ECN
Energy research Centre of the Netherlands

Operation and Maintenance Cost Estimator (OMCE)

Final Report

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we@sea

Acknowledgement/Preface

This report is written in the context of the project "*Operation and Maintenance Cost Estimator*", which is carried out within research line 5 (RL5) of the Dutch research program We@Sea. The aim of this project is to develop a methodology for owners and operators of offshore wind farms to better estimate and control the future O&M costs taking into account operational experience.

In addition to We@Sea, who has partly financed this work also Nordex AG is thanked for supplying the required information of the Nordex N80 wind turbines. The project made use of the Nordex N80 wind turbines located at the ECN Wind turbine Test site Wieringermeer (EWTW). EWTW supplied maintenance sheets, SCADA data, and PLC data to the project team for further processing and enabled various measurement campaigns.

Finally, the authors want to thank Noordzeewind and SenterNovem for providing O&M and logistics data of the Offshore Wind farm Egmond aan Zee.

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Summary

As part of the We@Sea funded project OMCE (Operations & Maintenance Cost Estimator) a model has been developed which can be used to determine the future O&M effort with associated costs of offshore wind farms during their operational phase. This model describes how the O&M effort and associated costs for the coming period can be calculated taking into account the operational experience available at that moment, where the uncertainty in the predicted values is of great importance also.

The OMCE consists of two parts: (1) the OMCE Building Blocks to process the operational data, and (2) the OMCE Calculator to assess the future costs.

1) The OMCE requires feedback of operational data of a specific wind farm under consideration, such as O&M data, data from load measurement campaigns, SCADA data, and data from condition monitoring programs. Data about failures, repair actions, the vessel usage, spare parts, and weather conditions are analysed to estimate the effort for unplanned corrective maintenance. Data from condition monitoring and load measurements are analysed to estimate the effort for condition based maintenance. For this purpose five so called OMCE Building Blocks (BB) have been specified, each covering a specific data set.

- BB *Operation and Maintenance*
- BB *Logistics*
- BB *Loads & Lifetime*
- BB *Health Monitoring*
- BB *Weather Conditions*

The main objective of these building blocks is to process all available data in such a way that useful information is obtained.

2) The OMCE Calculator will be used to asses the O&M cost for the coming period of say the next 1, 2 or 5 years, based on the results of the BB's. The OMCE calculator considers three types of maintenance: (1) unplanned corrective maintenance (2) condition based maintenance, and (3) calendar based maintenance.

The We@Sea project has resulted in the specifications for the BB's, the OMCE-Calculator and the model description of the OMCE-Calculator. For the development of the BB's data from onshore and offshore data has been used.

This report describes the principles for modelling O&M costs for offshore wind farms, the development of the OMCE model, and summarises the specifications of the BB's and the OMCE-Calculator model. Furthermore in Annex A the report briefly discusses the execution of the project itself, compares the results with the initial objectives, and indicates the deviations from the original plans.

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1. Introduction

1.1 Background

In 2004, 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 determine the costs of O&M for the next coming years. The inspiration for this development was partly based on a question of an operator: *"Can you tell us how many gearboxes we need to replace in the next two years and how much will it cost?"* It was clear that this question was very relevant, but very difficult to answer. It was also clear at that stage that ECN could not develop such a tool on its own. Input and contributions from potential users and parties experienced in O&M was necessary.

Therefore in 2004 a consortium was established with partners of the We@Sea consortium: ECN, NUON, Fabricom Oil & Gas, Shell Wind Energy, Vestas Nederland, Delft University of Technology, and KEMA. A summary of the work program as contracted in 2005 and the results and deliverables per work package can be found in Appendix A.

The background and objectives of the OMCE project are explained in more detail by means of Figure 1.1 which shows the costs for corrective maintenance over the lifetime of a turbine from the owner's perspective. The data are derived from the WMEP data base in 2002 and represents turbines up to 1 MW. Although the data are not derived from wind turbines in the Multi MegaWatt class, the graph clearly shows that until the end of the warranty period turbine owners are not confronted with costs for corrective maintenance. At the end of the warranty period and even more at the end of the period with extended service contracts (often after year 5) the turbine owners need to reserve budgets for future O&M costs. As can be seen in Figure 1.1 the costs can strongly vary over time and vary from turbine make to turbine make. The objective of the OMCE is to estimate these future O&M costs more accurately and to quantify the uncertainties. In Figure 1.1 this is illustrated with the red dashed area. Operational data and O&M data collected during the first few years of operation can be used for more accurate estimates.

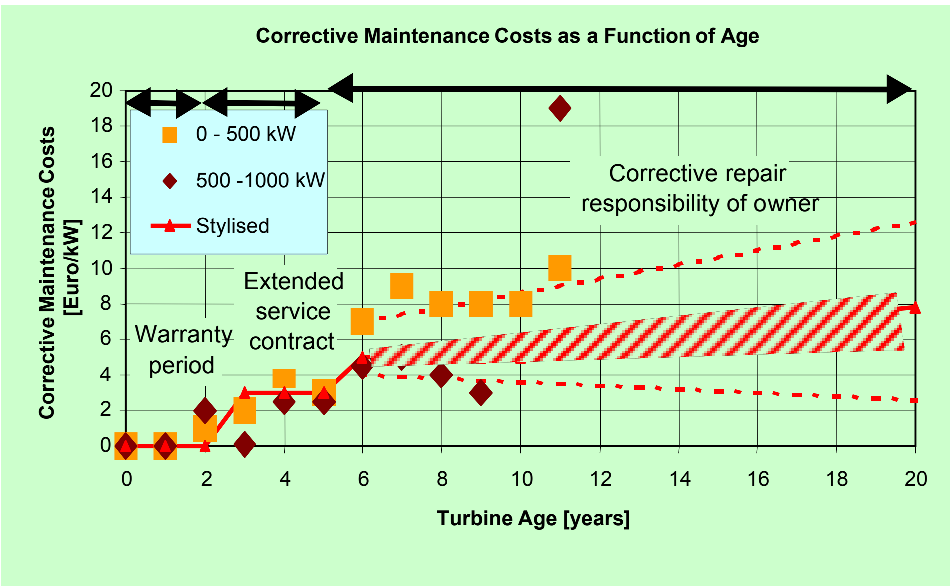

Figure 1.1: *Development of the costs for unplanned corrective maintenance in the different stages of the lifetime [40]*

1.2 The OMCE project

The OMCE project was initiated in 2004 with the following partners: ECN, NUON, Fabricom Oil & Gas, Shell Wind Energy, Vestas Nederland, Delft University of Technology, and KEMA.

The project consisted of 8 work packages.

- WP 1. Cost modelling (Planning Phase)
- WP 2. Wind farm modelling (Planning Phase)
- WP 3. Decision support system for operation and maintenance actions (Operational Phase – Short term)
- WP 4. Data collection and analyses (Operational Phase – long-term)
- WP 5. Contracts (Operational Phase – long-term)
- WP 6. Wind farm effects and loads (Operational Phase – long-term)
- WP 7. Development of Operation and Maintenance Cost Estimator
- WP 8. Project Coordination and Dissemination of Results

In fact the first 6 work packages were defined to carry out research in order to obtain sufficient knowledge and information to develop the OMCE in WP 7. The background research carried out in the first 6 work packages will be mentioned only briefly in this report. The emphasis is on the results of WP 1 and WP 7.

In WP 1 the first version of the already existing ECN O&M Tool has been used to model the O&M aspects of a (fictitious) offshore wind farm in the North Sea. Based on the experiences with this model and based on the use of the O&M Tool for commercial purposes, two updates have been released in WP 1. In this report the ECN O&M Tool and the modelling approach will be discussed. The ECN O&M Tool can be considered as the predecessor of the OMCE Calculator and the description of the modelling approach clarifies why several assumptions and approaches have been chosen for the OMCE Calculator.

