or technician after analysing e.g. SCADA data or inspection results to shutdown the turbine immediately. The duration is usually longer than the repair time.

3. Condition based maintenance (or "planned corrective")
   It is not necessary to split up the condition based maintenance actions. The trigger for condition based maintenance can be (1) alarms or (2) findings from SCADA data, inspection results, or measurement results. As opposed to unplanned corrective maintenance an immediate shut down is not necessary. Similar to preventive maintenance: the downtime is more or less equal to the time the technicians actually spend on the maintenance action and a turbine shutdown is not always necessary.

4. Shutdown with automatic reset
   This event is not a type of maintenance but a normal control procedure, e.g. untwisting of cables, or the execution of functional tests. Such shutdowns however show up regularly and may lead to unwanted downtime. If data and information is collected about these shutdowns it can be decided later on if the number of shutdowns and the associated downtime needs to be changed (if possible). It is therefore recommended to consider them as a separate event type.

Some practical remarks should be made here.
- In some cases it is possible that two or more events can be combined during one turbine visit and it is then difficult for instance to report which part of the equipment costs should be charged to which event.
- The 'trigger' (or better "root cause") for a certain event is not always clear. If for instance an alarm shows up which can be reset remotely, it is possible that this alarm was already a first sign of a more severe failure. It may happen that the remote reset is reported separately from the more severe failure if the connection is not recognised by the operator.

11.2 Definition of fields

The most important function of the Event List is that a clear relationship can be established between a.o. the trigger of a maintenance visit, the resources (and costs) used, the sequence of the activities, the time spent, etc. The collection of the data can still be done in various data bases; the Event List should be considered as a kind of query on top of these databases. In this section an overview is given of the fields that should be filled in as a minimum on order to construct a meaningful Event List afterwards.

Event nr. Unique event number.

Start of event Start time of event

Event type One of the Event types defined in Section11.1. This is mainly meant to determine roughly the severity of the event and the equipment used.

1.1	Preventive maintenance (small)
1.2	Preventive maintenance (large)
1.3	Preventive maintenance (major overhaul)
1.n	*Preventive maintenance (???)*
2.1	Shutdown with remote Reset
2.2.1	Shutdown with visit (personnel only, small boat)
2.2.2	Shutdown with visit (replacement of intermediate parts with supply vessel)
2.2.3	Shutdown with visit (replacement with crane vessel)
2.2.n	*Shutdown with visit (???)*
3	Condition based maintenance (planned corrective)
4	Shutdown with automatic reset (control alarm)

Turbine ID, system ID Unique identification of the turbine to be maintained or of another system within the wind farm (e.g. transformer station, cable, etc.)

Main system ID Unique identification of the main system, only relevant in case of event type 2 (Shutdown) and 3 (Condition based maintenance)

Component ID Component ID, only relevant in case of event type 2 (Shutdown) and 3 (Condition based maintenance)

Work carried out Making use of a set of pre defined types of “Work carried out”, the available information becomes suitable for further (statistical) processing. If the information in this field (option “Replacement”) and the field “**Component”** are combined it becomes clear that spare parts have been used (see also considerations in Chapter 12). The limited set of types of work carried out may look as listed in the table below. More options like “flushing oil system” can be added if necessary.

1.	Remote reset
2.	Inspection and reset on site
3.	Repair, cleaning
4.	Replacement

In case a component is replaced it is also necessary to report the following:

Component on stock? Yes or No

Logistic time Time needed to bring the spare part to the harbour (or better: to the transportation vessel).

Consumables For the calculation of costs it is important to report the consumables used during the work carried out.

End of event Time at which the event is completed; all individual maintenance actions are completed and the turbine is taken in operation again.

Event duration End of event minus Start of event

Downtime Downtime of maintenance action which may differ from the duration of the event. Special care should be given to the determination of the downtime of the total event, especially if it is split up into different maintenance actions.

Each event consist of one but usually more than one maintenance action and for all maintenance actions and visits the following fields should be reported.

Maint. action nr. The numbers of the individual maintenance actions should be sub-numbers of the event itself.

Type of maint. action One or more of the maintenance actions (or phases) should be reported here. In some cases more than one inspection or remote reset are needed to fix the problem.

1.1 .. 1.n	Auto reset *(1 ..n resets)*
2.1 .. 2.i	Remote resets *(1..i resets)*
3.1 .. 3.j	Inspections *(1 .. j inspections)*
4.1 .. 4.k	Replacement (preparations) *(1 .. k preparations)*
5	Replacement (positioning)
6	Replacement (hoisting)
7	Replacement (finalisation)
8.1 .. 8.l	Finalisation *(1 .. l visits for finalisation)*

Start of maint. action Start time of maintenance action.

End of maint. action End time of maintenance action.

Duration of maint. action Duration of maintenance action.

Weather condition Value indicating if turbine access and/or execution of a maintenance action was possible (e.g. 0 = access was possible, 1 = too bad weather for turbine access for specific equipment) or actual values of wind and wave heights and/or other limiting factors like current and visibility.

Downtime Downtime of maintenance action which may differ from the duration and from the downtime reported by the SCADA system.

SCADA information In case of a maintenance action or a shut down, the SCADA system will generate a unique alarm code, event code, or a status signal. In practice however, it is not always clear if the code or signal indeed represents the actual cause of the failure or of the status. In many cases it is necessary that an operator verifies if the code or signal represents the exact failure or status. If not, the operator should manually overwrite the automatically generated category. E.g.: sometimes a SCADA system automatically generates the code “preventive maintenance” if technicians shut down the turbine for a certain visit but it might be that the technicians shut down the turbine for a inspection or replacement of a failed component.

Alarm code (or status signal) Code automatically generated by the SCADA system

Alarm code (or status signal) Brief description of event

SCADA downtime Brief description of event

In fact, the alarm codes and/or status signals should always be checked and confirmed (or maybe corrected) by an operator to see if they really match with the maintenance action or the event. Thus the SCADA information is mainly meant for additional information and later on the information can be used to check the adequacy of the alarm codes and to assess how useful they are for trouble shooting.

Crew Size The number of technicians for this specific maintenance action.

Vessel Personnel transfer In this field the used vessel for personnel transfer should be filled in, preferably selected from pre-defined options.

1.	Windcat
2.	FOB lady
3.	Helicopter
…	
n.	Equipment n

Other information about the vessels to be reported is:

Travel time to turbine Time to travel from harbour to the turbine or, if the vessel is already within the wind farm, the time to travel from platform or other turbine to the failed turbine.

Travel time from turbine Similar as above, but vice versa.

Mobilisation time Time needed to mobilise equipment.

In case other types of equipment are needed e.g. for transportation or hoisting of parts the following should be reported:

Type of Vessel This can be the name of the vessel, together with the task it has performed (crane vessel, supply vessel)

Mobilisation time Time needed to mobilise equipment.

Free format For each maintenance action it is possible to report free text and give background information on the action carried out.

11.3 Examples of reported events

In this section an example is given what kind of fields should be reported for:
- a preventive maintenance action consisting of 3 visits, see Figure 11-1;
- an alarm that can be reset remotely, see Figure 11-2;
- a failure which requires an inspection prior to the actual replacement, see Figure 11-3;
- and condition based maintenance after SCADA data showed degradation of a component, see Figure 11-4.

As mentioned in 11.2 , an event consists of at least one but usually more maintenance actions. An event starts for instance with an alarm and multiple remote resets and visits are often needed to solve the problem. In Figure 11-1 this is illustrated with the red arrow: it starts at the start of the event, goes through all three maintenance actions and after the last maintenance action the event can be closed. At that stage the total duration, downtime and inventory of equipment, spare parts, crew size, etc. can be determined and reported. In Figure 11-1, Figure 11-2, and Figure 11-3, the yellow areas refer to the "event information" and the tan coloured areas refer to the information about the individual maintenance actions.

It should be noted here that the examples of the event lists presented here indeed should be considered as examples. In reality, an event list will probably not have the form of tables and spread sheets. Most likely it will consist of a relational database that collects and combines the relevant fields from all kind of data sources. The examples in this section are mainly meant to illustrate how data of individual actions should be combined as one event.

Event nr.	1		
Start event [date] [time]	1-2-2008 8:00		
Event type	Preventive maintenance (small)		
Turbine ID or system ID	Turbine 3		
Nr. maintenance action	1.1	1.2	1.3
Start [date] [time]	1-2-2008 8:00	2-2-2008 9:30	4-2-2008 8:30
End [date] [time]	1-2-2008 18:00	2-2-2008 18:00	4-2-2008 17:20
Duration [hr]	10,0	8,5	8,8
Downtime [hr]	9,0	8,0	8,2
Type of maintenance action	Preventive maintenance	Preventive maintenance	Preventive maintenance
Weather condition	0 = good	0 = good	0 = good
Scada information	Code/text 1	Code/text 1	Code/text 1
Crew size	2	3	3
Vessel personnel	Windcat 1	Windcat 1	FOB lady
Travel time (one way)	0,75	0,75	0,75
Mobilisation time [hr]	0	0	0
Supply vessel	n.a.	n.a.	n.a.
Mobilisation time [hr]			
Crane vessel	n.a.	n.a.	n.a.
Mobilisation time [hr]	0	0	0
Explanations	First part of prev maint	Second part of prev maint	Third part of prev maint
Main system ID			n.a.
Component ID			n.a.
Work carried out			Preventive maintenance
Spare part in stock?			n.a.
Logistic time spare part [hr]			
Consumables			Consumable 2
End event			4-2-2008 17:20
Duration event [hr]			81,3
Downtime event [hr]			25,2

Figure 11-1 *Report of a preventive maintenance event consisting of three visits; the turbine was shutdown only during the actual visits and thus shorter than the duration of the event*

Event nr.	2
Start event [date] [time]	3-4-2008 1:15
Event type	Shutdown with remote Reset
Turbine ID or system ID	Turbine 1
Nr. maintenance action	2.1
Start [date] [time]	3-4-2008 12:20
End [date] [time]	3-4-2008 12:57
Duration [hr]	0,6
Downtime [hr]	0,6
Type of maintenance action	Remote reset
Weather condition	0 = good
Scada information	Code/text 3
Crew size	
Vessel personnel	
Travel time (one way)	
Mobilisation time [hr]	
Supply vessel	
Mobilisation time [hr]	
Crane vessel	
Mobilisation time [hr]	
Explanations	Perhaps a yaw error?
Main system ID	Yaw system
Component ID	....
Work carried out	Remote reset
Spare part in stock?	n.a.
Logistic time spare part [hr]	
Consumables	
End event	3-4-2008 12:57
Duration event [hr]	11,7
Downtime event [hr]	11,7

Figure 11-2: *Report of an alarm with a shutdown during the night that could be solved with a remote reset on the next day.*

Event nr.	3			
Start event [date] [time]	21-4-2008 19:36			
Event type	Shutdown with visit (personnel only, small boat)			
Turbine ID or system ID	Turbine 1			
Nr. maintenance action	3.1	3.2	[illegible]	3.4
Start [date] [time]	23-4-2008 9:00	27-4-2008 7:00	5-5-2008 7:00	6-5-2008 13:30
End [date] [time]	23-4-2008 16:40	27-4-2008 19:00	5-5-2008 18:20	6-5-2008 15:12
Duration [hr]	7,7	12,0	11,3	1,7
Downtime [hr]				
Type of maintenance action	Remote reset	Inspections	Finalisation (or repair)	Finalisation (or repair)
Weather condition	1 = bad	0 = good	0 = good	0 = good
Scada information	Code/text n	[illegible]	Code/text n	Code/text n
Crew size	[illegible]	[illegible]	4	2
Vessel personnel	[illegible]	[illegible]	[illegible] 2	Windcat 1
Travel time (one way)	[illegible]	[illegible]	[illegible]5	0,75
Mobilisation time [hr]	[illegible]	[illegible]	0	o
Supply vessel	[illegible]	[illegible]	n.a.	n.a.
Mobilisation time [hr]				
Crane vessel	n.a.	n.a.	n.a.	n.a.
Mobilisation time [hr]				
Explanations	Again yaw system??	Inspection: failed yaw motor; new one ordered	Replacement almost ready	System works OK
Main system ID				Yaw system
Component ID				Yaw motor
Work carried out				Replacement
Spare part in stock?				Yes
Logistic time spare part [hr]				24
Consumables				Consumable n
End event				6-5-2008 15:12
Duration event [hr]				355,6
Downtime event [hr]				355,6

Start and definition of event

Definition of individual maintenance actions

End of event and reporting

Figure 11-3: *Report of an alarm leading to an immediate shutdown which requires three on site visits after a remote reset has been tried first; the downtime is equal to the total duration of the event*

Event nr.	4	
Start event [date] [time]	26-7-2008 23:00	
Event type	Condition based maintenance (planned corrective)	
Turbine ID or system ID	Turbine n	
Nr. maintenance action	4.1	4.2
Start [date] [time]	27-7-2008 13:45	30-8-2008 7:00
End [date] [time]	27-7-2008 15:12	30-8-2008 15:10
Duration [hr]	1,45	8,2
Downtime [hr]	0,0	8,2
Type of maintenance action	Remote reset	Finalisation (or repair)
Weather condition	0 = good	0 = good
Scada information	Code/text 5	Code/text 5
Crew size	1	4
Vessel personnel	n.a.	Windcat 1
Travel time (one way)		0,75
Mobilisation time [hr]	0	0
Supply vessel	n.a.	n.a.
Mobilisation time [hr]		
Crane vessel	n.a.	n.a.
Mobilisation time [hr]		
Explanations	Analysis of alarm showed that component n is degrading.	Component n is cleaned; Due to bad weather in August the repair had to be postponed.
Main system ID		Main system n
Component ID		Component n
Work carried out		Repair, cleaning
Spare part in stock?		n.a.
Logistic time spare part [hr]		
Consumables		Consumable n
End event		30-8-2008 15:10
Duration event [hr]		832,2
Downtime event [hr]		8,2

Figure 11-4: *Report of a condition based maintenance event consisting of one action to interpret the SCADA data and one repair action; the turbine was allowed to continue running with the degraded component and was only shutdown during the repair action*

11.4 Implementation of the Event List as a workflow

During the analyses of wind farm data, the authors had to derive the information from different data sources with different formats and it was unclear e.g. how an alarm reported in the SCADA system was connected to an onsite visit. Reverse engineering was the only solution to make such connection but it appeared to be very time consuming and unreliable. Unfortunately, collecting the data in this manner is still common practice for most operators of large offshore wind farms. The authors have also concluded that at present most offshore wind farms do work with an automated data collection system, incorporated in a state-of-the-art computerised maintenance management system (CMMS). When using such a CMMS it should be easy to implement the Event List in a workflow.

In this section attention is paid to the situation where operators have more control about their O&M activities instead of receiving activities reports from OEM's and other sub contractors. In case the operators are the parties that initiate all the events, they can also initiate the individual maintenance actions and connect them through a unique event code in the workflow. A workflow that could be applicable for an offshore wind farm is given in Figure 11-5.

At the early start of a wind farm the O&M manager starts with a list with preventive maintenance actions (called "jobs" in Figure 11-5). The technicians carry out the jobs (process 6 and 7) and the O&M manager closes them (process 8) if no abnormalities are found. In fact the technicians that have executed the maintenance actions report on these individual actions (the tan coloured fields in Section 11.3) and the O&M manager should report on the closing of the total event (yellow coloured fields in Section 11.3). The closing of the events and thus the final reporting is indicated in Figure 11-5 as the green processes 2, 8 and 9.

During the operation of the wind farm, abnormalities may be determined on site during the execution of jobs, or the SCADA system shows alarms or component degradation. The abnormalities and SCADA information may lead to new events that require either condition based maintenance actions or corrective maintenance actions. The O&M manager then defines new jobs (process 3 and 4) to solve the problem and these jobs are combined with the preventive maintenance jobs and executed depending on a.o. the priorities (process 5 and 6).

If such a work flow is followed, it will be clear that a certain vessel with spare parts and personnel sails to a turbine to fix a problem that was initiated e.g. by a certain alarm. If other maintenance actions have been executed prior to this visit and did not lead to a closing of the event, it will also be clear that these actions are all related to the same event. A unique event code throughout the entire workflow is thus crucial to connect all the individual maintenance actions.

It should be noted here that the workflow sketched in Figure 11-5 is very limited. In reality each of the nine processes do consist of numerous sub-process. The definition of new jobs for the technicians by the O&M manger (process 5) does also include updating the planning, checking work permits, arranging vessels and parts, etc. However this level of detail is beyond the scope of the OMCE project.

Implementing such a workflow in the daily procedures of wind farm operation is not only a technical but also an organisational matter. In most cases during the warranty period the maintenance of the wind farm is done by the turbine manufacturer (or other contractors). In some cases the service providers have the obligation to report the work carried out. For operators it is then difficult to implement a workflow and to become in charge of the initiation and follow up of maintenance actions. A close collaboration between the wind farm operator, OEM's and sub-contractors is crucial.

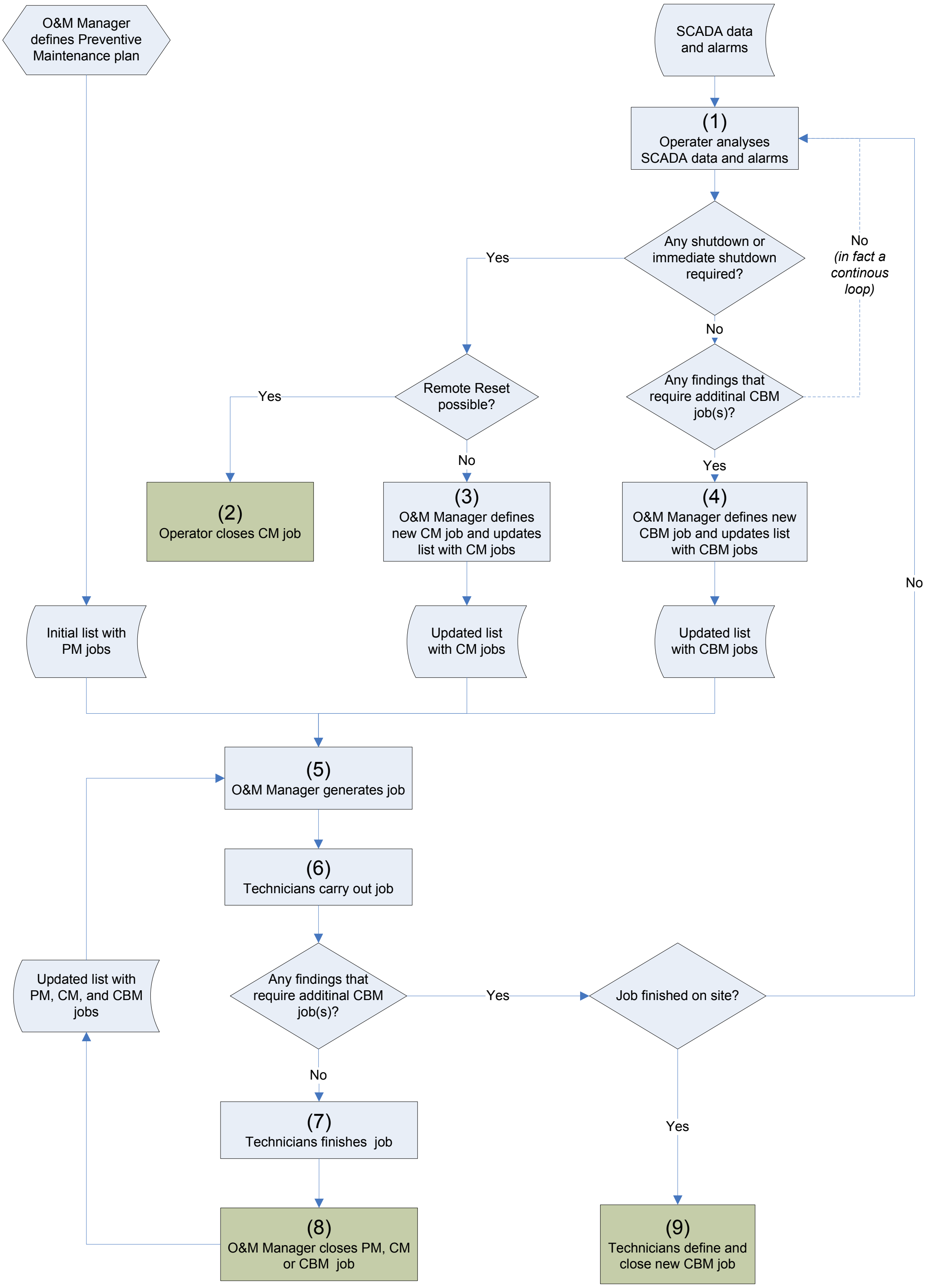

Figure 11-5: *Example of a workflow for maintaining an offshore wind farm which ensures the connection between the an event and the individual maintenance actions*

12. Building Block “Operation & Maintenance”

12.1 Purpose

The purpose of the Building Block “Operation & Maintenance” is to process and analyse the maintenance data from the offshore wind farm in order to decide whether the original input data in the O&M Cost Estimator (e.g. failure frequencies of the different wind turbine components) should be updated or not.