The output that is most relevant for the OMCE project has been obtained in WP 7, namely the actual development of the OMCE structure, the functional and technical requirements and the model description. The Operation and Maintenance Cost Estimator (OMCE) developed in WP 7 consists of two parts: (1) the OMCE Building Blocks to process the operational data, and (2) the OMCE Calculator to assess the future costs.

1) The OMCE requires feedback of operational data of a specific wind farm under consideration, such as O&M data, SCADA data, data from measurement campaigns, and data from condition monitoring programs. Data about failures, repair actions, the vessel usage, spare parts, and weather conditions are analysed to estimate the effort for unplanned corrective maintenance. Data from condition monitoring and load measurements are analysed to estimate the effort for condition based maintenance. For this purpose five so called OMCE Building Blocks (BB) have been specified, each covering a specific data set.

- BB *Operation and Maintenance*
- BB *Logistics*
- BB *Loads & Lifetime*
- BB *Health Monitoring*
- BB *Weather Conditions*

The main objective of these building blocks is to process all available data in such a way that useful information is obtained. (The BB "Weather Conditions" has not led to a research task within the OMCE project since it only requires on site measurements of wind and wave conditions. This BB will therefore not be discussed furthermore in this report.)

2) The OMCE Calculator will be used to asses the O&M cost for the coming period of say the next 1, 2 or 5 years, based on the results of the BB's. The OMCE calculator considers three types of maintenance: (1) unplanned corrective maintenance (2) condition based maintenance, and (3) calendar based maintenance.

In this report, the following results will be described.

- The structure of the OMCE Calculator

- The functional specifications of the OMCE Calculator
- The technical requirements of the OMCE Calculator
- The model description of the OMCE Calculator
- The technical specifications of the OMCE Building Blocks
- Specifications for the "Event List" to structure raw data before they can be processed by the BB's

The OMCE project started 1 November 2004 and was supposed to end at 30 June 2007. Unfortunately until 30 June 2007 none of the partners was able to submit Operation & Maintenance data and logistics data of an existing wind farm which was necessary to develop the OMCE Building Blocks. First half of 2007 it became clear that a useful data set of the OWEZ wind farm (Offshore Wind farm Egmond aan Zee) would become available in 2008. It was therefore agreed with the We@Sea management to postpone the end date until 31 December 2008. At the end of the project, the partners concluded that indeed the OWEZ data set was essential for the development of especially the Building Block "Logistics".

Details on the progress and results per work package can be found in Appendix A.

2. Cost Modelling

2.1 Offshore wind farms and their 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 20 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 the total installed capacity will be 200 to 500 MW. New and innovative substructures are presently being developed to enable wind turbines to be sited in deeper waters and to lower the installation costs.

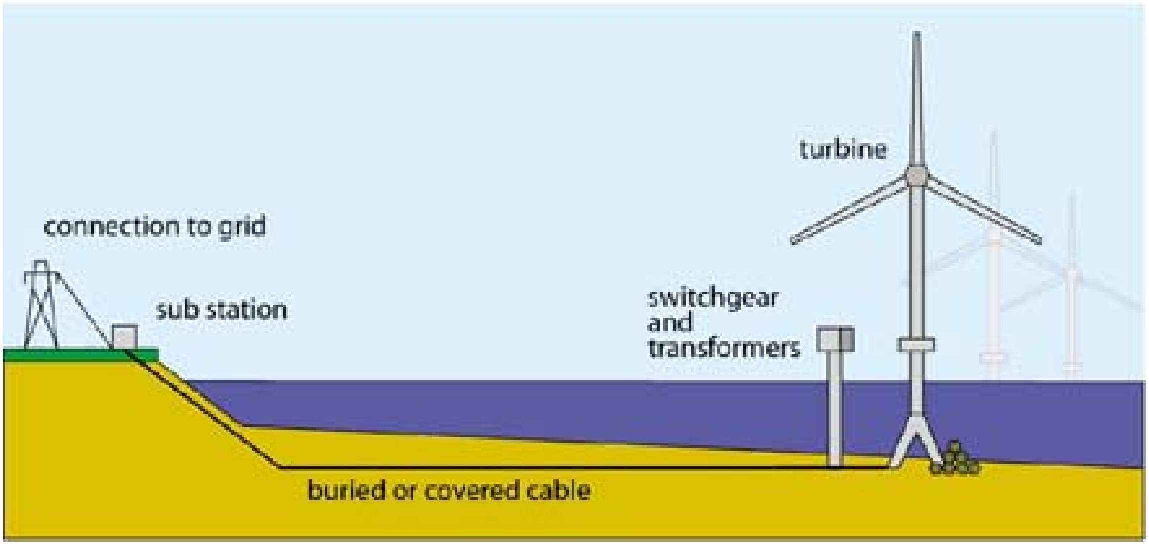

Figure 2.1: *Typical lay-out of an offshore wind farm (http://www.offshore-sea.org.uk/site/)*

All systems and components within the wind farm need to be maintained. Typically, turbines are being visited twice a year and each visit has a duration of 3 to 5 days. 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. 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 2.2.

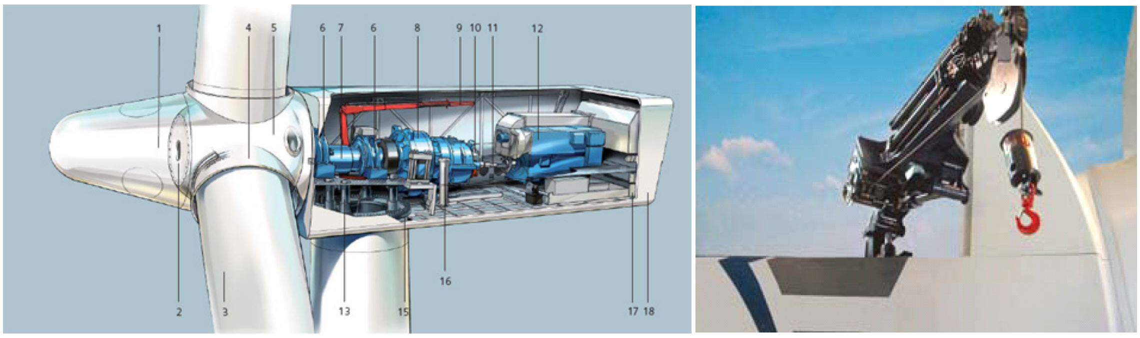

Figure 2.2: *Examples of internal cranes in the Siemens 3.6 (left) and Repower 5M (right) turbines*

- **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. The maintenance activities and replacement of large components van 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 2.3. 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 2.3 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).
- **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 2.4.

Figure 2.3: *Examples of transportation and access equipment for maintenance technicians; clockwise: Windcat workboat, Fob Lady, helicopter, and SWATH boat*

Figure 2.4: *Examples of external cranes for replacement of large components; Jack-up barge ODIN (left) and crane ship Sea Energy (right)*

2.2 Types of maintenance

At a general level, maintenance can be subdivided into preventive and corrective maintenance. Corrective maintenance is performed after a breakdown or an obvious fault has occurred. Preventive maintenance is intended to prevent equipment breakdown and consists of repair, service, or component exchange. Preventive and corrective maintenance can be split up further. For wind turbine technology the following subcategories seem to be appropriate, cf. Figure 2.5 .