The failure rates can be calculated directly from the BB “Operation & Maintenance” but should interpreted carefully and possibly be combined with the results of BB's “Health Monitoring” and “Loads & Lifetime” in order to assess if the calculated failure rates are representative for estimating the future O&M effort. The BB “Operation & Maintenance” should analyse the failure data stored in the Event List in order to generate minimum, mean, and maximum values for the failure rates of components and/or failure modes. *(Minimum and maximum values, or upper and lower limits are required if uncertainty analyses are to be carried out!)* The information derived from the BB's “Health Monitoring” and “Loads & Lifetime” may give reasons to adjust the values somewhat, for instance if significant differences in load accumulation exist between the different wind turbines in the farm.

The output of the Building Block ‘Operation & Maintenance’ is in the form of one or more datasheet(s)/report(s) where the relevant (processed) data extracted from the operational experience is presented. Using this datasheet/report the user of the Building Block should be able to identify which part(s) of the (original) input data in the OMCE-Calculator is/are not in accordance with the data extracted from the operational experience. It is up to the user to decide whether the input data should be altered.

Besides the functionality of updating (a part of) the input data set for the OMCE-Calculator the Building Block ‘Operation & Maintenance’ should also be able to be used as stand-alone software, which can be used to get detailed insight in the performance (with respect to failure behaviour) of the offshore wind farm.

12.2 Specifications

In this section the specifications for the Building Block “Operation & Maintenance” are discussed. Basically two types of analyses can be performed; ranking and trend analysis. The requirements for each will be treated in a separate subsection.

As has been mentioned in Chapter 9 the Building Block ‘Operation & Maintenance’ serves a twofold purpose. On the one hand it should be suitable for general analyses, which can provide the user of the program with a general overview of the performance and health of the offshore wind farm with respect to failure behaviour. On the other hand the program should provide the possibility of analysing the Event List data in such a way that it can be determined if the failure frequencies used for making O&M cost estimates with the OMCE-Calculator are in accordance with the observed failure behaviour. The aspects that are relevant for generating input for the OMCE-Calculator will be particularly highlighted in the following subsections.

12.2.1 Definition

Before any analysis can be performed first a definition step needs to be performed. Aspects that need to be specified here are discussed in the following subsections.

12.2.1.1 Wind farm breakdown

The breakdown of the wind farm needs to be defined. The number of turbines and, for each turbine, the main systems, components and fault type classes needs to be entered. By default it should be possible to obtain this breakdown from the OMCE-Calculator. Furthermore, it is essential that the specified wind farm breakdown for the OMCE-Calculator and Building Blocks is exactly equal to the breakdown according to which data are stored in the Event List format.

12.2.1.2 Wind farm commissioning date

In order to calculate the operational time correctly it needs to be specified at what date the wind farm was commissioned.

12.2.1.3 Turbine clusters

Firstly, the turbines are grouped as clusters of turbines. The turbine clusters could be defined on the basis of information from the other OMCE Building Blocks. As an example, the Building Block ‘Loads & Lifetime ‘ could provide information on the load accumulation on the turbines in the wind farm, which again could be used to define sensible clusters of turbines (f.i. low/ medium/high loading) for the analysis of the failure behaviour;

12.2.2 Ranking analysis

As mentioned before, the stored maintenance data is subject to two types of analyses; namely ranking and trend analysis. Using ranking analyses different breakdowns of the registered failures can be generated, which can, for instance, be used to study the influence of the location in the wind farm and seasonal dependency of the failure behaviour. Furthermore, ranking analysis gives the user a good overview of the most unreliable main systems and components and the distribution of the total failure frequency over small, medium and large failures. The general process of creating such output is shown in Figure 12-1.

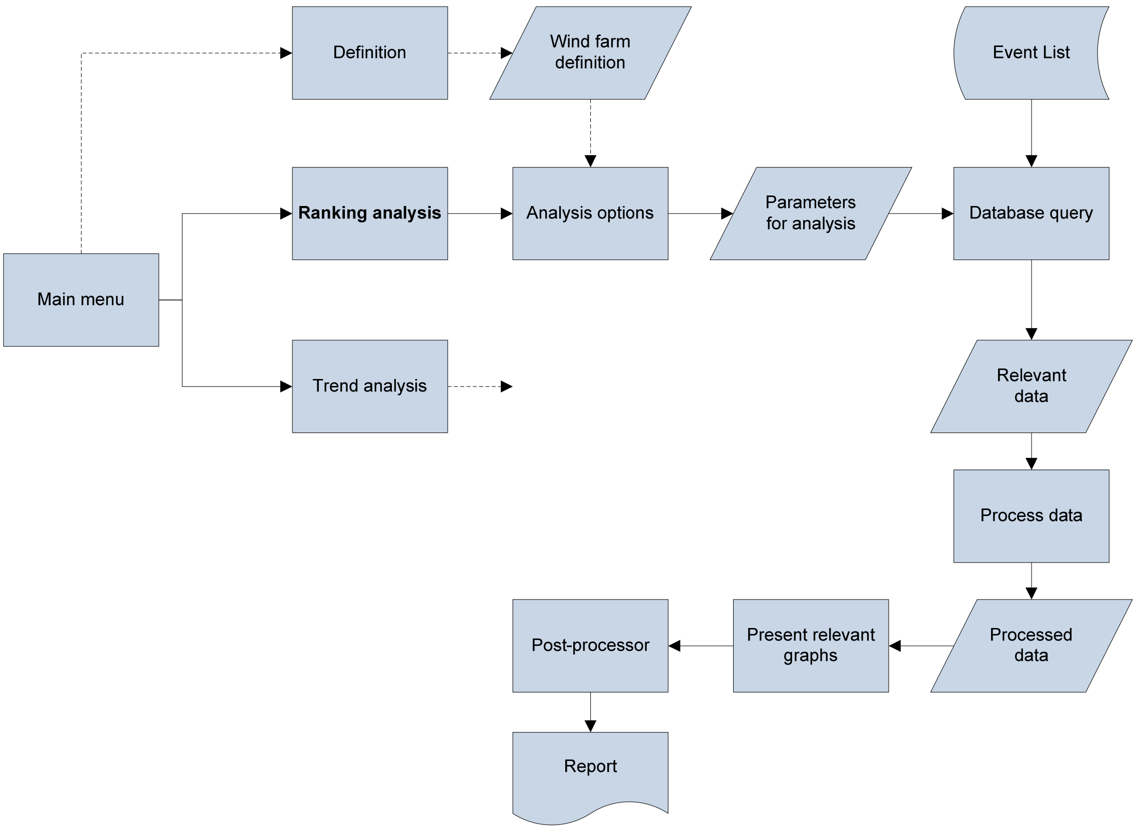

Figure 12-1 *Flowchart for performing ranking analysis of the maintenance data using the building block ‘Operation & Maintenance’.*

As can be seen in the flowchart, in the main menu of Building Block ‘Operation & Maintenance’ the user is prompted to select the type of analysis that should be performed. After selecting the option ‘Ranking Analysis’, several steps have to be performed in order to generate the desired output. The requirements for the different steps of the process will be discussed in the following subsections.

12.2.2.1 Analysis options

Obviously, there are numerous different breakdowns that can be generated from the stored maintenance data in the Event List. The first step that should be performed is selecting what type of breakdown should be visualised. Based on the specified options a database query can be performed and the selected results can be presented to the user. The most important options that should be included in the software program will be discussed below.

12.2.2.1.1 Failures per turbine or cluster of turbines

The first type of ranking analysis that can be performed is comparing the failure behaviour of the different turbines in the wind farm. This type of analysis can be used to investigate whether the failure behaviour of the wind turbines depends on their specific location in the wind farm. It could be that the loading of certain components[6] is higher for the turbines located in the middle of the wind farm, causing a greater number of failures occurring on these turbines. For large wind farms with a large number of turbines it might not be ideal to compare each turbine individually, but to define certain clusters of wind turbines. Therefore the software program should also offer the possibility of displaying the number of registered failures per defined wind turbine cluster.

The comparison of turbines (or clusters of turbines) can be done taking all failures into account. These kinds of analyses give a general insight of how the overall failure behaviour depends on the location in the wind farm. However, it is probably more relevant to use only a selected main system, component or failure mode.

Careful consideration should be given to the fact that the possibility exists that not all turbines in a large offshore wind farm are commissioned at the same time. This might influence the comparison and therefore it should be considered to normalise the number of failures on each turbine to its respective operational time.

12.2.2.1.2 Failures per main system, component or failure mode

The second type of ranking analysis is the comparison of the failure behaviour for each level in the breakdown of the turbine (main system, component or failure mode). This kind of analysis can be used to get insight in which main systems, components or failure modes are most prone to failures. This information can be used to determine on which main systems or components the effort of improving the reliability should be focussed.

The software program should allow the user to specify whether all turbines are taken into account for the analysis or whether the breakdown is shown for a single turbine or cluster of turbines.

12.2.2.1.3 Failures per season

The third and final type of ranking analysis that will be described in this document is the comparison of the failure behaviour per season. This kind of analysis can be used to determine whether the failure behaviour of the turbines is influenced by the external conditions, which tend to vary from season to season. Electrical components might suffer in summer, due to the high temperatures, whereas mechanical components might be more likely to fail in winter due to the generally higher wind speeds.

The comparison of the failure behaviour can be performed for different levels in the breakdown of the wind farm (e.g. for all failures or all failures on a certain main system, component or failure mode). In addition to this, the user should be able to specify whether data from all turbines are taken into account or whether only data from a specific turbine or cluster of turbines is used.

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[6] This kind of information is generated using the Building Block 'Loads & Lifetime'. The output of this building block can be also used to define sensible clusters of turbines; for instance low loading - medium loading - high loading.

When comparing the failure behaviour per season it is essential that for each season an equal amount of data is available. This implies that this analysis can only be performed over one or more whole years.

It should be noted that currently the OMCE-Calculator does not allow the input (failure rates) to be specified per season and therefore this functionality of Building Block 'Operation & Maintenance' should be seen as informative only.

12.2.2.2 Pre processing

Based on the selected options the software program should perform a query in the Event List from where the relevant failures are selected.

12.2.2.3 Results

After performing the Event List query, where the relevant data is selected, the results of the output have to be visualised. There are several ways of presenting the results, where the most suitable options are either using pie charts or so-called Pareto-plots. A pie chart gives a straightforward overview of the distribution of the failures over the selected parameters, where each slice of the pie represents the relative contribution of a certain aspect to the total. A Pareto-plot in fact is a type of histogram, where the relative contribution of each parameter is shown in combination with a cumulative line.

When displaying the graphs, the software program should offer the user the possibility to store the graph with the output in combination with the relevant input data in order to make the results reproducible.

12.2.3 Trend analysis

Besides the ranking analyses, which have been discussed in the previous sections, the OMCE-Building Block 'Operation & Maintenance' should also perform trend analyses on the maintenance data. The main goal of the trend analyses is to make accurate estimates of the failure frequencies of the different main systems, components or failure modes.

In Figure 12-2 a flowchart is presented which shows the step-by-step procedure of generating the desired output. In the following subsections the requirements for the different processes will be discussed in detail.

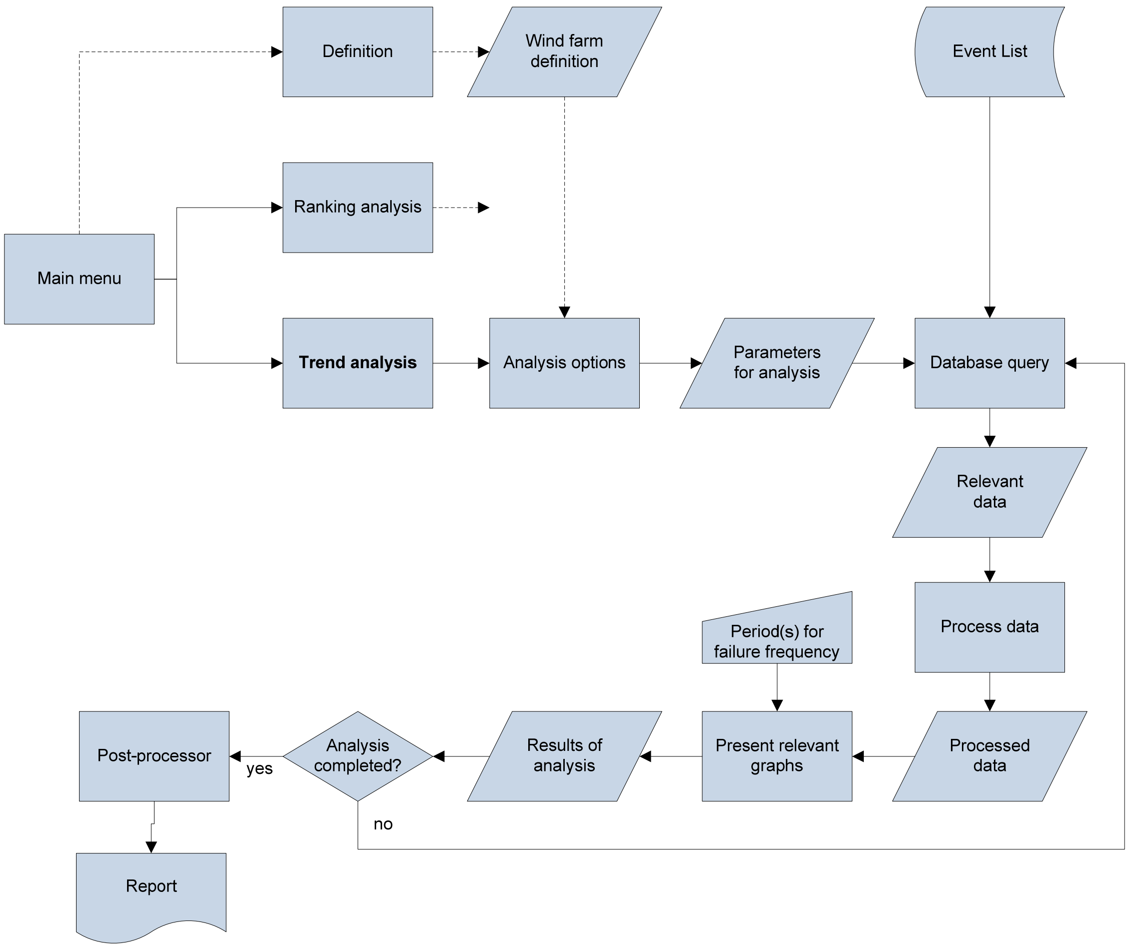

Figure 12-2 *Flowchart for performing trend analysis of the maintenance data using the building block 'Operation & Maintenance'.*

12.2.3.1 Analysis options

The main menu of the OMCE-Building Block 'Operation & Maintenance' prompts the user to choose between ranking and trend analysis. After selecting 'trend analysis' several options for the analysis need to be specified. These will be discussed in the following subsections.

12.2.3.1.1 Level of the analysis

It should be specified at what level in the breakdown of the wind farm (see also section 5.1) the analyses should be performed. The possibilities are to analyse the maintenance data at the level of wind farm, turbine, main system, component or failure mode. It should be noted that the failure frequencies in the OMCE-Calculator are specified at the level of failure modes (and subsequently grouped into so-called Fault Type Classes), which are coupled to the defined main systems (see Figure 5-1). Therefore it is strongly advised that, when the analysis is used to generate input for the OMCE-Calculator, the failure mode level is selected.

After selecting the level of analysis the software should prompt the user to select on what part of the breakdown the analyses are performed. For instance, when the main system level is selected the software should present the user with a list of all defined main systems in the breakdown. Using this list the user of the program should indicate for which main systems the analysis (as will be described in section 12.2.3.3) should be performed.

12.2.3.1.2 Turbine selection

After having decided at what level the analysis of maintenance is performed, the software should prompt the user to select which turbines should be taken into account in the analysis. The most obvious option is to use all turbines for the analysis, since this ensures a maximum use of the available data. However, for certain instances it might be desirable to investigate the failure behaviour of a selected group of turbines within the offshore wind farm.

12.2.3.1.3 Definition failure frequency

After specifying at what level the analysis is performed and which turbines are taken into account some information has to be specified which is relevant for the calculation of the failure frequencies.

Firstly, it should be indicated whether the calculated failure frequencies should be based on the reciprocal of the Mean Time To Failure (MTTF) or Mean Time Between Failures (MTBF). The meaning of these two parameters is explained in Figure 12-3.

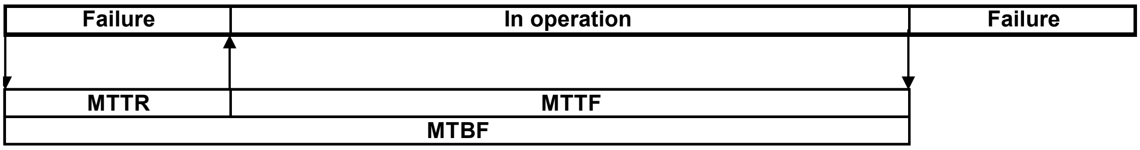

Figure 12-3 *Definition of MTTR, MTTF and MTBF.*

The MTBF is connected to the Mean Time To Repair (MTTR) and the MTTF as follows: *MTBF = MTTR + MTTF*. The *MTTF* value represents the reliability of the turbine, whereas the *MTTR* represents the adequacy of the maintenance strategy. The *MTTF* value should be the input value for the OMCE Calculator because the Time To Repair is determined by the selected O&M strategy and thus subject of investigation.

In order to be able to determine the MTTF it is essential that both the date of the stop of the turbine and the date the turbine is taken back in operation are registered in the Event List format. Without this information it is impossible to determine the MTTF.

12.2.3.2 Pre processing

Before presenting the user of the Building Block with the relevant graphs some pre-processing needs to be performed. These pre-processing steps are indicated in Figure 12-4.

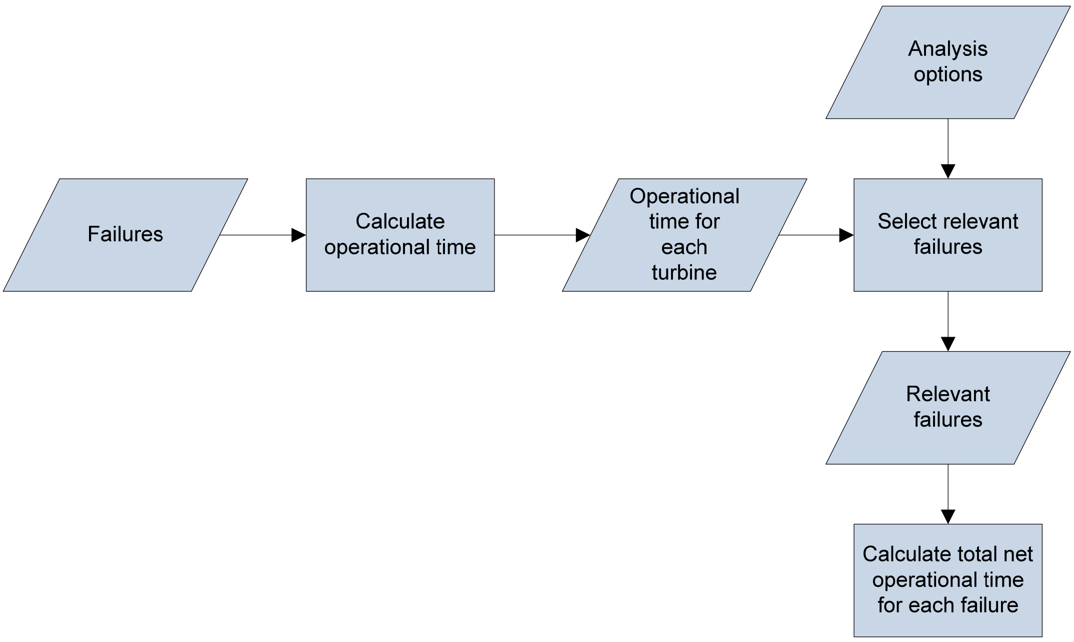

Figure 12-4 *Pre-processing process for analysis of maintenance data.*

For each turbine for each registered failure the operational time should be calculated. As mentioned in section 12.2.3.1.3 the failure frequency can be determined based on MTBF (gross operation time) or MTTF (net operational time).

12.2.3.3 Analysis

After performing the necessary pre-processing steps (see previous section) the actual analysis can be started. In fact the analysis consists of three steps:

1. Visualising trends in the failure behaviour;
2. Prompting the user for manual input;
3. Calculation of the failure frequency.

These three steps will be discussed in more detail in the following subsections.

12.2.3.3.1 Visualizing trends in the failure behaviour

When determining failure frequencies it is not sufficient to simply perform numerical analyses and calculate the mean values. Ignoring trends in the failure behaviour can lead to inaccurate estimates and thus erroneous cost estimates. Therefore the software program should show the trends in the failure behaviour. These trends should be visualised using a so-called CUSUM-plot, which shows the cumulative number of failures as function of the cumulative operational time.

An example of a CUSUM-plot is shown in Figure 12-5.

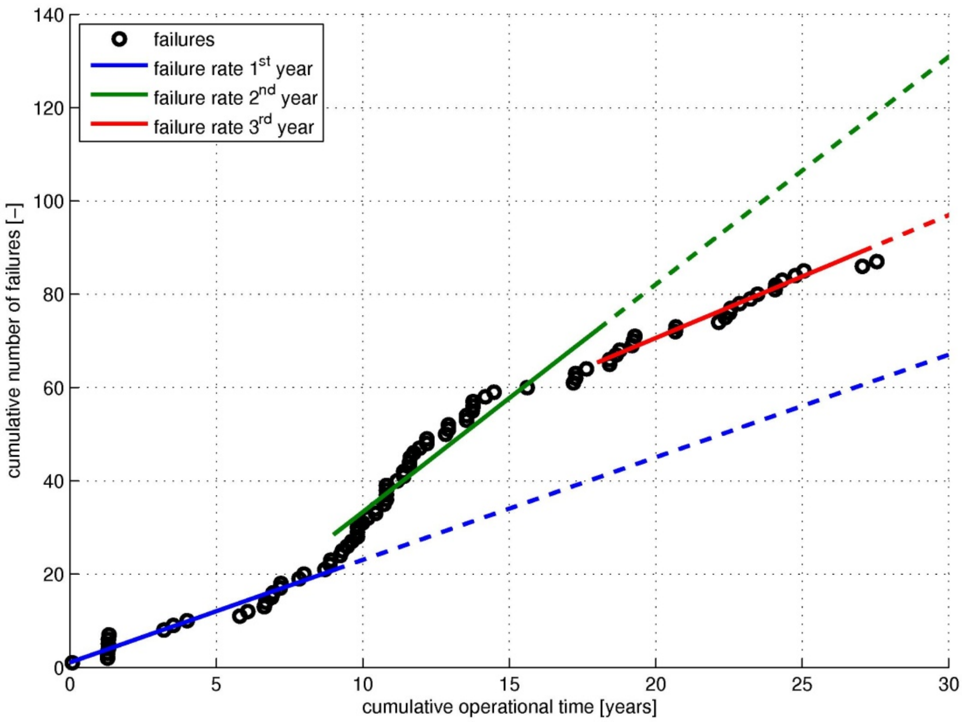

Figure 12-5 *Example of a CUSUM-plot used for visualizing trends in failure behaviour.*

12.2.3.3.2 Manual user input

After visualizing the failure behaviour in a CUSUM-plot the software program should prompt the user to specify the period over which the failure frequency should be determined. The program should allow the user to specify multiple periods. In the case of the example in Figure 12-5, the failure frequency could be determined over the periods of 0-8 and 15-28 years of cumulative operational time.

The software program internally stores the manual user input so that it can later be documented in the output of the software program. This ensures that the results are reproducible.

12.2.3.3.3 Calculation of failure frequency

The final step in the analysis is the calculation of the failure frequency. In this case the software program should determine the cumulative number of failures that have occurred during the period(s) specified by the user of the program. Furthermore, the cumulative operational time is determined by summation of the length of the user-defined periods. Finally, the confidence level is specified in the options menu, as has been discussed in section 12.2.3.1.3.

For a repairable system, for which the failure frequency is constant in time, the lower confidence limit λ_L, estimated mean λ and upper confidence limit λ_U can be calculated for a (1-α) confidence interval using the following formulae for a time terminated reliability test: [Ref. 21]

$$\lambda_L = \frac{\chi^2_{(1-\alpha),2x}}{2T} \qquad \lambda = \frac{x}{T} \qquad \lambda_U = \frac{\chi^2_{\alpha,2(x+1)}}{2T}$$

where x represents the cumulative number of failures, T the cumulative number of operational time and χ^2 represents a chi-square distribution with a (1-α) confidence interval.

12.2.3.4 Results

The final step is the presentation of the results of the analysis. This should be done in such a manner that the user of the program has a clear overview of the outcome of the calculations. Another important aspect is the fact that the results should be reproducible. Therefore, the relevant input parameters (see section 12.2.3.1), the corresponding CUSUM-graph (see section 12.2.3.3.1) and manual user input (see section 12.2.3.3.2) should be stored together with the actual results of the calculations (see section 12.2.3.3.3).

12.3 Software

Based on the specifications listed in the previous sections a demo software model of the OMCE Building Block 'Operation & Maintenance' has been programmed in MATLAB®. In this section the functionality of the software will be shortly highlighted and some screen shots of the software will be shown.

The demo version of the Building Block includes a Graphical User Interface (GUI) with which the user can easily navigate through the software and indicate what information should be plotted.

After starting the software the main menu of the Building Block is opened as can be seen in Figure 12-6. In the main menu firstly the project can be selected that is subjected to analysis. In the submenu 'Turbine breakdown' (see Figure 12-7) the user can define turbine clusters, browse the wind turbine breakdown and corresponding failure frequencies and specify the wind farm commissioning date (for specifications see section 12.2.1).

In addition to this, the user also needs to specify the location of the file which contains the maintenance data as stored in Event List format. After specifying the location the software will read the file and store the data internally in order to enable quick analyses later on.

As mentioned in the previous sections the main functionality of the Building Block 'Operation & Maintenance' includes ranking and trend analysis of the failure data stored in the Event List format. The submenus for both type of analyses can also be accessed from the main menu.

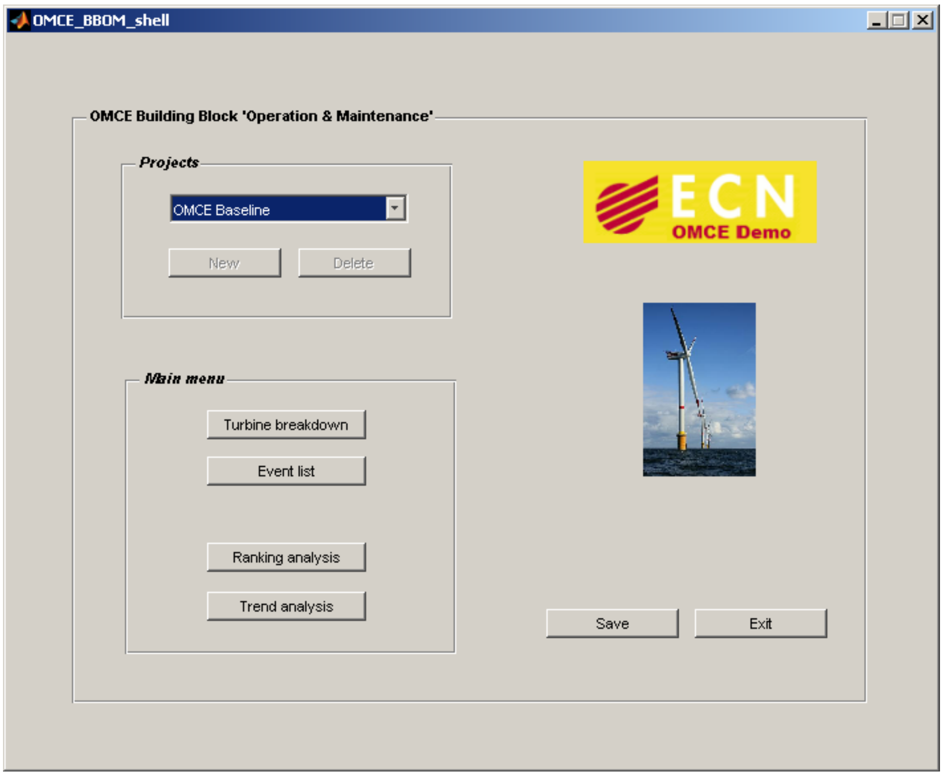

Figure 12-6 *The main menu of the OMCE Building Block 'Operation & Maintenance'.*

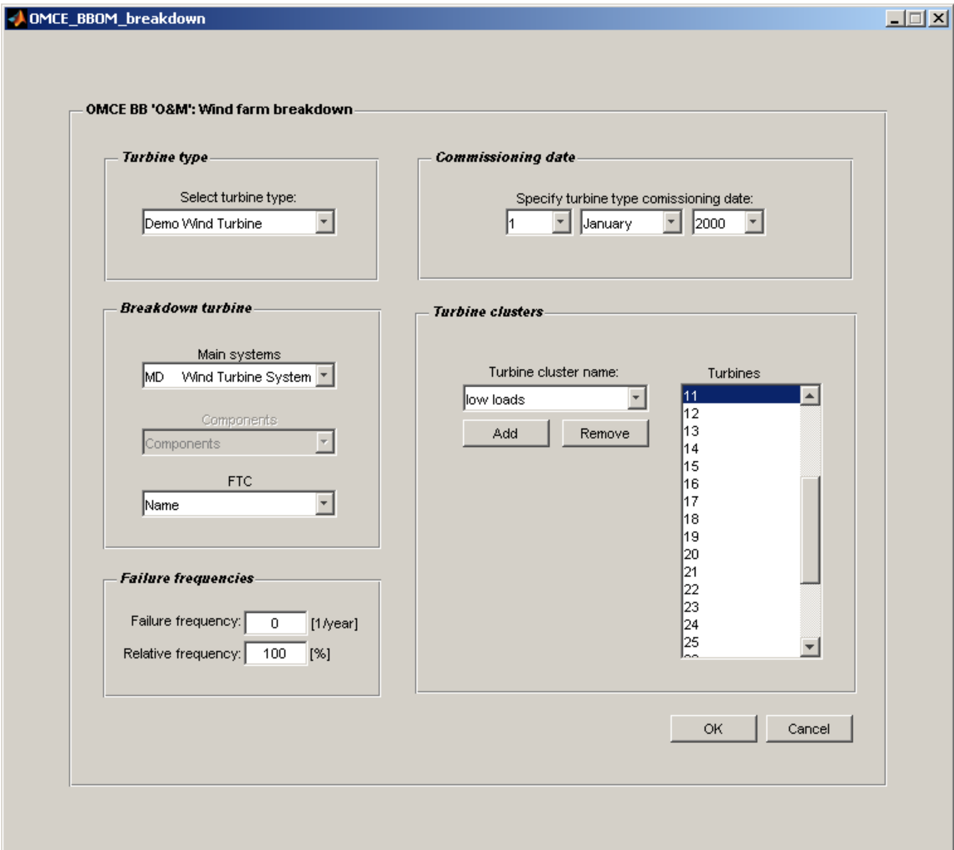

Figure 12-7 *The wind farm breakdown menu in the OMCE Building Block 'Operation & Maintenance'.*

The submenu for specifying the options for ranking analysis is shown in Figure 12-8. In this menu the user can specify what type of ranking analysis should be performed and enter which turbines, main systems and Fault Type Classes (FTC) should be considered. As analysis type also the options ‘Downtime per turbine (cluster)’ and ‘Downtime per system, component or FTC can be selected. These options are not meant to analyse the data in order to derive or update input data for the OMCE-Calculator, but can be used to get more general insight in the failure behavior of the wind farm. Using these options it can f.i. be investigated which components are responsible for most downtime.

After clicking the ‘Calculate’ button the software will perform a query in the stored Event List data and plot the graph corresponding to the selected options (for specifications see section 12.2.2).

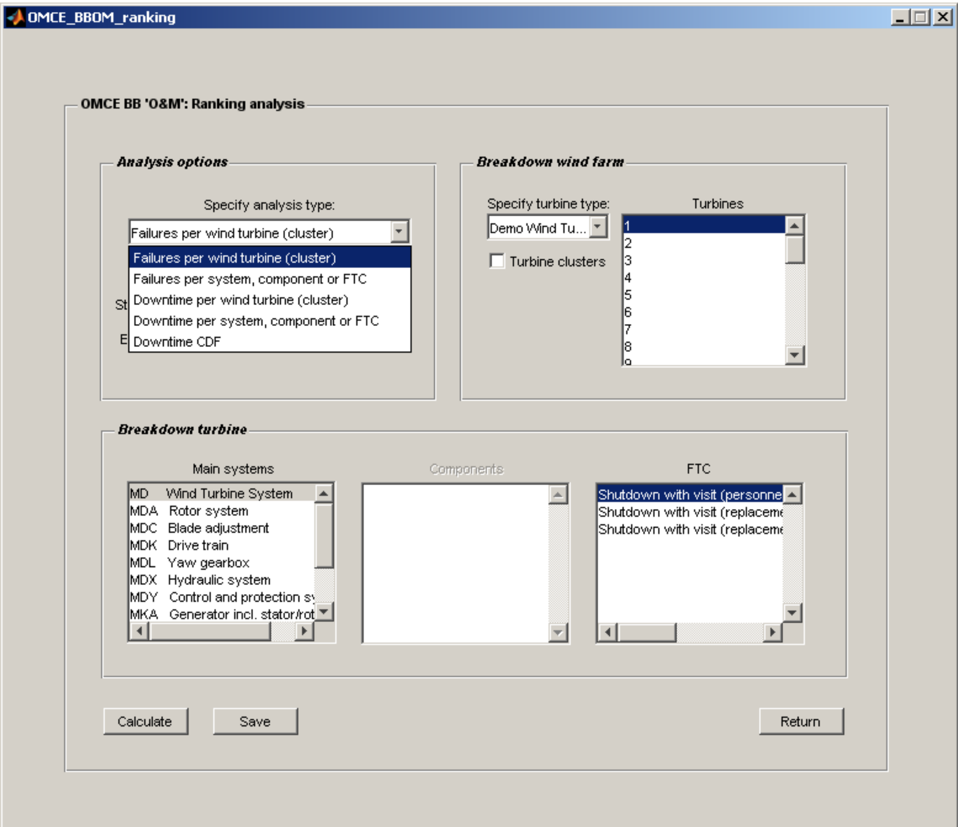

Figure 12-8 *The ranking analysis menu of the OMCE Building Block ‘Operation & Maintenance’.*

In Figure 12-9 a typical output of the ranking analysis is shown, where the number of failures are shown per main system. This type of output makes it easy to identify possible bottleneck systems. Similar pie charts can be plotted of the failures per (cluster of) turbines. This information could be used to identify whether f.i. the heavier loaded turbines (as could be determined with Building Block ‘Loads & Lifetime’) also show more failures.

In Figure 12-10 another example is given of the output of the ranking analysis of the Building Block ‘Operation& Maintenance’. Here, for one of the main systems, the distribution of the failures over the defined Fault Type Classes is shown. This information can be directly compared with the input data for the OMCE-Calculator (see also Figure 5-2) and serve as input for the decision whether the original assumptions in the OMCE-Calculator input should be updated or not.

Using the ‘Save’ button the graph and the corresponding input can be saved. It should however be noted that at the moment of writing this report this functionality has not yet been included in the demo version of the software.

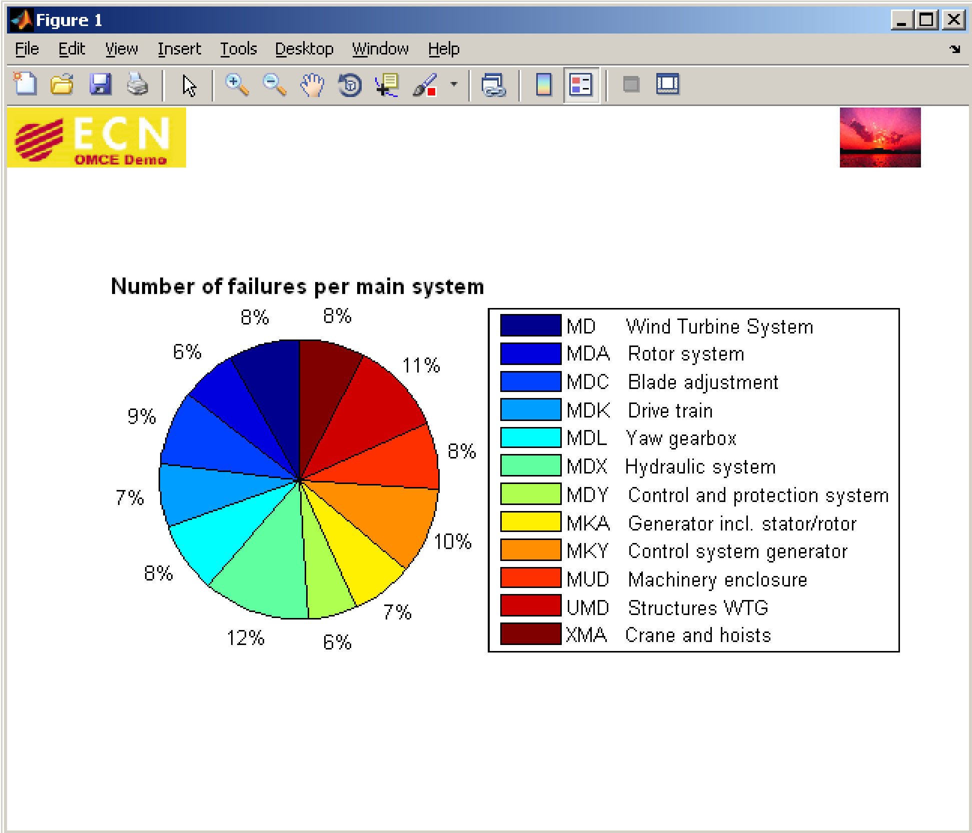

Figure 12-9 *Example of the output of the ranking analysis of OMCE Building Block 'Operation & Maintenance': Number of failures per main system.*

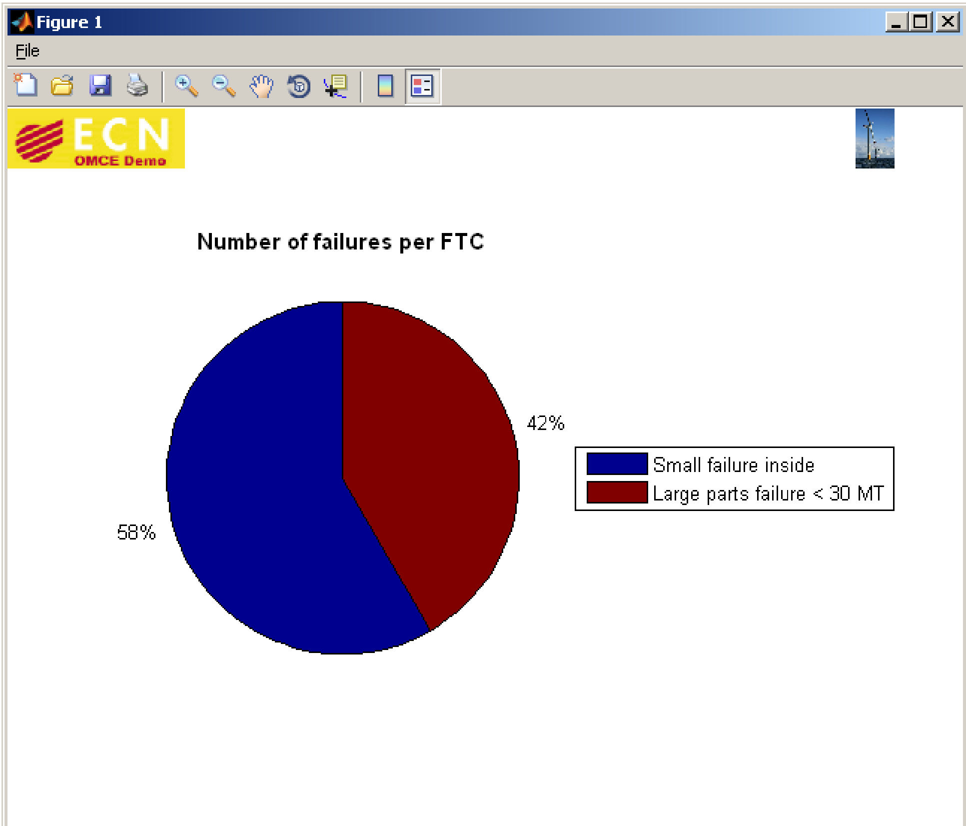

Figure 12-10 *Example of the output of the ranking analysis of OMCE Building Block 'Operation & Maintenance': Number of failures per FTC.*

The submenu for trend analysis looks almost similar as the submenu for ranking analysis. Again here the analysis options and which failures (turbine (clusters), main systems and FTC) need to be considered should be specified.

In Figure 12-11 a typical output of the trend analysis of building block O&M is displayed. The graphs shows, for a selected main system, the cumulative number of failures as function of the cumulative operational time.

The slope of the graph is a measure for the failure frequency. The software allows the user to specify the confidence interval and the period over which the failure frequency should be calculated. This is important when considering that the historical failure behavior does not always have to be representative for the future, which is modeled with the OMCE-Calculator. For instance, when after two years a retro-fit campaign is performed for a certain component, the failures which occurred during the first two years should not be included in the analysis with the goal of estimating the failure rate for the coming years.

In this example the failure frequency is calculated over the period starting at 215 and ending at 365 operational years. The resulting average failure frequency is indicated by the blue line, whereas the 90% confidence intervals are shown by the red dotted lines. The calculated upper and lower limits can be compared with the failure frequency which is used as input in the OMCE-Calculator. If this value lies outside the calculated boundaries it is recommended to consider adjusting the input for the OMCE-Calculator. If the OMCE-Calculator allows for stochastic input, the average and upper and lower confidence limits can be specified directly as input.