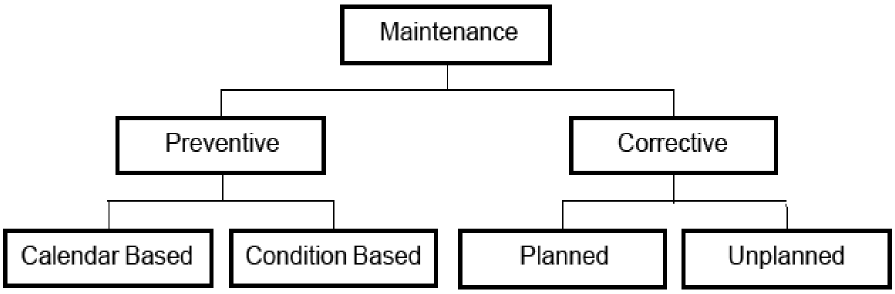

Figure 2.5: *Schematic overview of different maintenance types*

- Preventive maintenance:
  - Calendar based maintenance, based on fixed time intervals or on fixed numbers 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 failure is expected in due time and should be maintained before it occurs);
  - 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.

2.3 Modelling approaches

An inventory of existing tools for modelling the O&M aspects of offshore wind farms has resulted in the following list.

- CONTOFAX from the Delft University of Technology [43]
- O2M from Garrad-Hassan [42]
- BMT SLOOP from BMT [www. bmtrenewables.com]
- ECN O&M Tool from ECN.

Such models are often based on Monte Carlo analysis with turbine failures occurring on a stochastic basis. Delays associated with poor weather are simulated using a statistical wave module based on spectral analysis. Wave heights are correlated with wind speeds such that the effect of poor accessibility during periods of high wind is captured in the calculation of lost production revenue.

The ECN O&M Tool [7], [43] works differently. It is intended to be used in the planning phase of an offshore wind farm and should be used to determine the long term annual average costs, downtime, and revenue losses. The ECN O&M Tool in fact is the only tool that has received a validation statement from the certifying body Germanischer Lloyd, see [7], and this tool will be discussed in more detail in the following sections.
In fact all models have in common that most emphasis is put on modelling the unplanned corrective maintenance aspects as:

*Annual O&M costs = Annual failure frequency of components * Repair costs.*

The repair costs consist among others of the costs for personnel, equipment, spare parts, and revenue losses.

2.4 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 2.6. 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.

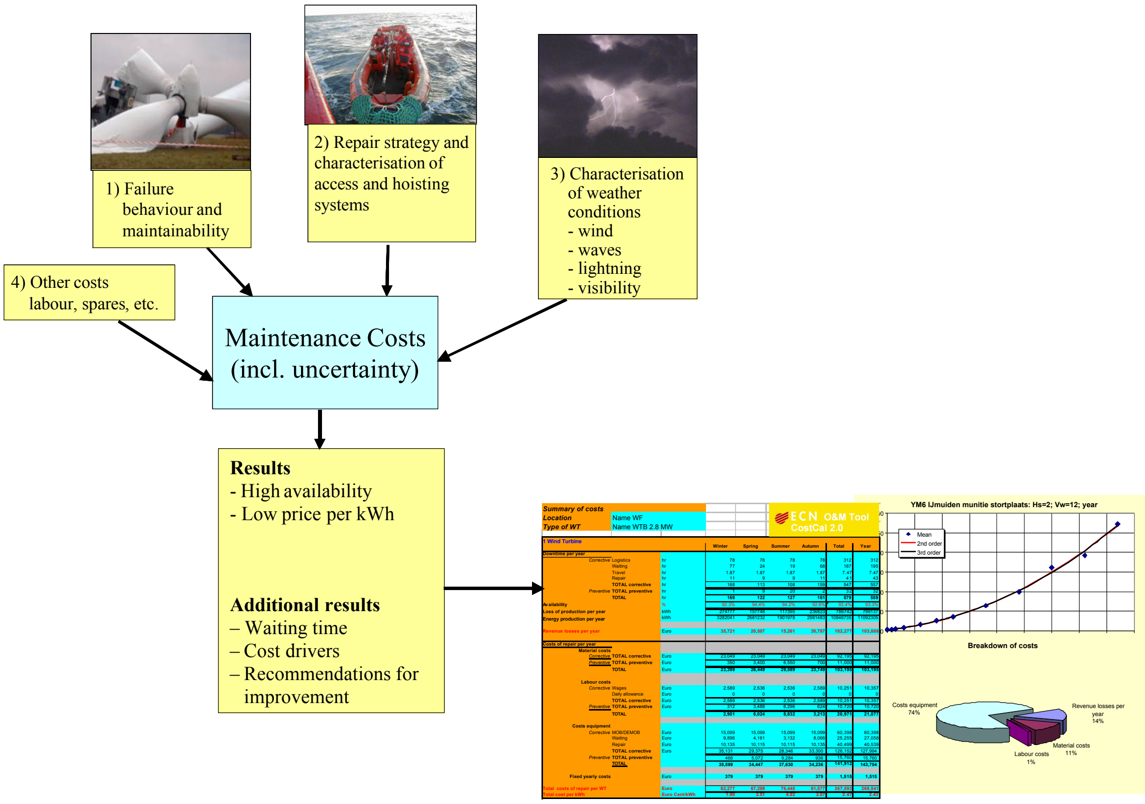

Figure 2.6: *Schematic representation of the ECN O&M Tool for determining the O&M costs and downtime of an offshore wind farm.*

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 2.7. 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 2.7). 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.

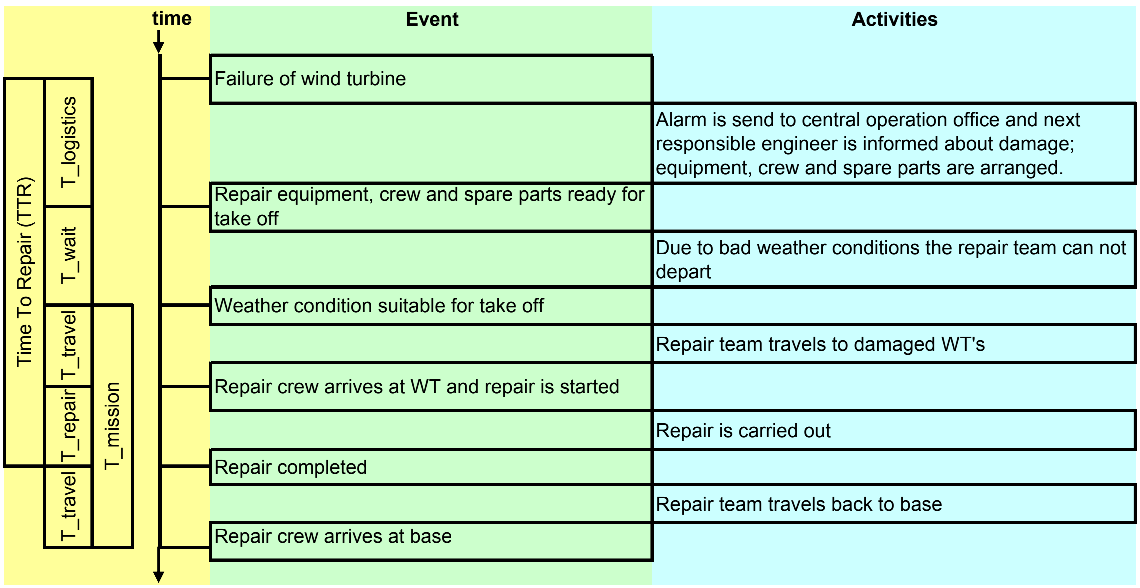

Figure 2.7: *Repair process*

The ECN O&M Tool 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.

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 2.8 an example is given of such a polynomial.