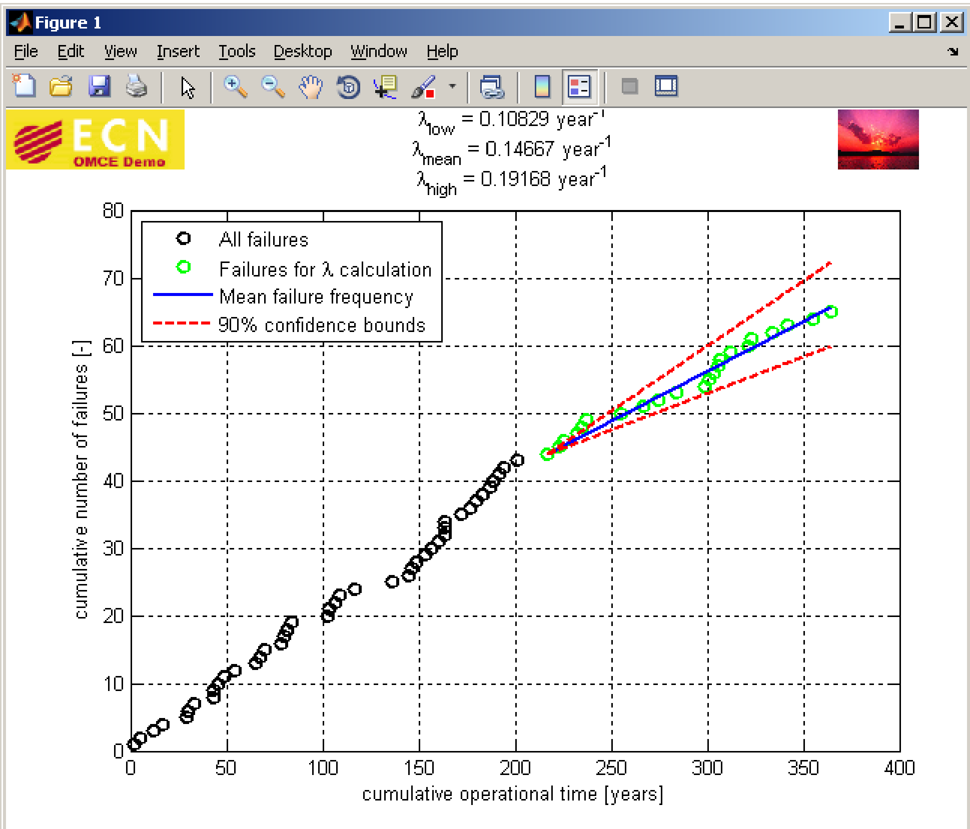

Figure 12-11 *Example of the output of the trend analysis of OMCE Building Block 'Operation & Maintenance'.*

13. Building Block “Logistics”

13.1 Purpose

The objective of the BB “Logistics” is (similar to the objectives of Building Block “Operation & Maintenance”) twofold:

1. To generate information about the use of logistic aspects (equipment, personnel, spare parts, consumables) for maintenance and repair actions.
2. To generate updated figures of the logistic aspects (accessibility, repair times, number of visits, delivery time of spares, etc.) to be used as input for the OMCE Calculator.

Within the OMCE-Calculator, the numerous different possibilities for carrying out repairs (from small repairs to large repairs with large crane ships) are categorised as a limited (and thus manageable) number of Repair Classes. As already mentioned in section 5.1.2 each Repair Class takes into account the:

- Successive activities (inspection, replacement, and/or repair)
- Time to organise the repair activity;
- Duration of each activity;
- Equipment used;
- Crew size.

In addition to the Repair Classes, which specify how a repair is carried out, in the OMCE-Calculator also a so-called Spare Control Strategy (SCS) should be selected for each Fault Type Class (see also section 5.1.3). Each SCS specifies:

- Whether consumables or spare parts are needed (and the associated costs);
- Whether stock control is applicable;
- The re-ordering and delivery times of the spare part.

Another logistic aspect that is important is the characteristics of the different types of equipment that are used for the different types of maintenance. For the OMCE-Calculator several things need to be specified in order to model the equipment:

- Travel time;
- Mobilisation/Demobilisation time;
- Weather limits during the various repair phases (e.g. travelling, access, hoisting, etc.);
- Costs (fixed, variable, MOB/DEMOB)

With respect to the second objective of the Building Block ‘Logistics’ (generating updated figures of the logistic aspects to be used in the OMCE-Calculator) the input data for the aspects listed above (Repair Class, Spare Control Strategy and Equipment) need to be characterised with this Building Block.

13.2 Specifications

In this section the specifications for the Building Block ‘Logistics’ are discussed. As already discussed in the previous section this Building Block is used to characterise three different parts of the input for the OMCE-Calculator; namely the Repair Classes, Spare Control Strategy and Equipment.

The general process of generating such the desired data is displayed in Figure 13-1. As can be seen the procedure is similar to the procedure for Building Block ‘Operation & Maintenance’ which was extensively discussed in section 12.2.

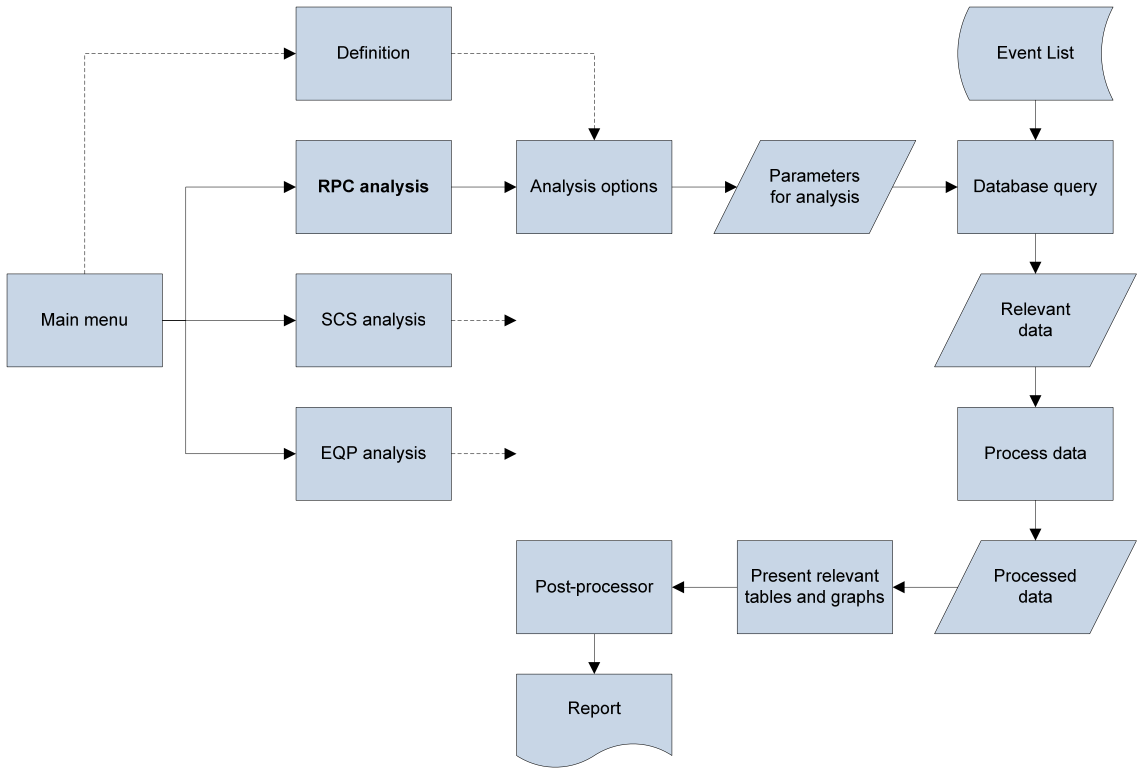

Figure 13-1 *Flow chart indicating the general procedure for the analysis of maintenance data using the Building Block 'Logistics'.*

Since the general process is similar in the following only the key aspects and differences with the procedures for the Building Block 'Operation & Maintenance' will be highlighted.

13.2.1 Definition

The 'Definition' part for this Building Block only consists of the specification of the wind turbine breakdown into main systems, components and failure modes (Fault Type Classes). In fact the wind turbine breakdown should be loaded directly from the one specified in the OMCE-Calculator. In addition to this again it is essential that the maintenance data are stored in the Event List format according to the exact same breakdown.

13.2.2 Repair Classes

This part of the Building Block 'Logistics' should analyse the data stored in the Event List format in order to decide whether the original input data to define a Repair Class in the OMCE-Calculator should be updated or not.

13.2.2.1 Analysis options

Here the user should be able to specify the main system and Fault Type Class for which the software should calculate the characteristics for the Repair Class. In addition to this the user should also select for what part of the maintenance action (e.g. remote reset, inspection, replacement, repair; see also section 5.1.2.1) the results should be calculated.

13.2.2.2 Pre-processing

Based on the selected analysis options the software should perform a query in the stored file in which the data are stored according to the Event List format.

13.2.2.3 Results

After performing the database query, where the relevant data are retrieved from the Event List file, the output results should be visualised. The output should be displayed both in tables and in graphs. The tables should display the average, standard deviation, minimum and maximum values for the following aspects:

- Time to organise;
- Repair time;
- Crew size;
- Usage of equipment.

Furthermore the software should also indicate how many failures have been recorded for the selected analysis options. Besides the listed values in tables the Building Block should also generate graphs, which show the cumulative density function of the listed aspects. These graphs provide additional insight in the scatter surrounding the recorded values. It should be noted that these type of graphs only have added value when a significant number of data points/failures are available.

The software should also allow to save the tables, graphs together with the corresponding analysis options into a data sheet/report in order to ensure that an expert can, in a later stadium, decide whether input data for the OMCE-Calculator should be updated or not.

13.2.3 Spare Control Strategy

The second part of the Building Block 'Logistics' should analyse the data stored in the Event List format in order to decide whether the original input data to define a Spare Control Strategy in the OMCE-Calculator should be updated or not.

13.2.3.1 Analysis options

Here the user should select the main system and Fault Type Class for which the spare part aspects should be analysed.

13.2.3.2 Pre-processing

Based on the selected analysis options the software should perform a query in the stored file in which the data are stored according to the Event List format.

13.2.3.3 Results

After performing the database query, where the relevant data are retrieved from the Event List file, the output results should be visualised. Again the output should be displayed both in tables and in graphs. The tables should display the average, standard deviation, minimum and maximum values of the logistic time of the spare part. This value should be calculated for both the situations where the spare part is out-of-stock and in stock. Only if this is done the delivery time and re-ordering time (which are required input for the OMCE Calculator) can be determined.

Furthermore the criteria listed in section 13.2.2.3 also apply for this part of the Building Block.

13.2.4 Equipment

The third part of the Building Block 'Logistics' should analyse the data stored in the Event List format in order to decide whether the original input data to characterise the different types of equipment in the OMCE-Calculator should be updated or not.

13.2.4.1 Analysis options

Here the user should select one of the equipment as specified in the OMCE-Calculator.

13.2.4.2 Pre-processing

Based on the selected analysis options the software should perform a query in the stored file in which the data are stored according to the Event List format.

13.2.4.3 Results

After performing the database query, where the relevant data are retrieved from the Event List file, the output results should be visualised. The output should be displayed both in tables and in graphs. The tables should display the average, standard deviation, minimum and maximum values for the following aspects:

- Mobilisation time;
- Travel time;
- Crew size (number of technicians on board).

Furthermore the criteria listed in section 13.2.2.3 also apply for this part of the Building Block.

13.3 Software

Based on the specifications, as summarised in the previous sections, a demo version of the Building Block ‘Logistics’ has been programmed in MATLAB®. Similar as for Building Block ‘Operation & Maintenance’ this demo version contains a graphical user interface in which the user can easily navigate and specify what should be analysed an displayed.

In the remainder of this section some screen shots with some basic explanation of the demo version of the software of the Building Block ‘Logistics’ are shown.

The main menu for Building Block ‘Logistics’ is shown in Figure 13-2. As can be seen the menu is almost similar to the one for Building Block ‘Operation & Maintenance’. In this menu the project can be selected, the location of the Event List file can be specified and the three submenus can be accessed.

The first submenu, for characterisation of the Repair Classes for the OMCE-Calculator, is shown in Figure 13-3. On the left part of the menu the analysis options can be specified. Here the main system, Fault Type Class and maintenance phase (e.g. remote reset, inspection, repair or replacement) can be selected. Furthermore, boundaries can be set on the occurrence dates of the failures. This is useful if for instance at a certain date a change in the repair strategy has been implemented. In order to assess whether the ‘new’ repair strategy is in line with the input data for the OMCE-Calculator, the recorded failures where the ‘old’ repair strategy was still applied should not be included in the analysis with this Building Block.

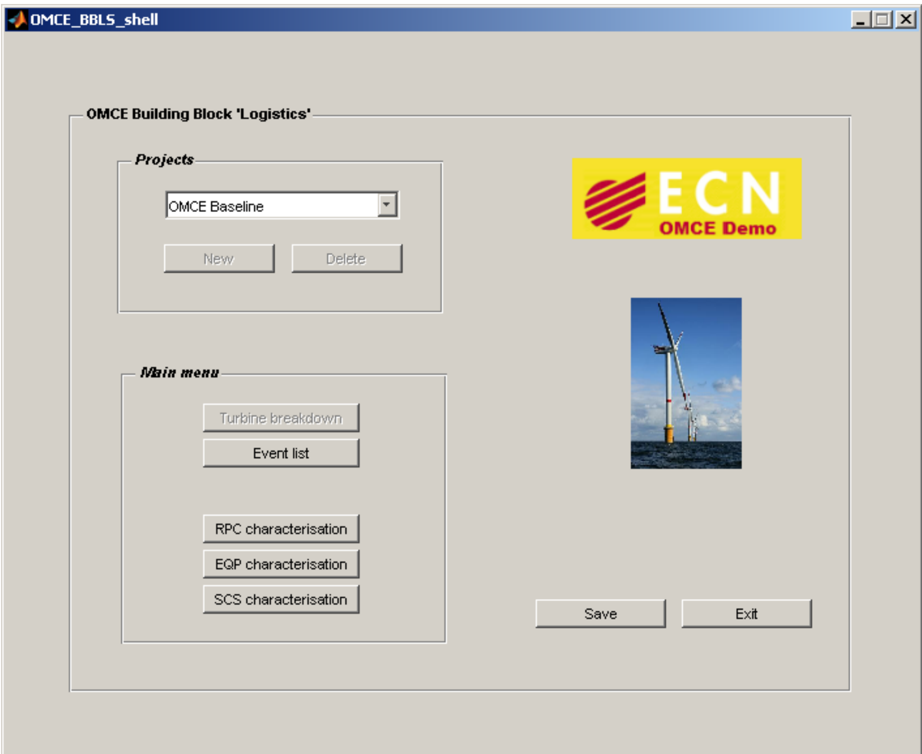

Figure 13-2 *Main menu of the Building Block ‘Logistics’.*

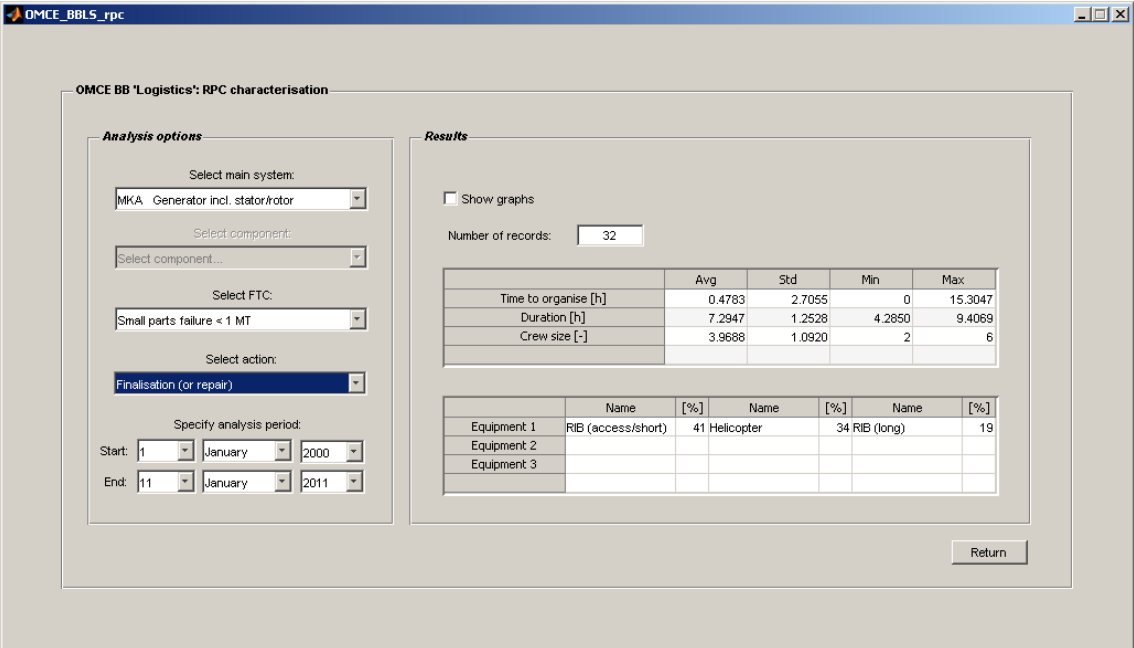

Figure 13-3 *Submenu for RPC characterisation of the Building Block 'Logistics'.*

On the right part of the menu the results are displayed in two tables. The upper tables shows the average, standard deviation, minimum and maximum for time to organise, duration and crew size for the selected analysis options. The bottom table shows the usage of equipment. Furthermore also the number of records/failures that correspond to the selected analysis options are listed.

In Figure 13-4 an example of the graphical output of the Building Block is presented. In this figure a cumulative density function (CDF) is shown of the duration of a small repair on the generator. This type of information gives additional insight in the scatter surrounding the average value. Furthermore, the information in the graph can also be used to determine whether, in this example, the duration of the repair should be modelled as a stochastic quantity in the OMCE Calculator and, if so, what distribution function (e.g. normal, etc.) is most appropriate.

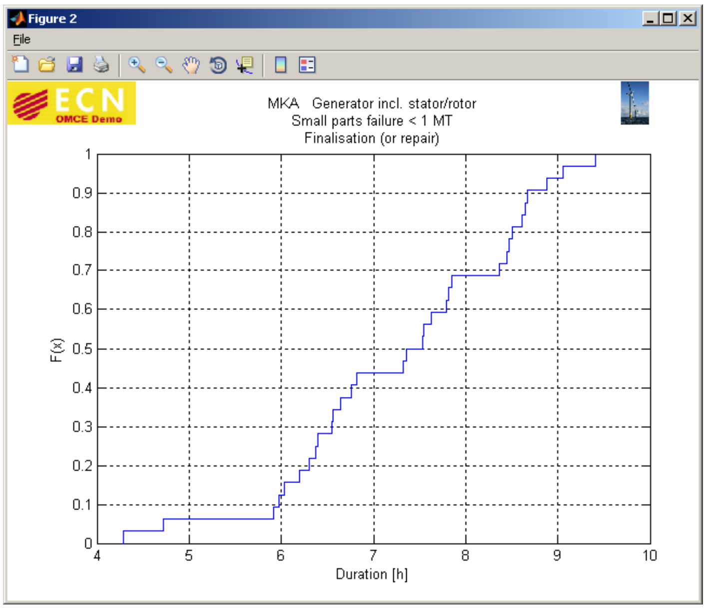

Figure 13-4 *Example of the output of the RPC characterisation of the Building Block 'Logistics'. Here the CDF of the duration of a small repair on the generator is shown.*

In Figure 13-5 another example is shown. Here the usage of equipment is visualised for a selected Repair Class. The graph illustrates that in total five failures have been recorded which represent a large replacement of a drive train component. It can be seen that for access three different vessels have been used; once a RIB, twice a large access vessel and twice a helicopter. Furthermore, twice a crane ship and three times a jack-up barge has been used for hoisting the components.

The submenus for the characterisation of the Spare Control Strategy and Equipment are shown Figure 13-6 and Figure 13-7 respectively. The layout is similar as for the submenu for RPC characterisation; on the left the analysis options can be specified, whereas on the right the results are displayed in a table. Furthermore, also graphical output (cumulative density functions) can be generated, both for characterisation of the results for Spare Control Strategy and Equipment.

As can be seen by the figures presented in this section the demo version of the software of the Building Blocks matches for a large part with the specifications with have been outlined in section 13.2. However, the demo version of the software does not yet offer the possibility to export the results (both tables and graphs) together with the selected analysis options.

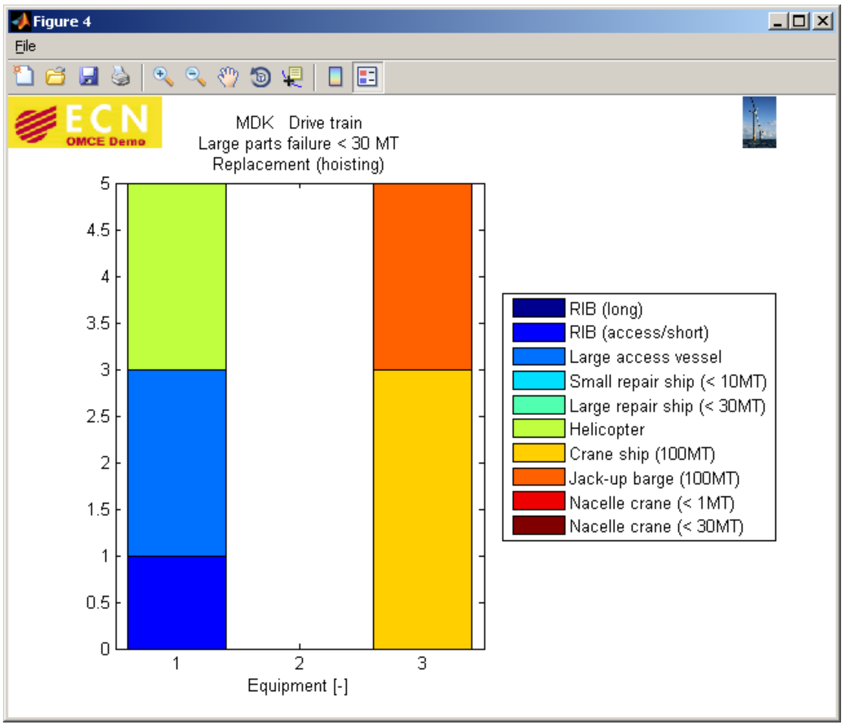

Figure 13-5 *Example of the output of the Repair Class (RPC) characterisation of the Building Block 'Logistics'. Here the usage of equipment is shown for a large replacement of the drive train.*

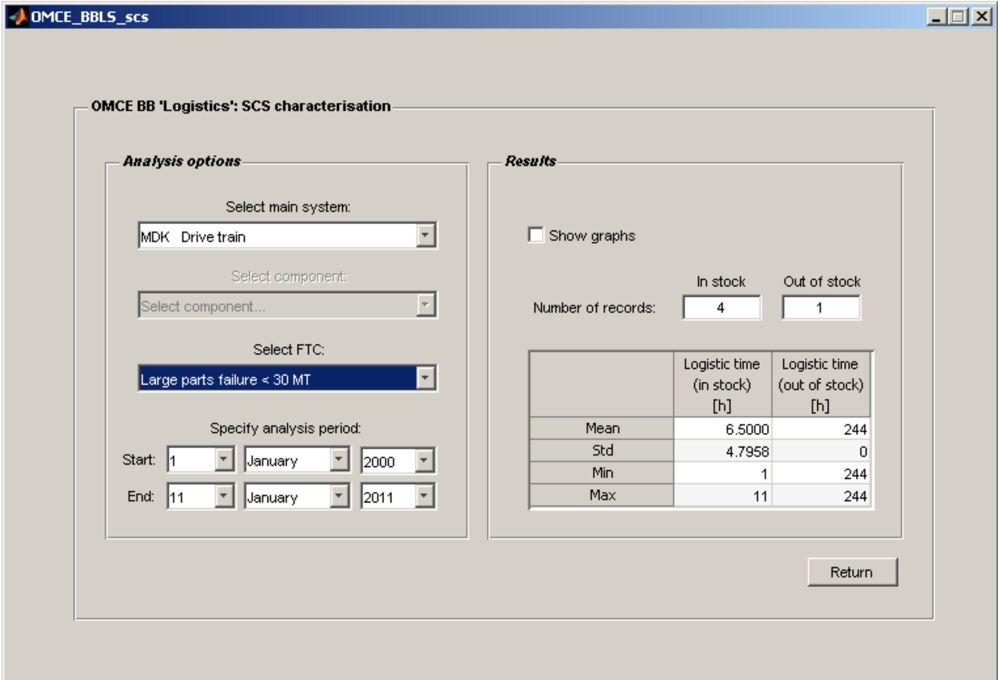

Figure 13-6 *Submenu for Spare Control Strategy (SCS) characterisation of the Building Block 'Logistics'.*

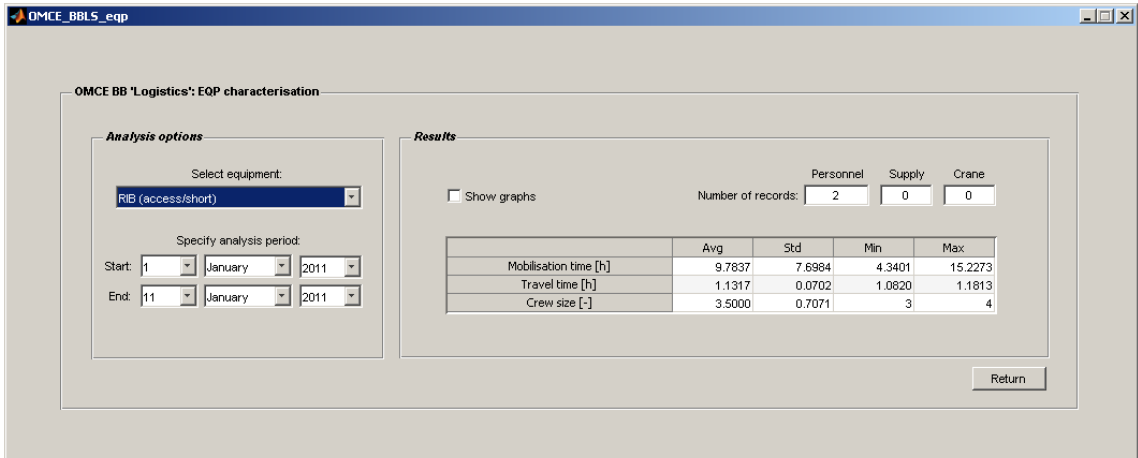

Figure 13-7 *Submenu for Equipment (EQP) characterisation of the Building Block 'Logistics'.*

14. Building Block "Loads & Lifetime"

14.1 Purpose

As outlined in Chapter 9 the Building Blocks 'Loads & Lifetime' and 'Health Monitoring' are used to make estimates of the degradation, or even better, the remaining lifetime of the main wind turbine components. The main goal of the Building Block 'Loads & Lifetime' is to keep track of the load accumulation of the main wind turbine components and to combine this information with other sources (e.g. condition monitoring systems, SCADA information, results from inspections, etc.) in order to assess whether (and on which turbines) condition based maintenance can be performed.

Previous research has shown that the power output of a turbine, and more importantly, the load fluctuations in a wind turbine blade, strongly depend on whether a wind turbine located in a farm is operating in the wake of other turbines or not. These observations imply that the loading of the turbines located in a large (offshore) wind farm is location specific; the turbines located in the middle of the farm operate more often in the wake of other turbines compared to the turbines located at the edge of the wind farm. Therefore, it is expected, that during the course of the lifetime of the wind farm certain components will degrade faster on the turbines experiencing higher loading, compared to the turbines subject to lower loading.

This kind of information could be a reason to adjust maintenance and inspection schemes according to the loading of turbines, instead of assuming similar degradation behaviour for all turbines in the farm. When a major overhaul of a certain component is planned the turbines on which the specific component has experienced higher load can be replaced first, whereas the replacement of the component on the turbines which have experienced lower loading can be postponed for a certain time. This approach could result in important O&M cost savings.

The most obvious way to get insight in the loading of all turbines in an (offshore) wind farm is to instrument all turbines with load measurements on the critical components. However, in practice, after a wind farm is built, the actual loads on components are measured in only very few occasions. Such measurements are relevant for model verification or for the detection of (unexpected) high loads. The main reason for not measuring these effects is that an adequate measurement campaign is costly and time consuming, especially if all turbines need to be instrumented.

In order to monitor the load accumulation in a wind farm in a cost-efficient manner the so-called 'Flight Leader' concept has been developed in order to make estimates of the accumulated loading on the critical components of all turbines in an offshore wind farm. The basic idea behind the Flight Leader concept is that only a few turbines in an offshore wind farm are equipped with mechanical load measurements. These are labelled the 'Flight Leaders'. Using the measurements on these Flight Leader turbines relations should be established between load indicators and standard SCADA parameters (e.g. wind speed, yaw direction, pitch angle, etc.), which are measured at all turbines. Once such relationships are determined for the reference turbines in a wind farm (the Flight Leaders) these can be combined with SCADA data from the other turbines in the wind farm. This enables the determination of the accumulated loading on all turbines in the farm. This is illustrated in Figure 14-1.

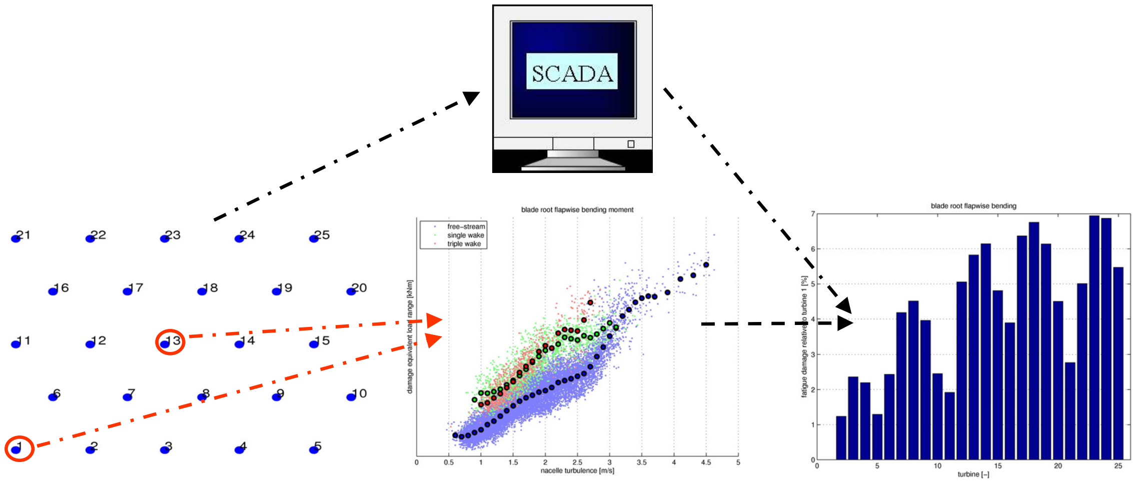

Figure 14-1 *Illustration of the Flight Leader concept; the load measurements performed on the Flight Leader turbines (indicated by the red circles) are used to establish relations between load indicators and standard SCADA parameters; these relations are combined with the SCADA data from all other turbines in the wind farm in order to estimate the accumulated loading of all turbines in the farm.*

14.2 Specifications & software

The proof-of-concept study and the development of a demo software tool of the Flight Leader was performed in a separate project. The results were reported in a number of publications [Ref. 22, 23, 24, 25] and in a public report [Ref. 26]. Therefore, in this section only a basic overview of the specifications and developed software are given.

Developing an empirical software model has been one of the main goals of the Flight Leader project. A demo version of the software has been programmed in MATLAB. The software includes all aspects of the Flight Leader concept and is intended to be used by operators of offshore wind farms and can be applied to process the SCADA data and mechanical load measurements from an (offshore) wind farm. The main output of the model is a comparison of the accumulated mechanical loading of all turbines in the offshore wind farm. This information can subsequently be used to optimise O&M strategies, for example by prioritising the inspection or replacement of certain components on the heavier loaded turbines.

The general structure for the Flight Leader computer model is shown in the flowchart in Figure 14-2.

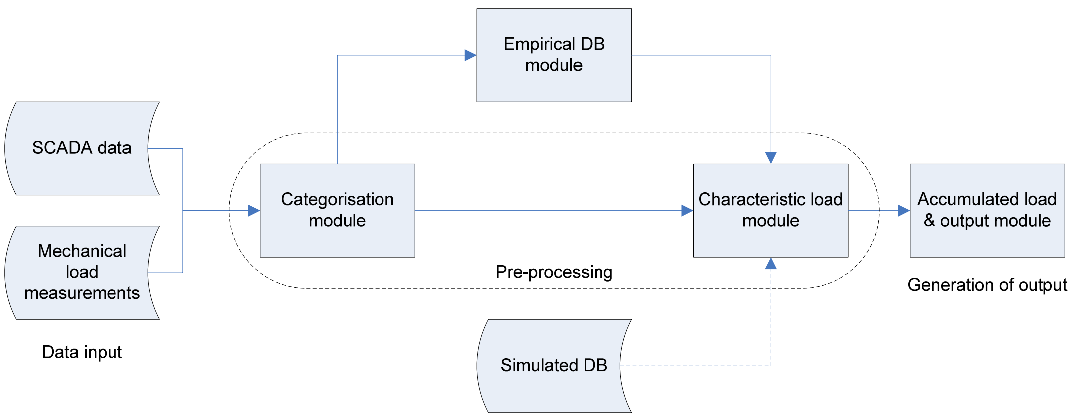

Figure 14-2 *General structure for the Flight Leader computer model.*

14.2.1 Data input

An important difference with the two previously discussed Building Blocks is the fact that the Building Block 'Loads & Lifetime' does not use the maintenance data stored in an event list. The most important input for the empirical Flight Leader model are the data collected from the offshore wind farm. Two types of data can be distinguished; (1) SCADA data, which is being collected from all turbines, and, (2) mechanical load measurements, which are being collected from the Flight Leader turbines.

Usually the SCADA data is delivered to the (offshore) wind farm owner/operator by the manufacturer of the wind turbines in the form of 10-minute statistics. The mechanical load measurements should be collected as time series. These time series need to be processed in order to calculate load indicators (10-minute statistics), which are representative for the degradation or ageing of a certain wind turbine component. Since the mechanical load measurement campaign is usually performed independently from the wind turbine manufacturer, the processing (including quality control/post-validation) of the mechanical load measurements should be done by either the wind farm owner/operator or the party performing the mechanical load measurement campaign. The resulting processed 10-minute statistics of the load signals, together with the 10-minute statistics of the different SCADA parameters subsequently serve as input for the Flight Leader model. This is indicated in Figure 14-3.

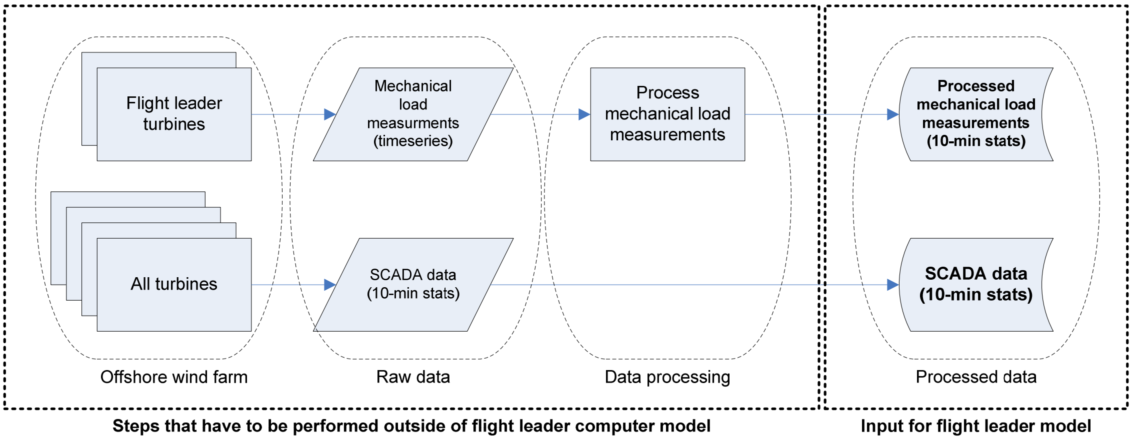

Figure 14-3 *Flowchart indicating the different steps for generating the (measured) input (SCADA and mechanical load measurements) data for the Flight Leader computer model.*

14.2.2 Data categorisation

Unfortunately a wind turbine does not always operate in normal power production mode. Furthermore, when located in an (offshore) wind farm, wind turbines do not always experience free-stream wind conditions. Both mentioned conditions are expected to have an effect on the mechanical loading. In order to take this into account the first step of the Flight Leader model is to categorise each timestamp in the dataset in one of the possible combinations of the five pre-defined turbine states j and three pre-defined wake conditions k. The possible combinations are indicated in Table 14.1.

Table 14.1 *Possible combinations of turbine states & transitional modes and wake conditions.*

ID	Turbine state or transitional mode j	Wake condition k
1.1	Normal power production	Free-stream
1.2		Partial wake
1.3		Full wake
2.1	Parked/Idling	*Not Applicable*
3.1	Start-up	
4.1	Normal shutdown	
5.1	Emergency shutdown	

14.2.3 Empirical database

After all available data have been categorised the measurements from the Flight Leader turbines can be used to establish relations between (standard) SCADA parameters and load indicators, which are representative for the damage, aging or degradation of a certain component. As mentioned in the previous section, these relations are expected to differ for the identified turbine states & transitional modes and wake conditions. Therefore the relations between SCADA parameters and load indicators have to be determined for each of the possible combinations shown in Table 14.1. The software model offers the possibility to characterise the relations using more traditional methods such as interpolation or multivariate regression but also using artificial neural network techniques. An example of the software's empirical database module is shown in Figure 14-4.

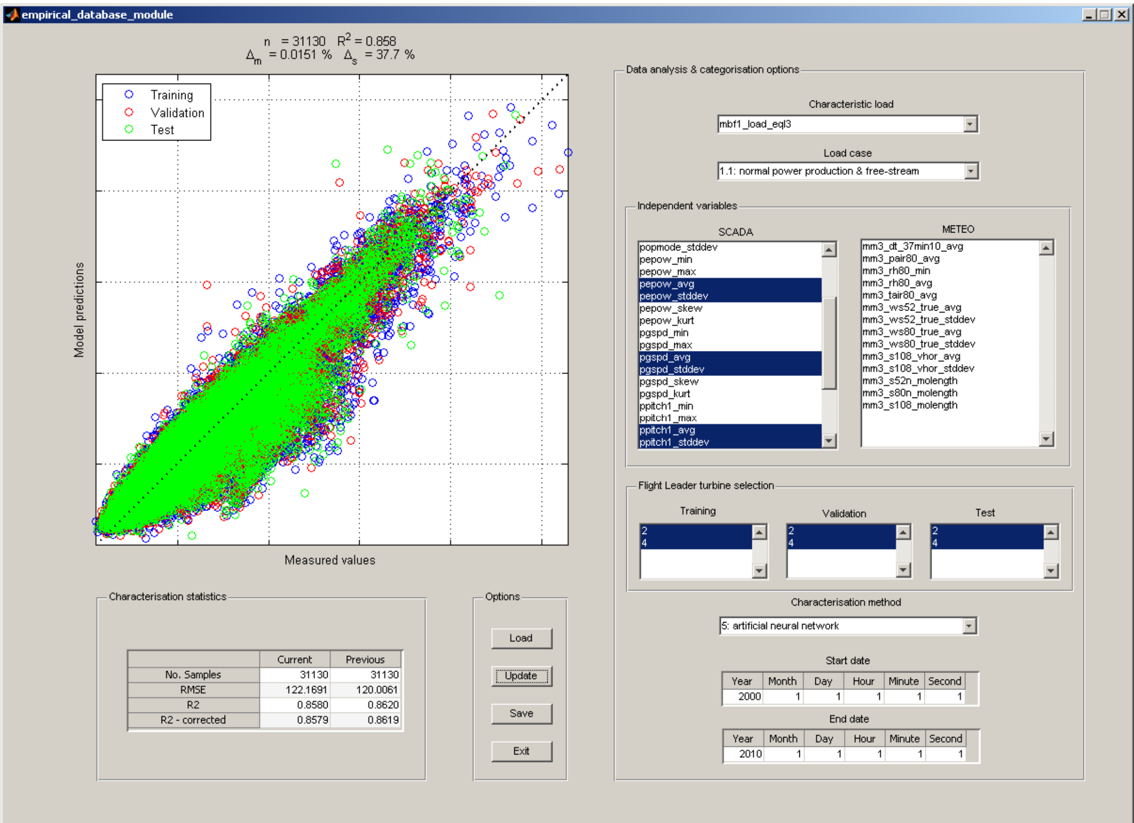

Figure 14-4 *The Flight Leader's empirical database module for establishing relations between SCADA parameters and load indicators.*

14.2.4 Simulation database

The Flight Leader concept is mainly an empirical concept. However, the software also offers the possibility to include results from aero-elastic simulations. This can be useful in case not (yet) enough data are available for establishing a solid relation between SCADA parameters and the load indicator. This is most likely to occur in the period directly after the commissioning of the offshore wind farm when little measured data are available. Furthermore, also for those situations with a low probability of occurrence, such as emergency shutdowns or extremely high wind speeds, including results from simulations might be beneficial.

14.2.5 Estimating load indicators

Next step is estimating the load indicators at all turbines in the offshore wind farm. This is achieved by combining the SCADA data, collected at all turbines, with the relations between SCADA parameters and load indicators as stored in the empirical database. Optionally, for this process also results from aero-elastic simulations can be incorporated.