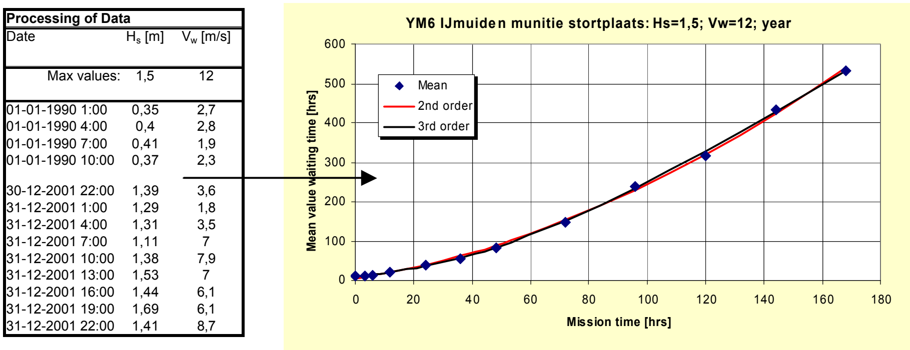

Figure 2.8: *Example of determining relationship between average waiting time and mission time*

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 Hs and Vw.

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 (e.g. [40]), 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 2.1.

Table 2.1: *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 2.2. 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 2.8). 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 2.7). 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 2.9. 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 2.3. The program also generates plots and pie charts to determine e.g. cost drivers or aspects that dominate downtime, see Figure 2.10. 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 [44] 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 2.11.

Table 2.2: *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.

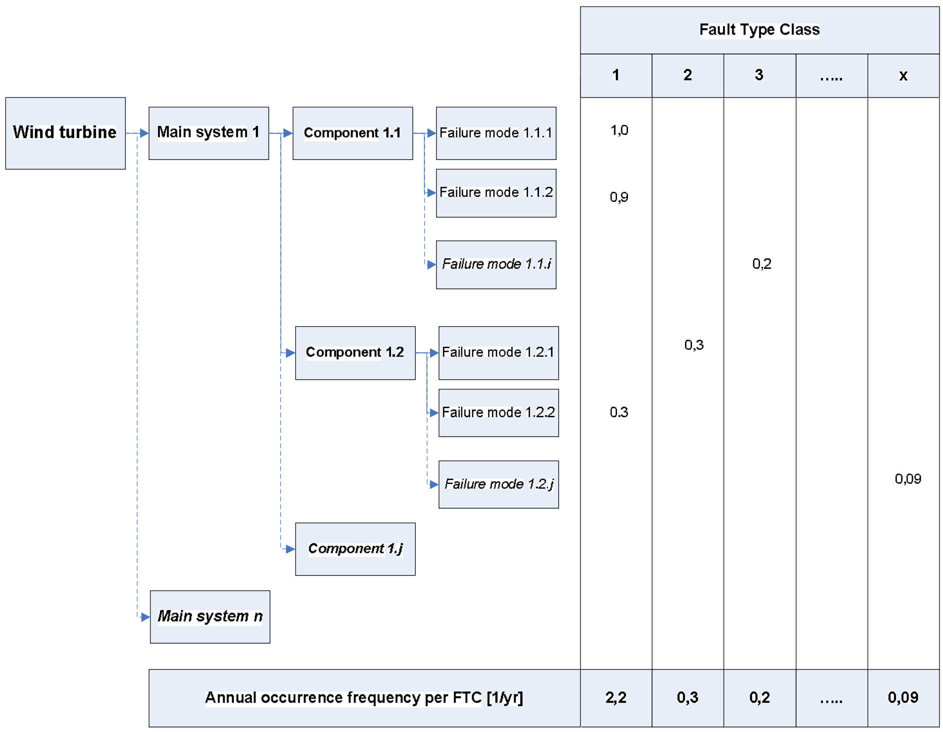

Figure 2.9: *Process of grouping small and severe failures into manageable set of FTC's*

Table 2.3: *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**

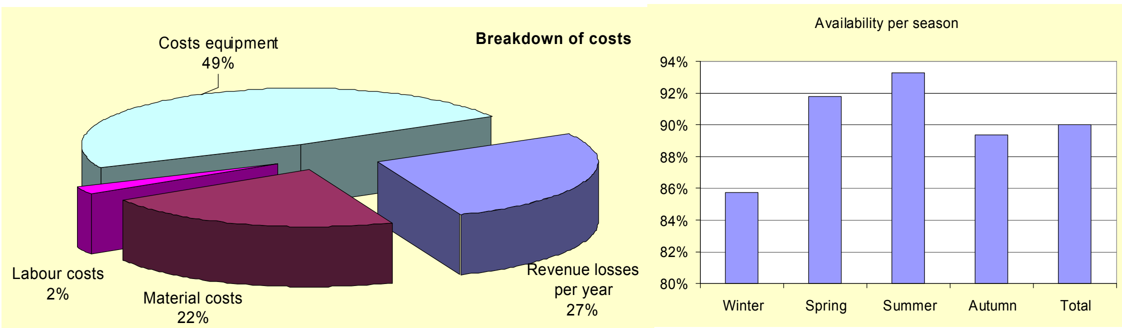

Figure 2.10: *Example of model output (graphs and pie charts)*

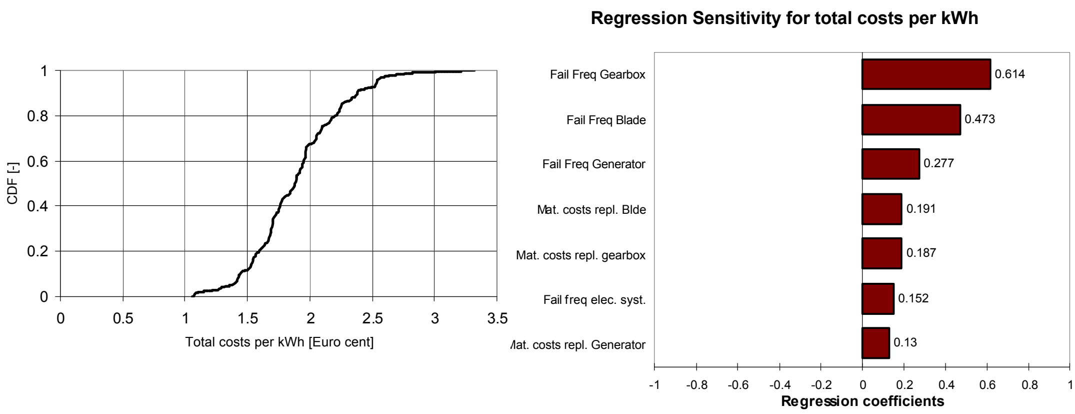

Figure 2.11: *Example of CDF and tornado diagram*

3. OMCE Concept

3.1 Structure

The structure of the OMCE is simplified presented in Figure 3.1. The OMCE consists of two parts: (1) the OMCE Building Blocks to process the operational data, and (2) the OMCE Calculator to assess the future costs.