The situation might occur that for a certain turbine for a certain amount of time no SCADA data are available. For these periods the load indicators cannot be estimated neither with the empirical nor the simulation database. In order to ensure a fair comparison of the total accumulated loading the software also contains a procedure for handling missing data.

14.2.6 Output

Finally, the last part of the model is the process of generating and displaying the desired output of the Flight Leader model. The main output consists of a comparison of the accumulated mechanical loading of all turbines in the offshore wind farm. This output needs to be shown for the several load indicators (e.g. blade root bending, tower bottom bending or main shaft torque).

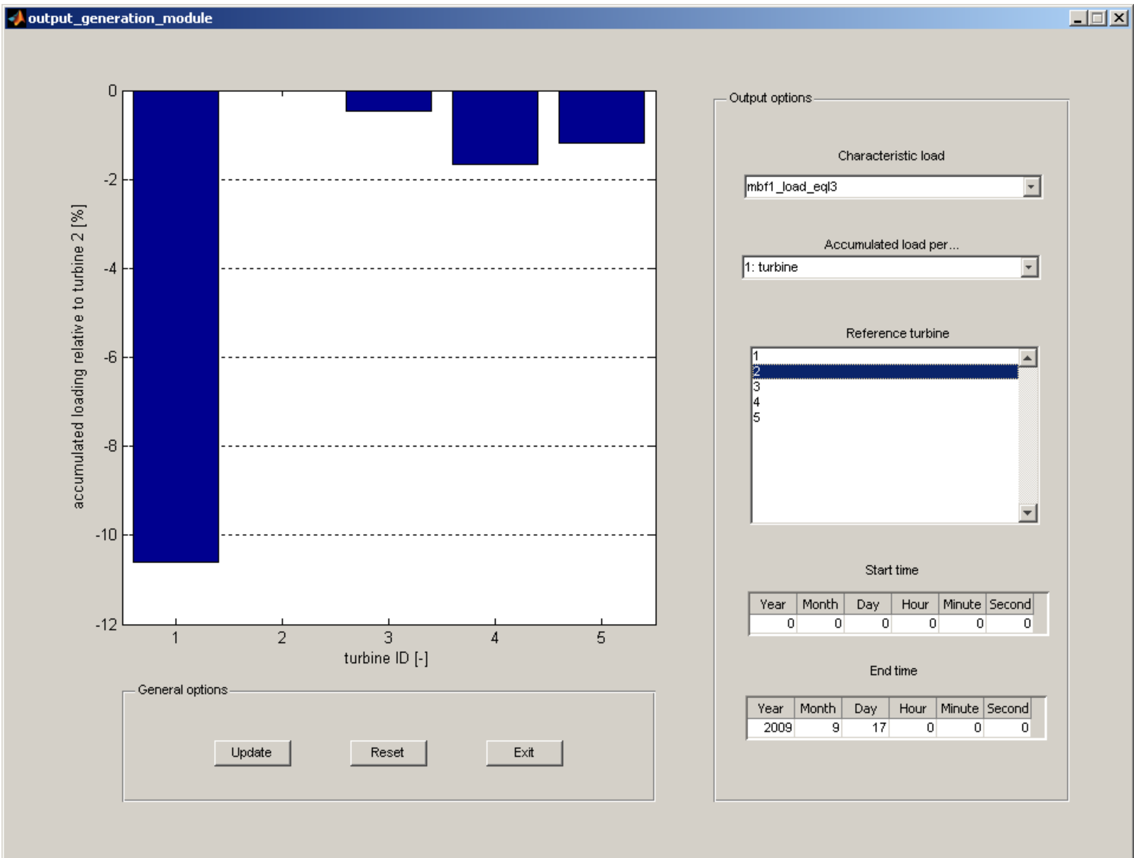

Figure 14-5 *Example of the output generation model of the Flight Leader software, where the relative (to turbine 3) load accumulation of all turbines is displayed.*

Besides the main output the software model can calculate and display various breakdowns of the accumulated loading. For instance the contribution of each turbine state or transitional mode or wake condition to the total accumulated loading can be displayed. Furthermore the load accumulation per time period can be studied. These outputs can be used to get more insight in the performance of the offshore wind farm and what operating conditions have the largest impact on the loading of the turbines in the offshore wind farm. An example of such output is depicted in Figure 14-6.

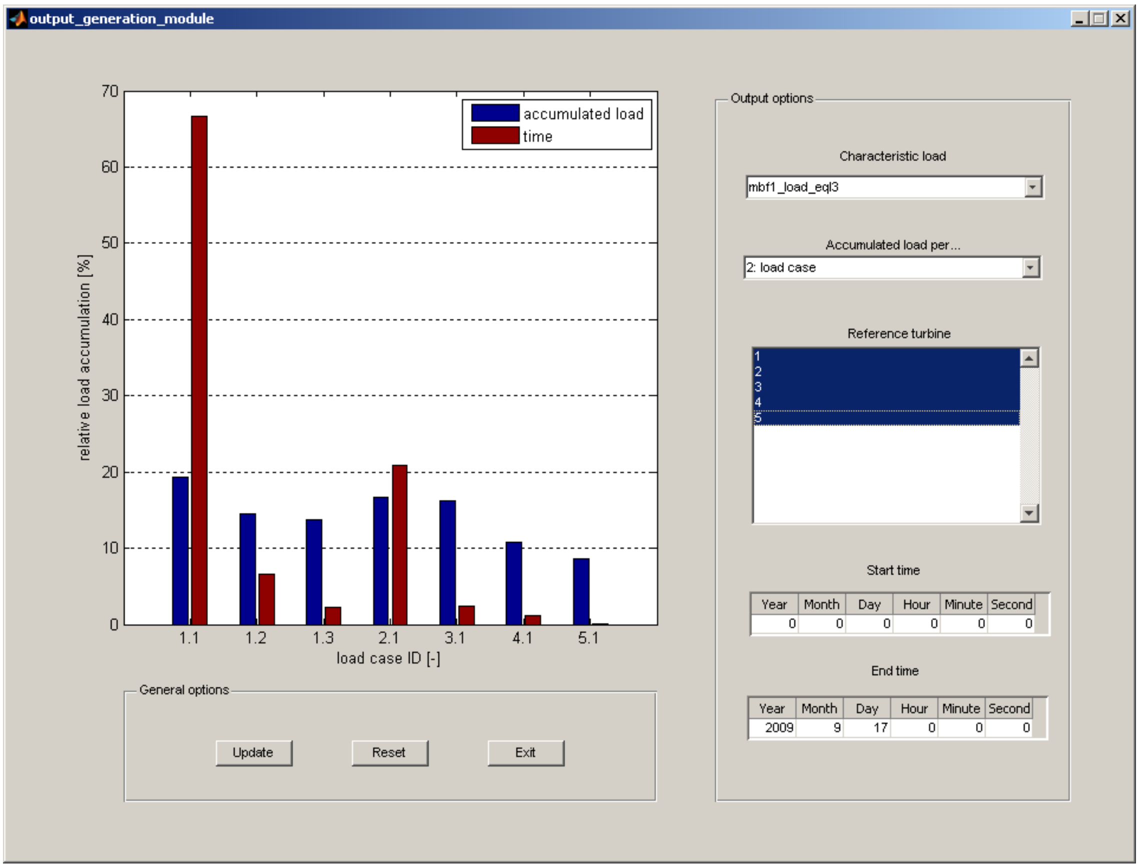

Figure 14-6 *Example of the output generation model of the Flight Leader software, where the contribution of each load case to the total load accumulation is shown.*

Besides calculating and comparing load accumulation the Flight Leader software also offers the opportunity to validate the accuracy of its predictions, by comparing the measured load accumulation with the predicted load accumulation for the Flight Leader turbines. This can be done for each individual load indicator and load case.

15. Building Block "Health Monitoring"

15.1 Purpose

The purpose of the BB "Health Monitoring" is to process and analyse the available data that can provide information on the health of the wind turbine components. The results of the BB "Health Monitoring" in combination with the results of the BB "Loads & Lifetime" will provide information on the expected time to failure of components. The data providing information on the component degradation is stored in various data sources, a.o. the SCADA system, condition monitoring systems, and periodic inspections. The BB "Health Monitoring" should analyse these data and provide the wind farm operator with an assessment of the health and remaining lifetime of the various wind turbine components. The expected time to failure can be used to estimate the amount of condition based maintenance in the next coming months or years.

15.2 Specifications

Within the OMCE project, but especially within the CONMOW project [Ref. 12] ECN has carried out many experiments with methods to assess the health and degradation of wind turbine components. The most relevant findings are:

1. Vibration monitoring systems are able to accurately determine which component in a drive train is failing. Such measurements are suitable to organise additional inspections and limit consequence damage.
2. Offline and online monitoring of gearbox oil by particle counters do indicate degradation of gearboxes at an early stage.
3. For all techniques tested in the CONMOW project, viz. analysis of time series, SCADA data, and vibration measurements, there was insufficient knowledge in order to assess if critical limits were exceeded and how fast failures would develop. The latter two are minimum requirements to be fulfilled in order to change from calendar based maintenance to condition based maintenance.
4. It was concluded (and also confirmed by experts outside the CONMOW project) that at present there is insufficient knowledge available on criteria to assess the *green, yellow* and *red* status of a failure and to make prognoses how the failures will develop over time. Such knowledge should be obtained from a larger population of identical wind turbines and longer measurement periods during which faults occur. It is therefore recommended to store data centrally so cross analyses and comparisons between turbines and sites can be made.
5. Drive-train vibration monitoring should be permanent and online since failures may develop within a period of time that is shorter than the regular maintenance interval. If failures are detected at an early stage, consequence damage can be avoided. Further, vibrations often show up under specific operating conditions.
6. The systems produce large amounts of data which are difficult and time consuming to interpret by wind turbine owners. The first analyses of raw data should be done by a dedicated expert team in order to derive information relevant for maintenance planning and feedback. Only this information should be provided to operators and design teams. An example of a parameter changing over time is the bearing temperature, see Figure 15-1. De-trending, using the rotational speed and nacelle temperature, has drastically reduced the signal variability. The effect is that the resulting plots show only little variability as long as the component is not degrading.

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[7] The ECN Wind turbine Test location Wieringermeer (EWTW) [10], [11], [12] is located in the province Noord-Holland, 35 km east of ECN Petten. The EWTW contains five Nordex N80 turbines that have been used for the validation.

Because the methods to derive the remaining lifetime from all available data, are so complex and depending on the means of diagnostics (often firmware from third parties), the BB "Health Monitoring" should not be considered as standalone software. Instead, the BB is a combination of methods to interpret the data that contains information on component degradation. Experts are needed to do this.

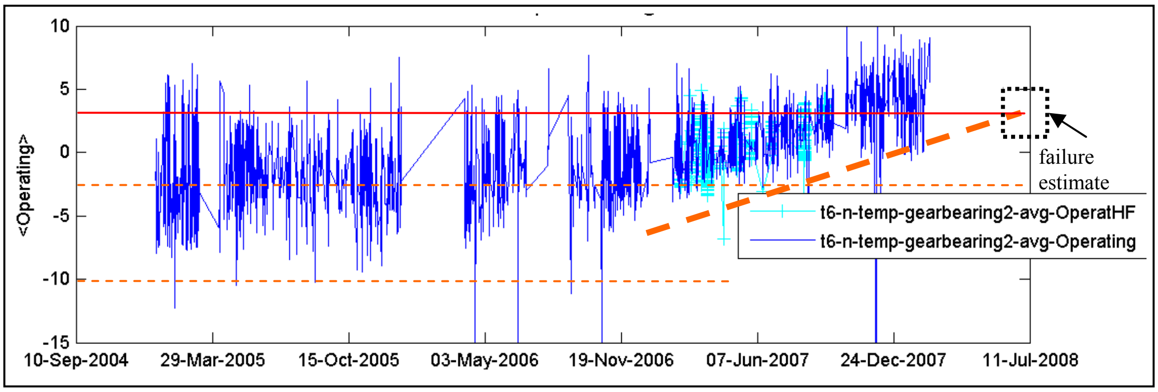

Figure 15-1: *Example of a visualisation from de-trended SCADA statistical data; slow increase of the bearing temperature indicating wear*

16. Status and Future Developments

16.1 OMCE-Calculator

At the publishing date of this report, July 2011, several companies that are using the ECN O&M Tool did receive a demo version of the OMCE-Calculator for evaluation purposes. Their feedback will be used to complete the definitive version of the OMCE-Calculator that will be released during autumn of 2011.

During the development of the OMCE-Calculator within the We@Sea and DOWES programs, the authors recognised that not all features that were initially specified could be implemented in the current version, mainly due to limitations in time and budget. Therefore when updating the version released during the autumn of 2011 at least the following features will be included.

- Stochastic input parameters
  In the current version the inherent variability of the weather conditions is taken into account by carrying out the simulations in the time domain based on the time series of the weather conditions. The random occurrence of random failures is modeled by means of a Poisson process, assuming a constant failure rate. Besides the failure rate, also the other parameters are assumed to be deterministic.
  When updating the current version it will be enabled to consider the statistical uncertainty in the following three groups of input parameters, see Appendix B.3:
    - Failure rate and number of turbines for condition based maintenance
    - Time related parameters
    - Cost related parameters
- Time dependent input parameters
  In the current version the input parameters are assumed to be constant during the simulation period.
  When updating the current version it will be enabled to take into account seasonal and/or yearly variation of the input parameters.
  In case the input parameters are specified as stochastic quantities, both the mean value and the standard deviation may be time dependent.

Furthermore, this list will be updated based on feedback from the user's of the OMCE Calculator.

16.2 Event List

The Event List as a list with specifications on how to collect data in a structured way has been derived from ECN's experiences with data collection from onshore and offshore wind farms. It should be the responsibility of the wind farm operator to use and implement the specifications in daily practice. ECN has no plans to further develop the specifications for the Event List, but on request, ECN is willing to assist operators in implementing the Event List. Once the Even List specifications are implemented in a CMMS, the operators could make use of ECN's software for data analyses, viz. the OMCE-BB's 'Operation & Maintenance" and 'Logistics'.

16.3 OMCE-Building Blocks

ECN has done extensive research on how wind farm data can be best collected and analysed in order to use it for reliability engineering and modelling the O&M aspects of offshore wind farms. This research has resulted in specifications for the four BB's. ECN has been able to develop software for the BB's 'Operation & Maintenance" and 'Logistics'. This software can be used by operators that have collected their data in accordance with the Event List specifications. The software has been programmed, tested, and documented and is ready for use.

The model for the BB "Loads & Lifetime' was too ambitious to be developed within the OMCE developments. This BB does not only consist of some software but also includes a working procedure and an extensive measurement programme to determine mechanical loads at one or 2 turbines. A separate project was carried out "*Flight Leader concept for Wind Farm Load Counting*" and finished end of 2009. The Flight Leader concept has proven to work well (validation studies were carried out at the ECN Wind Turbine test station Wieringermeer, EWTW, and at the Offshore Wind farm Egmond aan Zee, OWEZ). At present ECN is looking for launching customers that would like to apply the Flight Leader concept and investigate if indeed this concept allows to change from preventive and corrective maintenance to condition based maintenance. At present, the correct functioning of the Flight Leader concept is proven, but the added value for O&M optimisation is still to be determined.

ECN did investigate numerous possibilities to automatically analyse condition monitoring data (including SCADA data, condition monitoring systems from third parties, and results from oil samples and inspections) and use the results for O&M optimisation. Unfortunately, ECN did not succeed in this. It was concluded that the problem is too complex to develop a single piece of software. ECN did develop procedures for data reduction and generating key figures to be used by operators. But in all cases the data should be assessed by specialists in the field of e.g. condition monitoring. ECN has no further plans to develop new algorithms and software for this BB.

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Appendix A ECN O&M Tool

The ECN O&M Tool focuses on determining the costs and downtime resulting from unplanned corrective maintenance but also takes into account preventive maintenance. The process of cost modelling is illustrated in Figure A-1. At first a baseline O&M strategy is determined to maintain the intended wind farm. For the baseline strategy, best guesses are being made by the project team for the different input parameters (failure rates, characteristic values of vessels and equipment, and weather conditions). The model results in costs and downtime and the project team can start analyzing the results. Cost drivers can be identified and based on these possible areas for improvement (e.g. using more reliable components or vessels with improved accessibilities) can be identified. If the project team has selected an optimal maintenance strategy, it is recommended to analyze the uncertainties with the probabilistic part of the model. By doing so, insight is gained in how the different uncertainties in the input parameters contribute to the uncertainties in the outcome of the model.

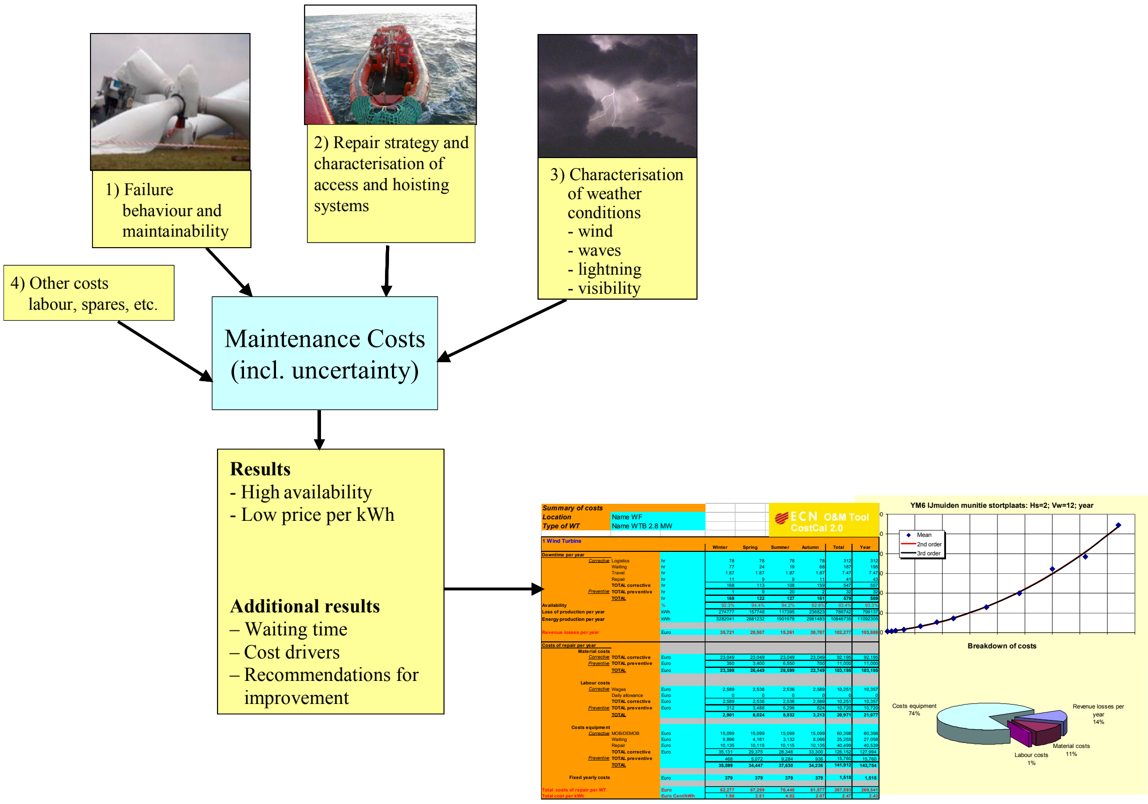

Figure A-1: *Schematic representation of the ECN O&M Tool for determining the O&M costs and downtime of an offshore wind farm.*

The model to determine the long term yearly average costs and downtime due to unplanned corrective maintenance is based on the repair process as depicted in Figure A-2. In general it can be stated that the central operation office will be informed that an alarm has been triggered. Once the operator has notified the alarm, he has to decide whether the turbine can be restarted remotely (or maintenance can be done remotely) or that a visit is necessary to determine whether the wind turbine can be restarted without maintenance or maintenance is required first. If repair is necessary the operator needs to organise the repair action, mobilise the crew, a ship and if necessary spare parts and large hoisting equipment.

The Time To Repair (TTR) can be split up into four time intervals.

1. The interval *T_logistics* denotes the period of time between the wind turbine was shut down and the repair crew is organised and ready to travel to the turbine for repair. In this period, also the time needed to organise equipment and spare parts is considered. So the length of this interval depends on the availability of an inspection team, the availability of materials, and the availability of equipment for travelling and hoisting. The availability of personnel or equipment strongly depends on the company policy. Own personnel or third parties can do the maintenance, equipment can be owned or hired, etc.
2. Once the repair crew and the equipment for travelling are in principle ready for take off it might happen that the weather forecast during the period the mission has to be carried out (*T_mission*) is such that it is not allowed or irresponsible to take off. This interval is denoted as *T_wait*. The length of this interval is dependent on the duration of the mission and the device planned (see also Figure A-2). Due to its dependency on weather conditions (wind speed and or wave height) the duration of this interval shows large scatter and should be treated as a stochastic quantity. As the ECN O&M Tool determines long term yearly average quantities the average value of the waiting time is used in this model.
3. The interval *T_travel* denotes the time needed to travel to the wind turbine that has to be inspected or repaired.
4. The interval *T_repair* is the time needed to carry out the repair.