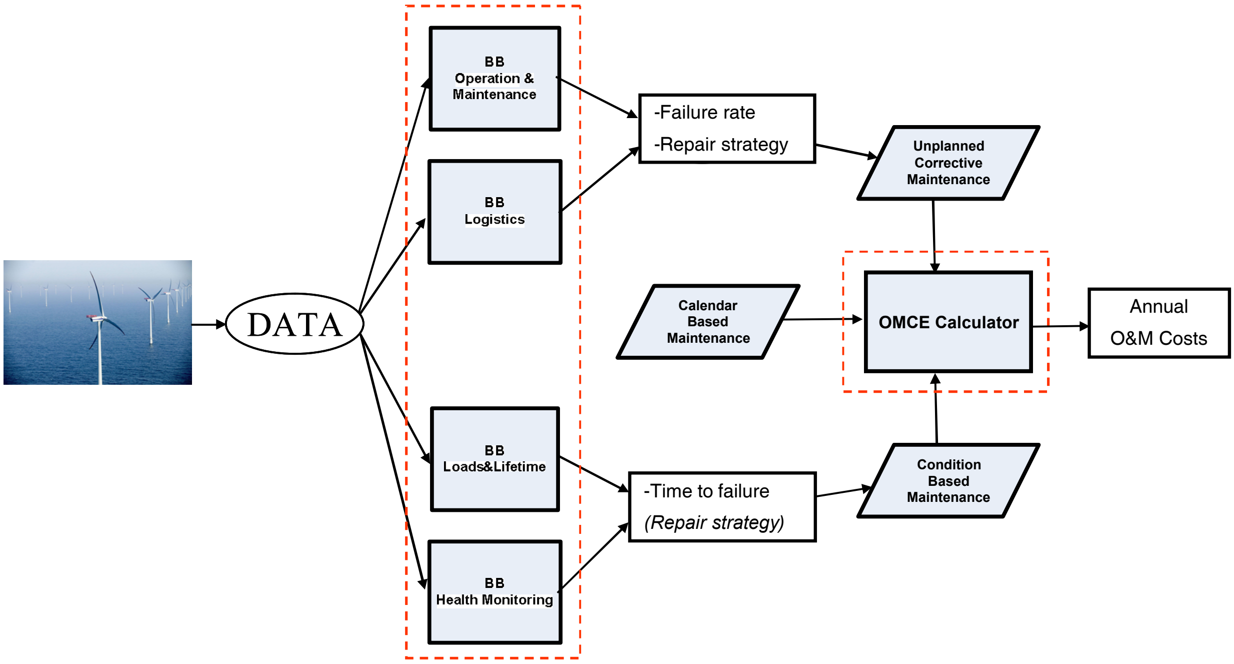

Figure 3.1: *OMCE concept showing the data flow from "raw data" to estimated O&M costs*

The OMCE Calculator requires information on three types of maintenance in order to estimate the near future O&M costs.

1. Calendar based maintenance: the effort and cost are usually determined by one or two visits per year. After 3 or 4 years the calendar based maintenance costs can be somewhat higher due to e.g. oil changes in gearboxes. The input for calendar based maintenance is determined as the number of repair days with associated costs for labour, equipment, spares, etc. and usually derived from the service manuals with prescribed intervals and procedures.

2. Unplanned corrective maintenance: Costs due to random failures 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. The input for estimating the effort for unplanned corrective maintenance is based on the failure rates of components and the associated repair costs (mainly equipment, personnel, spares, consumables, revenue losses)

3. Condition based maintenance: It might be that major overhauls have to be carried out, for instance due to unexpected wear out of components designed for the lifetime (e.g. replacement of gearboxes or pitch drives). This type of maintenance is not foreseen initially, but when it has to be carried out during lifetime it generally will be planned, hence it is categorized as condition based maintenance. The input for estimating the effort for condition based maintenance is derived from the number of components that are expected to fail in the next coming year(s) and the associated repair costs. The assessment if components are about to fail should come from a.o. inspection results or condition monitoring measurements.

In the OMCE structure it is foreseen that the data relevant for estimating the effort and costs for all three types of maintenance can be derived from data that are generated by the wind farm during its operation. The OMCE structure as summarised in Figure 3.1 is shown in more detail in Figure 3.2.. It is essential that the raw data from the wind farm are processed to provide information that can be used as input for the OMCE Calculator. Within the OMCE structure, Building Blocks are specified to transfer raw data into meaningful information.

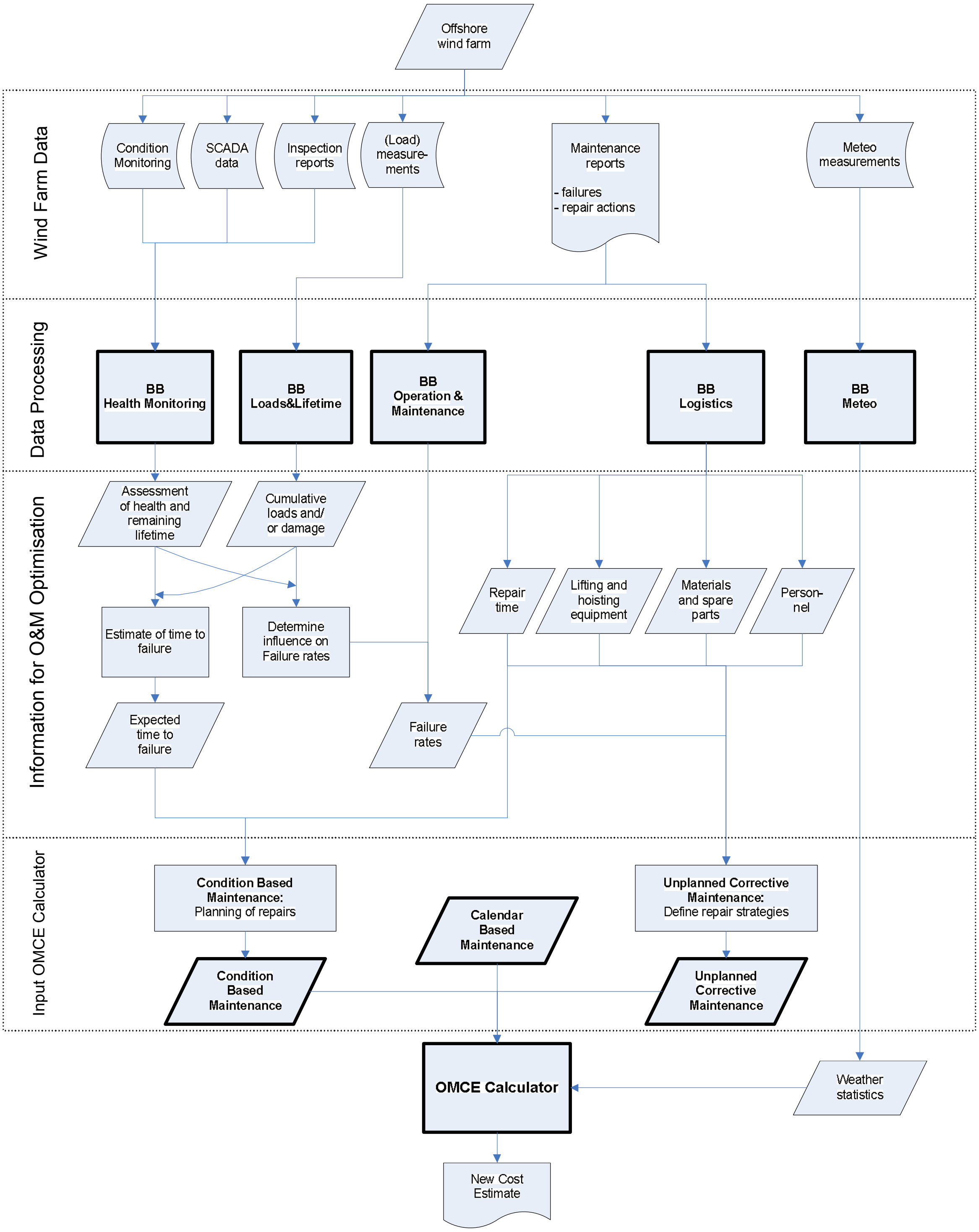

Figure 3.2: *Detailed Structure for the O&M Cost Estimator*

3.2 Functional Specifications

The OMCE structure as described in the previous section has been based on the requirements that (1) a calculation tool should be available to estimate the future O&M costs for three types of maintenance and (2) that operational data of the wind farm under consideration should be used as input. In addition to these requirements some functional requirements have been defined within the OMCE project in collaboration with potential users of the OMCE. Some of them are mentioned below (in random order).

- The results of the cost estimates are going to be used among others to:
  - decide how to continue with O&M after expiration of the warranty period;
  - make reservations for future O&M costs;
  - change and improve the initial O&M strategy if operating experiences give reasons to do so;
  - assess the profitability of the wind farm if it is going to be sold to another investor.
- The cost estimates of the OMCE should focus on three time windows: 1 year, 2 years, and 5 years.
- The OMCE-model should be usable for optimisation of the logistic aspects of O&M of off-shore wind farms.
  - The user of the OMCE wants to make trade-off studies in order to investigate whether it is worthwhile to invest in buying certain vessels instead of renting them. It should also be possible to determine the optimal (with respect to O&M costs), number of vessels to buy or to hire for a longer time.
  - Users want to use the OMCE to determine whether it is beneficial to have spare-parts for certain components in stock (e.g. in the harbour, at the transformer station or in the factory), and if so, the optimal number of each component that should be kept in stock.
  - The wind farm owners are interested in evaluating the effect of different maintenance strategies on the downtime and costs of their offshore wind farm. As a result it should be possible to implement various maintenance strategies in the OMCE. One can think of: clustering of repair actions, splitting of repair actions if it takes longer than one day, and the use of hotel boats or platforms to stay overnight.
- It should be possible to not only model the O&M aspects of the wind turbines but also of the substructures and the electrical infrastructure.
- The output of the OMCE and the presentation of the results should comprise the same tables, graphs, and charts as for the ECN O&M Tool (see also Section 2.4), including the results of uncertainty analyses. In addition, the users would like to see graphs where costs and downtime are presented as a function of the available number of equipment, spare parts, or stock control strategy.
- The output of the OMCE Building Blocks should be in such a format that it can be easily used as input for the OMCE Calculator.
- The OMCE should take into account the fact that different vessels and crane ships carry out work simultaneously but each have their own weather windows.
- It should be possible for the user to prioritise which type of maintenance is carried out first in case the number of vessels and/or spare parts is too limited to carry out all maintenance actions simultaneously.

4. OMCE Calculator

The OMCE-Calculator is the tool that actually runs the simulations to estimate the future O&M effort (mainly costs and downtime) for the offshore wind farm. As opposed to the ECN O&M Tool (see also Chapter 2) which is applied in the planning phase of a wind farm, an uses long term average values as input, the OMCE-Calculator will be applied during the operational phase of a wind farm, and uses acquired operational data of the specific wind farm as input. The structure of the simulation program is given in Figure 4.1.

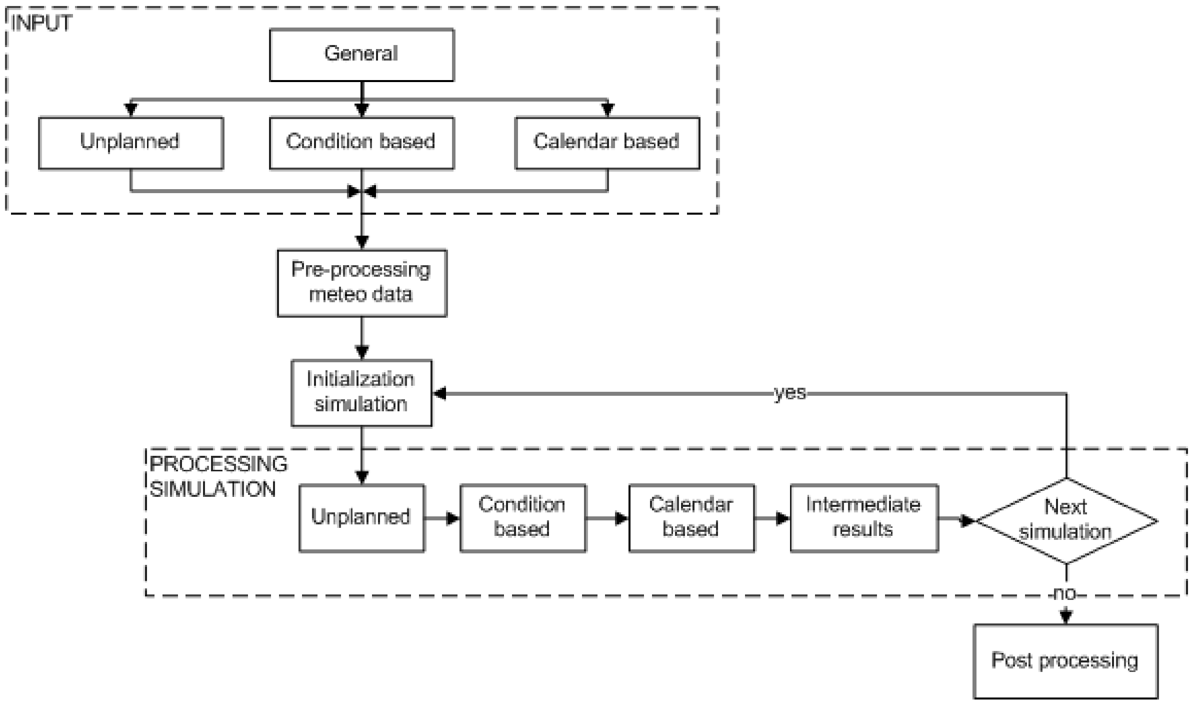

Figure 4.1: *Overall structure of OMCE-Calculator*

The OMCE Calculator is a time simulation model and is able to model three types of maintenance: calendar based, condition based and unplanned corrective. When defining the different maintenance actions, the user should do the following.

- Group all possible maintenance activities into a limited and manageable number of Fault Type Classes (FTC's).
- For unplanned corrective maintenance failure rates should be assigned to the individual components and systems.
- 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;
  - Priority Level: needed to determine which repair is carried out first in case simultaneous repairs are not possible due to lack of resources.
- Each Repair Class can be separated into different phases: inspection, replacement, and repair. The sequence and number of sub-phases can be defined by the user to a large extent. An example is shown in Figure 4.2.
- For each phase the following aspects need to be defined: lead time (or: time to organise), duration, equipment needed (with all its characteristic values), and the crew size. To assist the user in defining the repair classes and different phases a user friendly input sheet has been designed, see Figure 4.3.

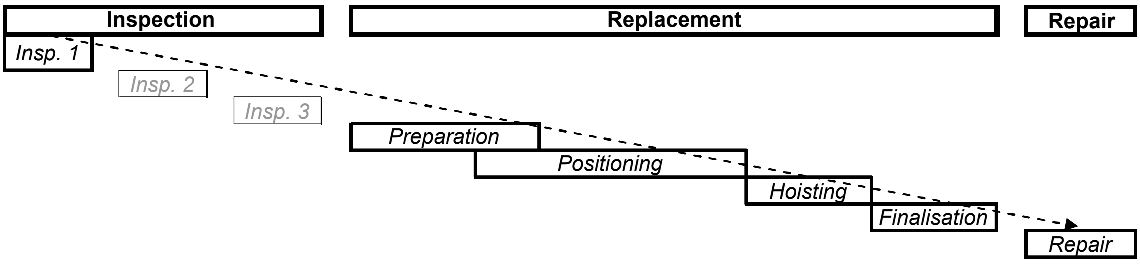

Figure 4.2: *Schematic representation of the possible maintenance phase and their sub-phases*