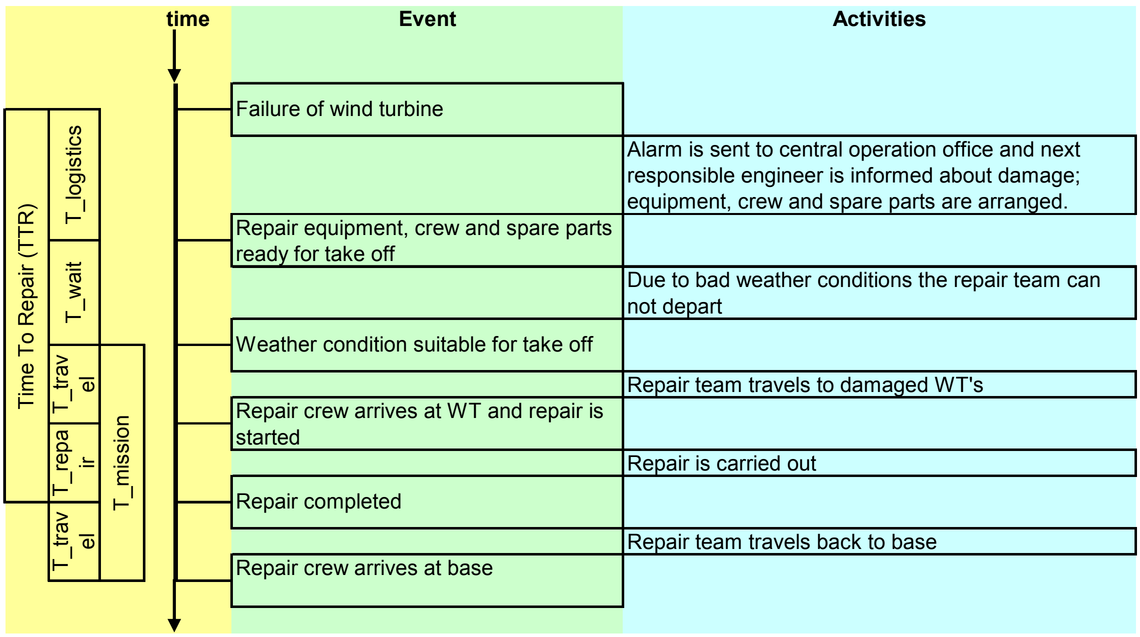

Figure A-2: *Repair process*

The ECN O&M Tool Version 3[8] has been implemented in two MS-Excel sheets:

WaitingTime.xls to determine the annual (or seasonal) average waiting time (*T_wait*) as a function of the mission time (*T_mission*), and the allowable significant wave height (H_{s_max}) and wind speed (V_{w_max}); and

CostCal.xls to determine the annual (or seasonal) average downtime and costs.

[8] In July 2011 Version 4 of the ECN O&M Tool is released and in that version the modules WaitingTime.xls and CostCal.xls are no longer two separate modules but integrated into one model.

WaitingTime.xls

Offshore equipment can be used or repair actions can be carried out if the wind and wave conditions are below certain values. Based on wind and wave data for a selected location the program WaitingTime.xls determines when the weather conditions are suitable for carrying out certain repair actions and calculates the average time one has to wait before a suitable weather window will occur after a failure. The program uses time series with three hourly wind and wave data as input. The program results in second or third order polynomials for the mean value and the standard deviation of the waiting time as a function of the duration of the maintenance activity. In Figure A-3 an example is given of such a polynomial.

Processing of Data		
Date	H_s [m]	V_w [m/s]
Max values:	1,5	12
01-01-1990 1:00	0,35	2,7
01-01-1990 4:00	0,4	2,8
01-01-1990 7:00	0,41	1,9
01-01-1990 10:00	0,37	2,3
30-12-2001 22:00	1,39	3,6
31-12-2001 1:00	1,29	1,8
31-12-2001 4:00	1,31	3,5
31-12-2001 7:00	1,11	7
31-12-2001 10:00	1,38	7,9
31-12-2001 13:00	1,53	7
31-12-2001 16:00	1,44	6,1
31-12-2001 19:00	1,69	6,1
31-12-2001 22:00	1,41	8,7

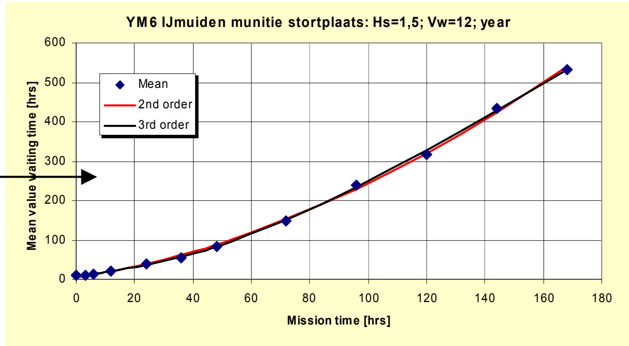

Figure A-3: *Example of determining relationship between average waiting time and mission time*

The example represents the annual average waiting time as a function of the mission time at the location "IJmuiden Munitiestortplaats" and is based on 11 years of measured data. The mission can be carried out up to a significant wave height of Hs = 1.5 m and a wind speed of Vw = 12 m/s. Similar polynomials can also be generated per season and for different weather limits H_s and V_w.

CostCal.xls

The program CostCal.xls is being used to determine the long term annual (or seasonal) costs for O&M and the associated downtime. The program focuses on unplanned corrective maintenance but incorporates also preventive maintenance actions. The program uses among others the following input:

1. weather windows and waiting time polynomials as generated with WaitingTime.xls;
2. wind turbine and wind farm information such as number of wind turbines, capacity factor of the wind farm, investment costs of turbines, costs of technicians, length of working day, etc.;
3. failure behaviour of the turbines and the repair actions which are foreseen;
4. characteristic values of access systems (weather limits, costs, mobilisation time, etc.);
5. preventive maintenance actions with costs and long term fixed costs like annual contracts.

During the modelling process, users spend most time on generating input parameters for item 3 which is discussed here in more detail. First of all, the ECN O&M Tool requires the occurrence frequencies of failures and associated repair actions as input. Unfortunately, such data are hard to obtain. Often data should be derived from generic databases, or (more preferred!) from similar turbines. If such data can be obtained, mostly only overall annual failure frequencies of the main components are available. Engineering judgement is required to determine the different failure modes of these components. A certain percentage of the component failures comprises failure modes that are small and easy to repair, whereas another percentage comprises failure modes that are more severe and require for instance large crane ships during the repair action. In order to avoid that the model needs to analyse each individual failure mode and its associated repair actions, all maintenance actions are categorised into a different maintenance categories (MC's). An example of the categorisation of maintenance actions with associated equipment is given in Table A-1.

Table A-1: *Example of possible subdivision in Maintenance Categories*

MC 1:	Remote reset, no personnel and equipment, no repair time
MC 2:	Small repair inside, only personnel and tools, repair time less than 1 day (e.g. replacement of carbon brushes)
MC 3:	Small repair outside, only personnel and tools, repair time less than 1 day (e.g. cleaning of blades)
MC 4:	Replacement of small parts, small internal crane hoisting outside, repair time around 1 day (e.g. replacement of pitch motor)
MC 5:	Replacement of large parts, large internal crane needed (e.g. replacement of gearbox, generator. etc.); repair time typically 1 to 2 days
MC 6:	Replacement of large parts, large external crane needed (e.g. replacement of, hub, nacelle, yaw system); repair time typically 2 to 3 days

In addition to the categorisation of maintenance classes, it is also necessary to exactly describe how the repair is going to be carried out and how the equipment is going to be used. An example of a detailed description is given in Table A-2. This step-by-step description is considered by all users as very relevant; often it is concluded afterwards that repair actions are more complex than originally foreseen.

The information per maintenance class is limited to the use of equipment (vessels and crane ships). Subsequently, each maintenance class is again split up into a limited number of Fault Type Classes (FTC's). A FTC determines the average costs per repair action taking into account: labour costs, costs of spare parts and consumables, costs of equipment, and revenue losses caused by downtime. A FTC also determines the mission time per repair action and thus the associated waiting time due to bad weather conditions (see also Figure A-3). The total downtime consists of the four intervals given above: logistic time to organise equipment and spare parts, waiting time due to bad weather, travel time, and repair time (see also Figure A-2). The model CostCal.xls is equipped with input sheets to define the above mentioned costs, mission times, and capabilities of vessels and crane ships.

The process of “grouping” the different failure modes into a manageable set of FTC's with identical costs and downtime, and the determination of the annual average occurrence frequencies of each FTC is given in Figure A-4. The ECN O&M Tool typically deals with 10 to 15 FTC's.

If for the baseline O&M scenario all input parameters have been defined, the program immediately shows the output, e.g. in a table as presented in Table A-3. The program also generates plots and pie charts to determine e.g. cost drivers or aspects that dominate downtime, see Figure A-5. The results may be a reason to optimise the O&M strategy, e.g. by selecting different vessels, changing the turbine design, improving component reliability, or using a hotel boat.

The ECN O&M Tool model will in most cases be used as a deterministic model in which only mean values or the maximum likelihood are considered. The model can also be used as a probabilistic model to take into account the uncertainties in the parameters, e.g. failure frequencies and costs. To do this, the add-in module @Risk[9] should be used. The model can generate for instance the cumulative density function of the O&M costs per kWh, or determine which uncertain input parameter influences the uncertainty of the results the most by means of a tornado diagram, see Figure A-6.

[9] “*Guide to using @Risk*”, Palisade Corporation

Table A-2: *Example of description (MC 4: Replacement of small parts)*

Smaller spare parts like a pitch motor, a yaw motor or parts of a hydraulic system need to be transported to the turbine, put on the platform and hoisted into the nacelle with the help of the internal crane. A typical maintenance action looks as follows:

1. An access vessel with 2 to 4 technicians and the spare part travels to the failed turbine;
2. The technicians are transferred from the access vessel;
3. Technicians inspect failed component and decide whether replacement is needed;
4. In case the failed component needs to be replaced the spare component is hoisted to the platform with the small crane on the lower turbine platform;
5. The failed component is dismantled and lowered outside the tower to the platform using the internal crane;
6. The spare component is hoisted from the platform using the internal crane and mounted;
7. The failed component is hoisted to the access vessel using the small crane on platform; (Depending on the capabilities of the platform and the crane, this step can be done later; the failed part can be stored for some time on the platform.)
8. Personnel return to the access vessel and travels back to the harbour.

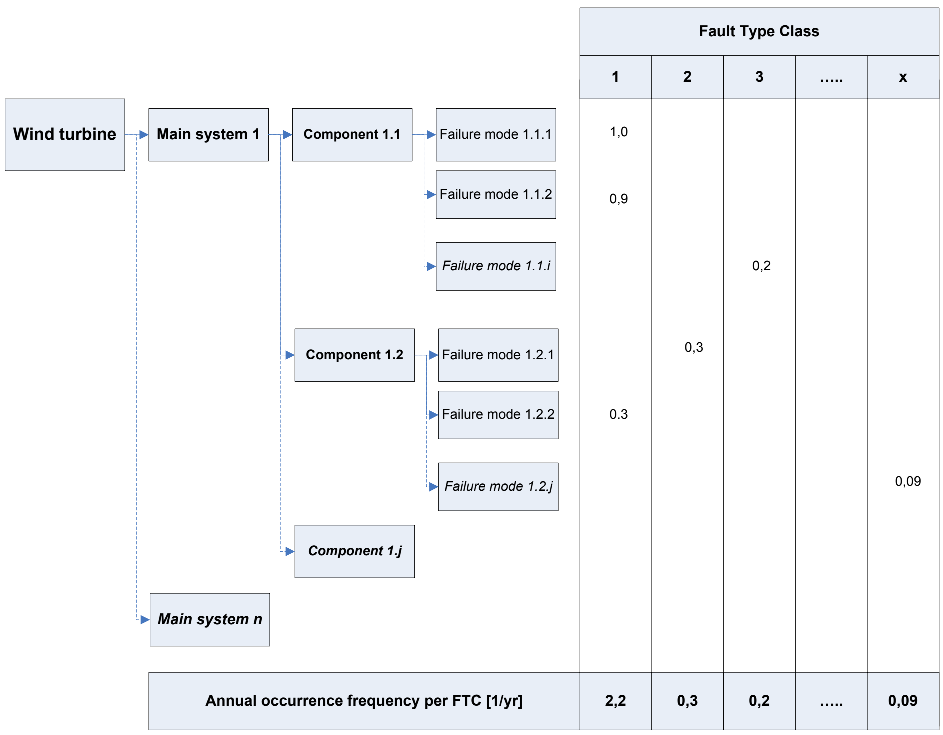

Figure A-4: *Process of grouping small and severe failures into manageable set of FTC's*

Table A-3: *Example of model output (table)*

1 Wind Turbine			Winter	Spring	Summer	Autumn	Total	Year
Downtime per year								
	Logistics	hr	190	141	124	164	618	618
	Waiting	hr	107	28	13	56	204	160
	Travel	hr	2	2	1	2	7	7
	Repair	hr	14	10	9	12	44	44
	TOTAL	hr	313	181	148	233	874	829
Availability		%	86%	92%	93%	89%	90,0%	90,5%
Loss of production per year		kWh	370528	158611	114579	238240	881957	808224
Energy production per year		kWh	2224140	1765284	1586460	2002090	7577974	7727863
Revenue losses per year		Euro	**29642**	**12689**	**9166**	**19059**	**70557**	**64658**
Costs of repair per year								
Material costs		Euro	16236	12038	10644	14018	52936	52936
Labour costs								
	Wages	Euro	1758	1303	1152	1518	5731	5731
	Daily allowance	Euro	0	0	0	0	0	0
	TOTAL	Euro	1758	1303	1152	1518	5731	5731
Costs equipment								
	MOB/DEMOB	Euro	9506	7048	6232	8208	30994	30994
	Waiting	Euro	29281	9367	6413	15550	60612	53055
	Repair	Euro	9522	7060	6242	8221	31046	31046
	TOTAL	Euro	48309	23475	18888	31979	122651	115095
Total costs of repair per WT		**Euro**	**66302**	**36817**	**30684**	**47515**	**181318**	**173762**
Total cost per kWh		**Euro Cent/kWh**	**2,98**	**2,09**	**1,93**	**2,37**	**2,39**	**2,25**

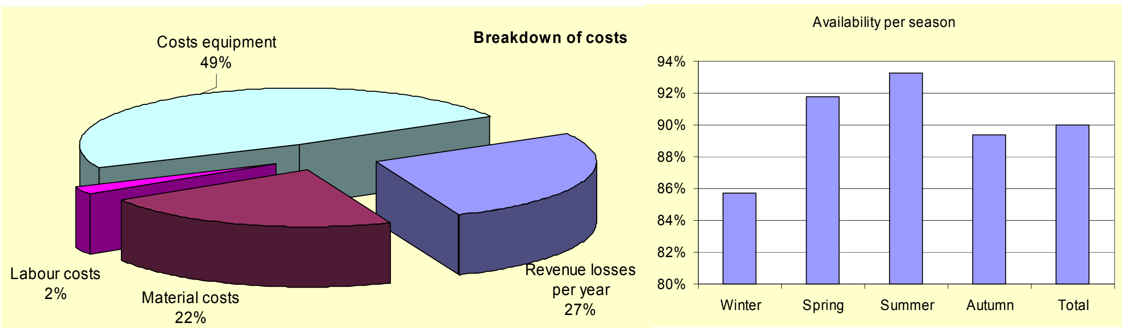

Figure A-5: *Example of model output (graphs and pie charts)*

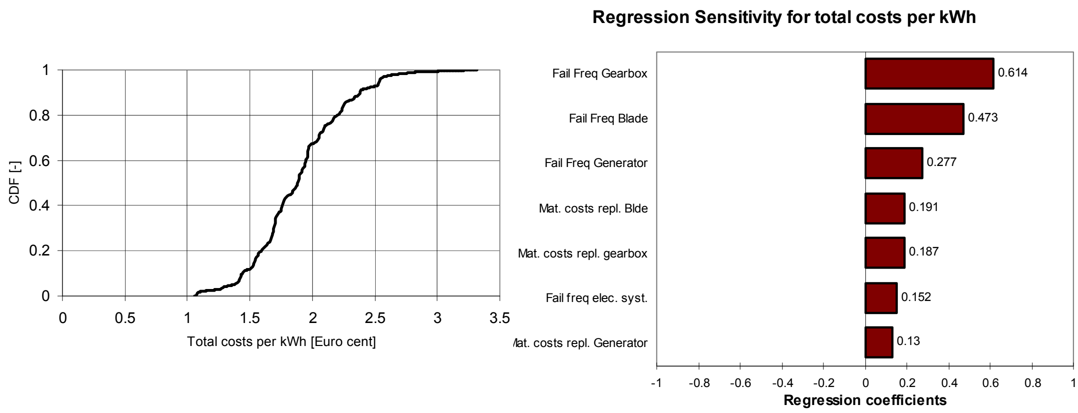

Figure A-6: *Example of CDF and tornado diagram*

Appendix B OMCE Calculator Uncertainties

Generally uncertainties can be categorized as inherent variability or as statistical uncertainty. Inherent variability is a result of the physical process and so the uncertainty cannot be reduced; examples are the wind speed, the wave height, and the moment of occurrence of random failures. Statistical uncertainty is caused by lack of knowledge about the parameters, and sometimes it can be reduced through further measurements or study, or through consulting more experts. Even if all operational data is made available, estimates will be covered with large uncertainties, and it is of great importance to take into account these uncertainties to get insight in the risks. Also contracts may be of importance, f.i. when the price of offshore equipment has been settled in a contract the uncertainty in the price will be relatively small, while the uncertainty will be much higher when the same equipment has to be hired on the free market. Although the moment of occurrence of a random failure will show inherent variability, the mean value of the number of failures to be expected per year might show statistical uncertainty.

The total uncertainty, which is a combination of inherent variability and statistical uncertainty, will lead to uncertainty in the calculated results (f.i. downtime, costs, number of ships needed, number of spares required, etc.). So it may be clear that when making predictions for the coming period of 1 to 5 years not only the expected (average) value is of importance but the uncertainty or variability in these expected values is equally important. Therefore for the OMCE calculator it is of importance to be able to quantify the uncertainty in the calculated results and to provide insight in the effect of the uncertainty in the input variables on the uncertainty in the calculated results.

Below the various sources of uncertainty to be dealt with are discussed and it is indicated where in the modelling process the different types of uncertainty have to be considered.

B.1 Random failures

The occurrence of the random failures is a stochastic process, which will be modelled by means of a Poisson process. A Poisson process is a stochastic process which can be used for modelling random events in time that occur independently of each other. Hence it is suitable to model the occurrence of random failures of the components in a wind turbine. In a Poisson process the following quantities can be considered [B.1]:

- α_t : the number of events that may occur in a period t
- t_α : the amount of time one will have to wait to observe α events
- λ : the average number of events that could occur, known as Poisson intensity

When the average number of events that will occur in a year is known to be λ, the number of events that will occur during t years is given by the Poisson distribution,

$$\alpha_t = \text{Poisson}(\lambda t) \tag{B.1}$$

The time until the occurrence of the first event for a Poisson distribution is given by the exponential distribution,

$$t_1 = \text{Expon}(1/\lambda) \tag{B.2}$$

Examples of the Poisson distribution and the exponential distribution are shown in Figure B.1.

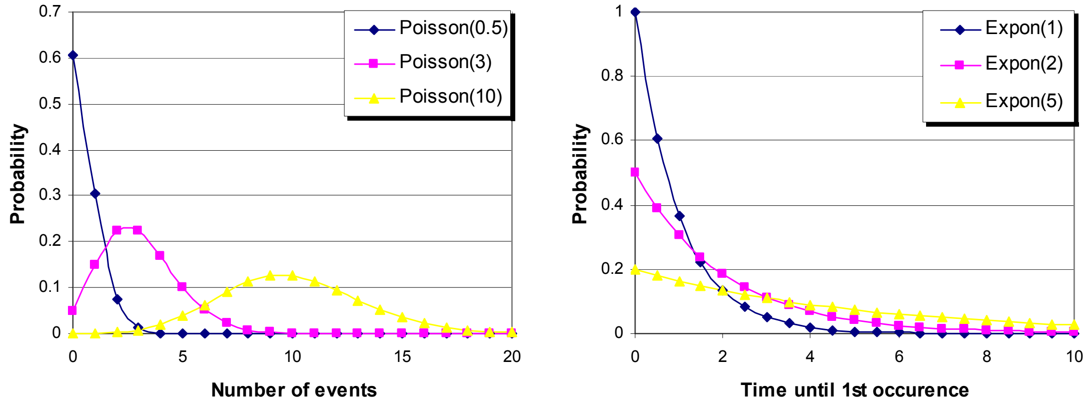

Figure B.1: *Examples of probability density function of Poisson distribution (left) and Exponential distribution (right)*

As part of the simulation process it has to be determined when a wind turbine will fail again after it has been restarted after the previous repair has been concluded, see Figure B.2.

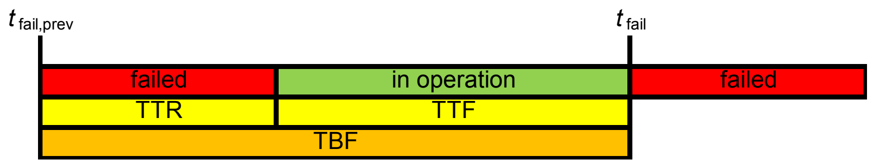

Figure B.2: *Definition of MTTR, MTTF and MTBF*

According to Figure B.2 is it expected that the next failure will occur at

$$t_{\text{fail}} = t_{\text{fail,prev}} + TTR + TTF \qquad \text{(B.3)}$$

where

$t_{\text{fail,prev}}$: the time the previous failure did occur

TTR: Time To Repair
TTR is dependent on the availability of resources (technicians, spares, and equipment). So TTR is a stochastic quantity, and its instantaneous value has to be determined as part of the simulation process

TTF; Time To failure
Within the OMCE-Calculator, the *TTF* will be set equal to the *TBF* which can be derived from the failure rate λ as follows:

$$TBF = \text{Expon}(1/\lambda) \qquad \text{(B.4)}$$

In fact λ is defined as the annular failure rate, hence $\lambda = 1/MTBF$ (*MTBF:* mean time between failures). The *MTBF* is connected to the *MTTR* (Mean Time To Repair) and the *MTTF* (Mean Time To Failure) as follows $MTBF = MTTR + MTTF$. The *MTTF* value represents the reliability of the turbine whereas the *MTTR* represents the adequacy of the maintenance strategy. The *MTTF* value should be the input value for the OMCE Calculator because the Time To Repair is determined by the selected O&M strategy and thus subject of investigation[10].

Wind turbine components fail typically say less than once per year (MTBF > 365 days) whereas the downtime per failure is typically 1 to 3 days (MTTR ≈ 2 days). So in general it can be said that:

$$\frac{MTTR}{MTBF} << 1 \tag{B.5}$$

and it is justified estimate the *TTF* by the *TBF* value.

The overall approach described above assumes that only one type of failure with failure rate λ can occur. In practice each component can fail generally in several ways, so several fault type classes should be distinguished. For this purpose a structural breakdown of the turbine has to be made identifying all fault types classes to be considered (see section 5.1.1). Each fault type class is assumed to occur independently and can be treated as above. However, during the simulation process it may occur that a failure for a certain fault type class is predicted to occur during the repair of a previous failure. In this case the failure time of this latest failure is postponed to the start up time following the ongoing repair, see Figure B.3.

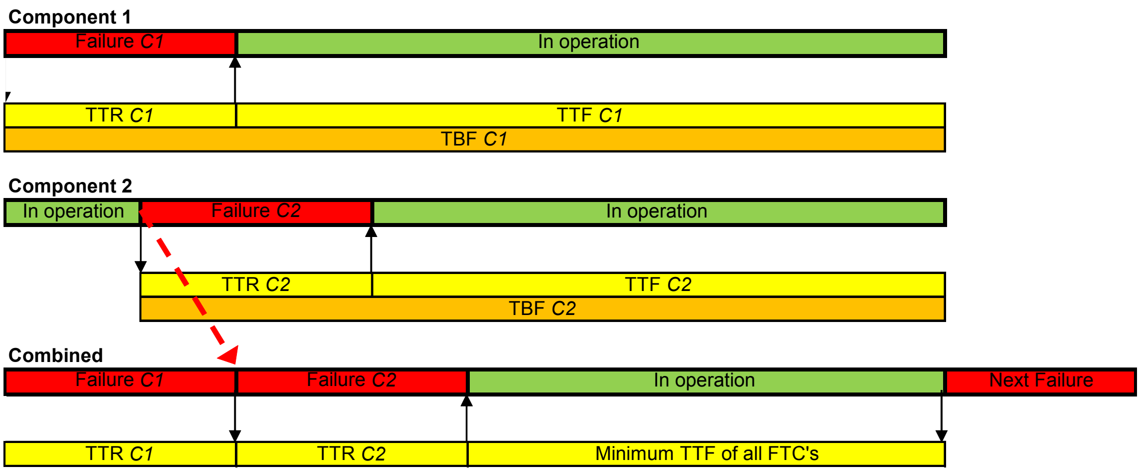

Figure B.3: *Illustration of two component failures and the delay in repair of component 2*

During the simulation process it is determined when the subsequent fault type classes are expected to occur. At the start of each simulation, for all fault type classes for each turbine the expected failure time is calculated by means of Eq. (B.2). Now for each turbine it can determined when this turbine will fail for the first time and in which fault type class this failure has to be categorized. After the repair for this FTC has been finished Eq. (B.1) is applied to calculate when this fault type class will occur next. Now again it can be determined when and how (i.e. which fault type class) this turbine will fail again.

10 When analysing O&M sheets to determine failure rates, the difference between *MTTF* and *MTBF* should be considered. Roughly, the *MTTF* value turbine equals the annual failure frequency of the turbine (*MTBF*) minus the annual average downtime. When drawing specifications for the Building Block "Operation & Maintenance" the authors will also pay attention to this.

B.2 Weather conditions

The weather conditions have a large influence on the O&M of offshore wind farms, because the wind farm is not always accessible due to bad weather conditions. In this section the effect of wind speed and wave height on the O&M of offshore wind farms is discussed. For some access systems, fog and visibility (e.g. helicopters) or tidal flows are also factors that limit accessibility. For the time being they will not be taken into account in the OMCE-Calculator. From experiences it is learned that historical data are hardly available as input for the model. If needed later on they can be added; the authors have the impression that the model does not have to be changed significantly.

Each phase of the maintenance process, as described in Appendix A, indicates that the whole process can roughly be divided into four basic phases with each a different duration:

1. Organisational phase: analysing the failure report generated by the wind turbine, or analysing results of previous phase (T_{org}):
2. Logistic phase: arranging crew, spare-parts and equipment (T_{log});
3. Waiting phase: waiting due to bad weather conditions (T_{wait});
4. Mission phase: actual maintenance mission ($T_{mission}$).

T_{wait} is determined by the statistical parameters H_s (significant wave height [m]) and V_w (average wind speed [m/s]), since these parameters are used to determine the accessibility.

Wave data

Irregular waves are a mixture of heights, periods, wave lengths and directions [B.2]. Statistical approaches should be used to describe these parameters and derive them from measured time series. Two measurement methods are commonly applied to record such time series and to determine the statistical parameter viz. the ship borne wave recorder and the wave rider buoy. Common practice to measure wave data is to measure time series with a length of fifteen minutes every three hours. More details on how short and long term wave data are being recorded and processed can be found in Appendix C.

For analysing the accessibility of offshore wind turbines, especially the once per three hours value of the significant wave height is of importance.

Wind data

Wind data are usually measured with cup anemometers. Usually time series are being recorded for 10 minutes. From these time series statistical data are derived, especially mean value, standard deviation, minimum and maximum values. Statistical parameters published by met-offices usually represent hourly averages. The hourly averages can be determined by using six 10-minute values in that hour, or if only one 10-minute time series per hour is measured, the hourly average can derived from this value, [B.3].

For analysing the accessibility of offshore wind turbines, the three hourly average values are needed.

Waiting Time

The waiting time, T_{wait} in the OMCE-Calculator can either occur at the beginning of a new repair or during an ongoing repair that has to be interrupted due to bad weather. After the logistic phase has been finished for a certain repair and all preparations have been completed (e.g. the crew, spare-parts and equipment have been arranged and are ready to start the repair) it may occur that the weather conditions are such that it is not allowed to travel to the failed turbine. Travelling and execution of maintenance can only be done under the condition that the weather conditions are suitable. The suitability of the weather conditions is determined by the equipment used to perform the maintenance and by the safety regulations (e.g. technicians are not allowed to work in the nacelle at high wind speeds). Usually equipment (vessels or helicopters) have requirements on the maximum allowed wind speed, wave height and, for helicopters, a minimum requirement on visibility. In case the wind speed or wave height is higher (or visibility is lower) than is allowed, the maintenance action cannot be started or continued and the equipment with crew (and spare-parts) will stay on stand-by in the harbour or will return to the harbour (or possibly hotel-boat). For a suitable weather window it is required that the actual weather conditions are more benign than the weather limits on wind speed and wave height, as is specified by the vessels.

For the determination of the waiting time two situations can be distinguished, viz.:

1. Maintenance phase that should be completed in one continuous operation, where during the whole operation certain limits w.r.t. wave height and wind speed should be fulfilled, f.i. the replacement of a main component for which a crane ship is being used. The limits determining the weather window may vary with time, f.i. during positioning of a crane ship limits for the wave height may be applicable while during hoisting only the wind speed is of importance.
2. Repairs that may be interrupted in which case one is looking for weather windows with a minimum length, such that within this weather window it is possible to travel to the wind farm and back to the harbour and to carry out some work, f.i. it may be required that at least during 2 hours work can be carried out the turbine (input parameter). In the OMCE-Calculator it is assumed that for repairs that do not need to be completed in one continuous operation the weather limits during travelling and during execution of work at the turbine are equal.

For situation 1 a weather window of a certain length has to be found during which the actual weather conditions are more benign than the weather limits on wind speed and wave height, as is specified by the vessels. The determination of the waiting time is illustrated using the simplified example presented in Figure B.4, which shows time series of wind speed (black solid line) and significant wave height (red solid line) data. The maintenance action is performed using equipment with a maximal allowable wind speed of 12 m/s and significant wave height of 1.5 m. These limits are indicated by the black and, respectively, red dotted lines. The maintenance action can only be performed if both wind speed and wave height are below their respective limits. The periods where this condition is met are indicated by the blue horizontal lines at the bottom of the graph. If a failure occurs at $t = 0$, which requires a repair mission of 40 hours, it can be seen that only after 96 hours a suitable weather window is found during which the repair mission is completed. In case the mission time would only be 20 hours, the waiting time would be 56 hours. So the stochastic nature of the waiting time is clear and when a failure occurs at another point in time probably other values for the waiting time would be found.

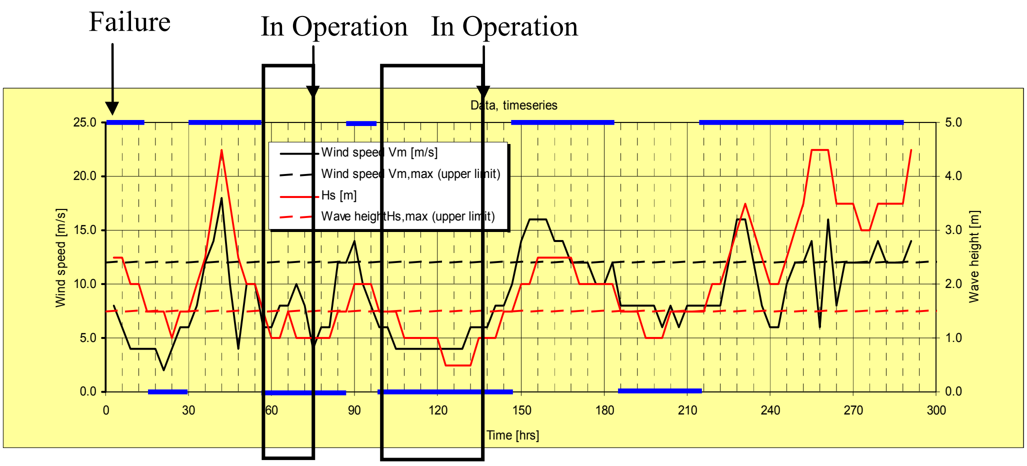

Figure B.4: *Example of determination of waiting time for a maintenance action that can be carried out if $H_s \leq 1.5$ m and $V_w \leq 12$ m/s and the duration is 20 hrs or 40 hrs.*

In the given example it is assumed that only one equipment is used and that the weather limits are constant in time (allowable wind speed of 12 m/s and significant wave height of 1.5 m). In the OMCE-Calculator it is possible to assign different types of equipment, where each equipment may have weather limits depending on the work carried out (travelling, hoisting, etc.). In this situation the limiting weather limits are characterised by the envelope covering all separate weather limits. Furthermore it is assumed that $T_{org} = T_{log} = 0$, while the repair could start immediately after the occurrence of the failure. In the OMCE-Calculator it is taken into account that work may be carried out during day time only and that the time to organise the subsequent activities need to be considered.

For situation 2 reference is made to Figure B.4 also, but now it is assumed that the repair may be interrupted, so the work can be distributed over a number of non successive days. Assuming a total travel time of 2 hours and a minimum period for working of 2 hours, weather windows have to be found with a minimum length of 4 hours. If a failure occurs at $t = 0$, and requires a repair time of 40 hours, it can be seen that the 1st part can be carried in the 1st low interval (between $t = 15$ and $t = 30$) and the work can be finalised in the 2nd low interval starting at $t = 60$. So the total waiting time is composed of 15 hours at start up and approximately 30 hours between the two periods. Also in this example it is assumed that $T_{org} = T_{log} = 0$, while the repair could start immediately after the occurrence of the failure. In the OMCE-Calculator it is taken into account that work may be carried out during day time only. Furthermore the time between the two periods during which work is being carried out is characterised as waiting time in the above example. In the calculator it is taken into account that during this period of waiting time also nights can be present during which in no case any work is carried out irrespective the weather conditions. So these night should not be included in the waiting time.

Remarks on weather forecast

In the process discussed above it has been assumed that the forecast of weather conditions has a reliability of 100%. In reality it might occur that a maintenance mission is postponed because weather conditions are expected to be unsuitable to perform the mission. It might be the case that afterwards it is discovered that the weather conditions were better than expected and the repair could have taken place. On the other hand a repair mission might be cancelled somewhere in the middle of the mission due to the weather conditions being worse than expected.

Both situations sketched above would lead to extra downtime. In order to judge whether the assumption of a 100% reliable weather forecast is reasonable it should be considered that the accuracy of a weather forecast decreases with the lead time of the forecast. A reliable forecast of the wind speed and wave height for the next 24 hours is reasonable to assume, whereas a forecast with a lead time of more than one week has a large uncertainty.

It has been discussed before that a maintenance mission consists of one or more phases. Not all phases have to be completed during one continuous operation, in fact, only the phase 'Replacement' has to be completed in one continuous operation (or over more than one working day, with the requirement that the weather conditions are suitable during a continuous period inside working hours). The other repair phases are assumed to be allowed to be performed over multiple working days. Therefore, generally only the weather forecast for the next 24 to 72 hours is of importance. As mentioned before, the short-term weather forecast is generally reliable and therefore the assumption of a 100% accurate weather forecast for the determination of waiting time can be justified.

B.3 Statistical uncertainty input data

In contrary to the inherent variability which is part of the process always, it is optional to take into account the statistical uncertainty of a number of input parameters. In the following sections three groups of parameters are considered.

Failure rate and number turbines for condition based maintenance
The failure rate λ denotes the expected number of failures per year and is specified at the level of fault type classes in conjunction with the structural breakdown of the wind turbine. Furthermore the failure rate may vary with location of the wind turbine within the wind farm. Dependent on the method the failure rate is being determined it will show more or less uncertainty.

To predict the O&M effort for the coming period the number of turbines for which condition based maintenance has to be carried out has to be specified. This has to be done for each type of maintenance when different types of condition based maintenance have to be carried out. For the coming next year the plans might be quite certain, but for the following years it might become more uncertain. To take into account this uncertainty for each type of condition based maintenance the number of turbines involved can be treated as a stochastic quantity, where the uncertainty can be specified per year (f.i. uncertainty for year 5 higher than for year 3).

At the beginning of each simulation the actual value of the failure rates of all FTC's specified and the number of turbines for which condition based maintenance has to be carried out and in which year, have to be generated by means of distribution functions specified.

Time related parameters
The following time related input parameters might optionally be treated as a stochastic quantity:
- logistic time of spare parts;
- re-ordering time of spare parts;
- the time for organizing the maintenance phases;
- mobilization and de-mobilization time of the equipment.

When one or more of these parameters are defined as stochastic the actual value to be applied has to be generated at the moment a new maintenance activity has to be added to the integral maintenance plan.

Cost related parameters
The following costs related input parameters might optionally be treated as a stochastic quantity:
- costs of spare parts;
- fixed costs of stock control;
- various costs of equipment;
- other costs (not defined yet).

The costs are being calculated at the end of the simulation based on the integral maintenance plan set up during the simulation. When one or more of these parameters are defined as stochastic the actual value has to be generated by means of the specified distribution function at the end of the simulation.

In case it is decided that an input parameter has to be treated as a stochastic quantity, the distribution function together with its parameters has to be specified in the input. At the moment during the simulation process a parameter has to be applied which has been characterised as stochastic a value will be generated by means of the distribution function specified.

B.4 References

[B.1] David Vose, Risk Analysis - A Quantitative Guide, John Wiley & Sons, Ltd.

[B.2] Crabb, J.A.: "*A Review of Wave Measurement and Analysis Methods Relevant to the Wave Energy Programme*"; Proceedings of the Wave Energy Conference, London, 22-23 November 1978.

[B.3] J. Wieringa en P.J. Rijkoort,: "*Windklimaat van Nederland*"; KNMI, Staatsuitgeverij, Den Haag, 1983

Appendix C Analysis of wave data

To record and analyse short- and long term wave data, roughly three steps can be distinguished.

1. *Analysing measured records:* The first step in the analysis is to determine a power spectrum, *S(f)*, of each measured time series using a Fast Fourier Transform (FFT) routine, which results in the energy contents as a function of the wave frequency. The area under the curve equals the variance of the signal and therefore the power spectrum is also called the variance spectrum. Since sea waves can originate from wind and swell, it s very likely that the power spectrum has two peaks, one at the frequency of the swell waves and one at the frequency of the wind waves. The variance of the wave record can also be determined directly from the recorded time series as follows:

$$\mathrm{var}(H) = \sigma_H^2 = \frac{\sum_{i=1}^{N} H_i^2}{N}$$

   where *N* represents the number of samples in a time series.

2. *Determination of statistical parameters*: Once the power spectrum *S(f)* has been recorded, some statistical parameters can be derived, viz. the significant wave height, H_s, and the energy period T_e. Both parameters are derived indirectly from the statistical moments of the power spectrum. The statistical moments are defined as follows for a discretised spectrum:

$$M_\mathrm{n} = \sum_{i=1}^{N} S(f_i)\cdot f_i^n \cdot \Delta f$$

   For an analytical expression of the power spectrum, the moments can be determined as follows:

$$M_\mathrm{n} = \int_0^\infty S(f)\cdot f^n \cdot df$$

   (Note: The first moment of a distribution, $n = 1$, corresponds to the mean value. The second moment, $n = 2$, corresponds to the variance, the third, $n = 3$, to the skewness, whereas the fourth moment, $n = 4$, corresponds to the kurtosis. For the analysis of wave data, $n = 0$ and $n = -1$ are also being used. $n = 0$ Corresponds to the area under the power spectrum, and $n = -1$ to the "mean value" if we put *T* on the x-axis instead of *f*.

   The significant wave height is defined as follows:

$$H_\mathrm{s} = 4\sqrt{M_0} = 4\sigma_H \quad (H_s \text{ is also called } H_{M0})$$

$$T_\mathrm{e} = \frac{M_{-1}}{M_0}$$

   Apart from the significant wave height and the energy period, other definitions are also being used to describe a certain sea state. A traditional definition closer to the intuitive idea of wave heights is that for the $H_{1/3}$ and $T_{1/3}$. $H_{1/3}$ is defined as the average height of the highest one third of the waves where "one third" refers to the third of the total number.(Not one third of the height; if a record contains for example 120 peaks, the $H_{1/3}$ is the average value of the 40 highest peaks.) For narrow band spectra, $H_{1/3}$ and $T_{1/3}$ are approximately equal to H_s and T_e respectively. $H_{1/3}$ and $T_{1/3}$ are unsatisfactory in practice since they cannot be related to any other wave parameter. Furthermore, we can define the "zero crossing period" T_z:

$$T_z = \frac{n_z}{D} = \sqrt{\frac{M_0}{M_2}}$$

   where n_z is the number of times the water surface moves through its mean level in upwards direction in a record of duration *D* seconds.

Long term wave data: Long term storage of wave data is usually being done by filling a so called scatter diagram. This is a matrix with the energy period on the x-axis, and the significant wave height on the y-axis and each partition of the matrix corresponds to a certain value of H_s

and T_e. Each wave record of lets say 15 minutes results in certain values of H_s and T_e. The numbers of occurrences of combinations of H_s and T_e are recorded in the scatter diagram; sometimes as a percentage of a whole year or of a season, and sometimes as a fraction of e.g. 10.000 wave records. It should be noted that when storing only H_s and T_e in the scatter diagram, information is lost about the shape of the spectra.