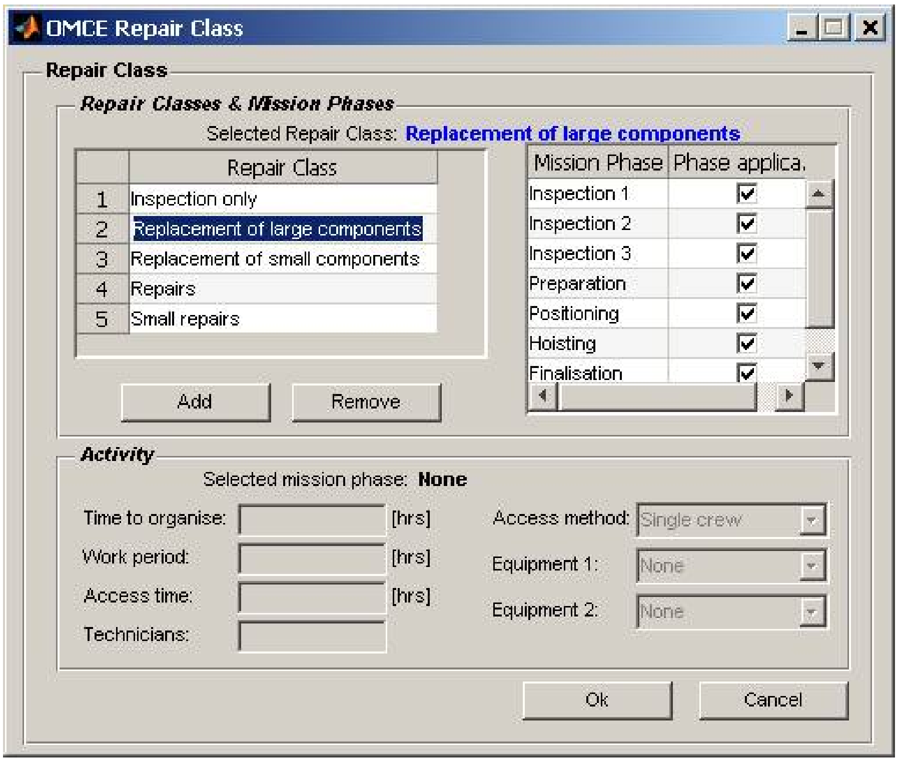

Figure 4.3: *Example of screen to define repair class "replacement of large components"*

- For the Spare Control Strategy the user should define if stock control is applicable and if so also the number of spares on stock, the delivery time and the re-ordering time.
- By means of defining Priority Levels, the user determines which type of maintenance is carried out first in case the number of vessels and/or spare parts is too limited to carry out all maintenance actions simultaneously.
- Finally, the user should input the local wind and wave conditions.

With the input data defined by the user, the OMCE-Calculator starts the simulations as shown schematically in Figure 4.1. The results are stored in files and a post processor is designed to analyse the results and make the tables, graphs, and charts as required with costs, downtimes, cost drivers, and uncertainties. An example is given in Figure 4.4.

Within the OMCE project, the functional and technical specifications of the OMCE Calculator have been described and the model for the OMCE Calculator has been designed and documented. The actual programming of the model, most likely in MatLab, is beyond the scope of the project.

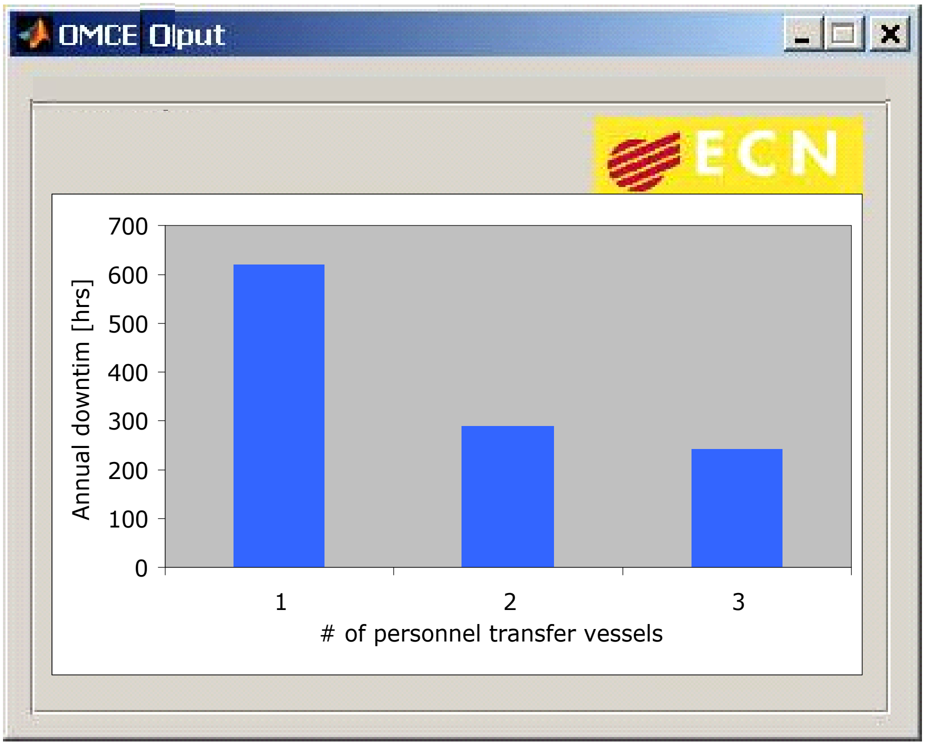

Figure 4.4: *Example of graph showing the influence on the downtime of having 1, 2, or 3 vessels available for inspections. In this specific case investing in more vessels would not make sense.*

5. Building Blocks

Five OMCE Building Blocks (BB) have been specified to process all available data generated by an offshore wind farm in such a way that useful information is obtained, each covering a specific data set.
- BB *Operation and Maintenance*
- BB *Logistics*
- BB *Loads and Lifetime*
- BB *Health Monitoring*
- BB *Weather Conditions*

5.1 BB Operation and Maintenance

The failure frequencies of the different wind turbine components have a significant influence on the O&M costs of an offshore wind farm. In the planning phase the estimate of the failure rates of the different wind turbine components is usually based on generic reliability data, which often shows differences with the 'experienced' failure rates on an offshore wind farm. In order to make a more accurate estimate of the O&M costs it is required to study the experienced maintenance need to determine whether the original assumed failure frequencies are in accordance with the 'experienced' failure frequency. Within the OMCE concept, the BB "Operation and Maintenance" is developed to feedback the relevant data. 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 (mainly failure frequencies of the different wind turbine components) should be updated or not. In fact the purpose of the BB is two fold:
1. generating information about the failure behaviour of the components among others to assess the adequacy of the maintenance strategy, e.g. by means of trend analyses and ranking of failures;
2. generating updated figures of the failure rates (and failure modes) and repair actions of components to be used as input for the OMCE Calculator.

Based on the ECN Maintenance Manager project [8], [15], [16], [17] a database structure has been developed to collect the maintenance information from wind turbines in a systematic manner. The database is specific for a certain turbine type because it contains the detailed breakdown of the turbine. The breakdown includes the failure classes and predefined repair classes. It is important that pre-defined answers are defined in this database, so that processing of the data can be automated. For this a breakdown of the turbine into main systems and subsequently in components has to be made:

Wind farm
- ↳ Wind Turbine
  - ↳ Main Systems
    - ↳ Components
      - ↳ Failure Modes
        - ↳ Repair Actions

For each separate component the possible failure modes and repair actions have to be specified beforehand to minimise the free format for description of the failures. This can be done by means of a Failure Mode and Effect Analysis (FMEA). In order to perform the required analyses, it is essential that for each maintenance action at least the following parameters should be registered:
- Report ID;
- Wind farm ID and/or name;
- Turbine ID and/or name;
- Date and time the turbine stopped;
- Date and time the turbine was re-started after the failure;
- The system and component the maintenance action is performed on;

- The failure mode the failure can be categorised in;
- The type of repair carried out.

An example of a registration form of a database for failure collection is shown in Figure 5.1.

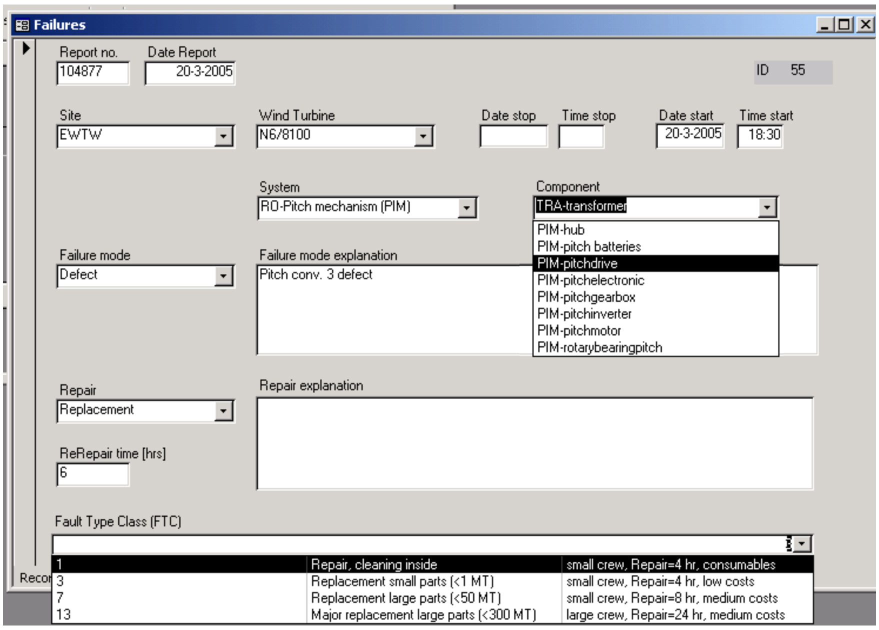

Figure 5.1: *Example of a database for failure collection. Using a breakdown of the wind farm predefined answers are defined, which enables systematic collection of wind turbine failures.*

The building block 'Operation & Maintenance' analyses the maintenance data stored in the database for failure collection in order to quantify the 'experienced' failure frequencies.

In Figure 5.2 an example is presented from the analysis of maintenance reports. In the top figure the distribution of the failures over the main systems of the turbine in question is shown. In the lower figure, the largest contribution to the failures is analysed using a CUSUM-plot, which represents the cumulative number of failures as function of the cumulative operational time. The derivative to this curve is by definition the failure frequency. By assessing yearly derivatives to this curve, it is easy to see the variation in failure rates over the three years. However, the yearly averages of the failure frequency neglect trends in the failure behaviour and are not always suitable as a future estimate of the failure frequency. In order to make an accurate estimation of the failure frequency for the coming years the failure frequency should be calculated over a user-defined period based on the observed trend in the failure behaviour in the CUSUM-plots.

In the example shown in Figure 5.2 the failure frequency after about 15 years of cumulative operational time is fairly constant. Therefore the future estimate of the failure frequency is best based on the failure frequency determine over the period after 15 years of cumulative operational time.

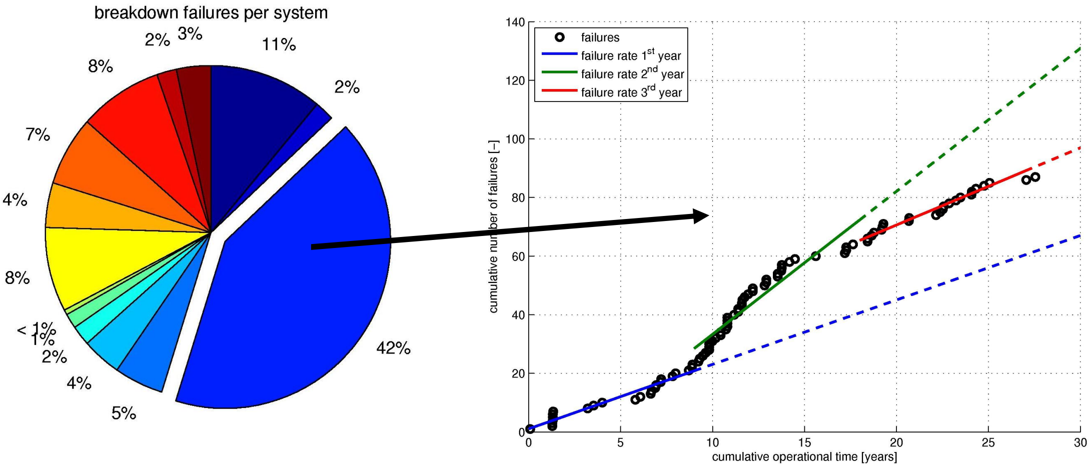

Figure 5.2: *In the left hand figure, the percentage of failures per component is presented. For the largest contribution, the cumulative number of failures as function of cumulative operational time is presented in the right hand figure.*

If in a certain period of elapsed time T an x amount of failures is observed the estimated failure frequency λ is calculated using:

$$\hat{\lambda} = \frac{x}{T}$$

When performing reliability analyses it is common practice to specify a confidence limit on the estimate of, in this case, the failure frequency. For a certain confidence level (1-α) the upper λ_U and lower λ_L confidence limits of the estimated failure frequency can be calculated using:

$$\lambda_U = \frac{\chi^2_{\alpha,2x}}{2T} \quad \text{and} \quad \lambda_L = \frac{\chi^2_{(1-\alpha),2x}}{2T}$$

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

For the example shown in Figure 5.2 the following values can be calculated based on a confidence level of 90%:

Table 5.1: *Future estimate of the failure frequency for the example shown in Figure 5.2*

	Failure frequency
Upper confidence limit	2.79 / year
Estimated mean	2.23 / year
Lower confidence limit	1.71 / year

This analysis using the building block 'Operation & Maintenance' has been applied to various wind farms, and it has been shown that it is quite useful to assess the condition of the turbines in the wind farm and estimate the future failure frequencies of the different wind turbine components.

5.2 BB Logistics

The objective of the BB "Logistics" is (similar to the objectives of BB "O&M") two fold.

1. generating information about the use of logistic aspects (equipment, personnel, spare parts, consumables) for maintenance and repair actions.
2. generating 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 Chapter 4, each Repair Class takes into account:

- the successive activities (inspection, replacement, and/or repair)
- the time to organise the repair activity(ies);
- the duration of each activity;
- the equipment used;
- the crew size; and
- spare part control strategy.

Furthermore, the OMCE-Calculator takes into account if parts are on stock, the stock size, delivery time, etc.

The BB "Logistics" is developed to analyse the data and information that are available in a wind farm on logistics aspects in order to quantify the different Repair Classes for the OMCE Calculator. The BB "Logistics" has been developed by making use of 14 months of data of the Dutch Offshore Wind farm Egmond aan Zee (OWEZ), owned by Noordzeewind. The OWEZ Wind farm consists of 36 Vestas V90 turbines. The data and information that have been analysed comprised the following. [1]

- SCADA data and overviews of alarms, including downtimes and production figures;
- Visits (planned and executed);
- Sheets with information on transfer and hoisting equipment and on the crew size;
- Weather conditions on a daily basis;
- Information on spares used;
- "Hand made" monthly reports with most relevant findings of the wind farm.

It was concluded that the data processing to obtain the relevant data for the different Repair Classes appeared to be very labour intensive. The different sources of information were complementary to each other but the relationship between them was not always clear. "Reverse engineering" was often necessary to re-construct what actually has happened and how failures were actually repaired. Two aspects appeared to be crucial in the data processing:

1. Often it was unclear from the individual reports what the trigger was for a certain visit or repair action. The trigger can be for instance an alarm leading to a shutdown, or the result of an inspection. If the trigger leads to a sequence of different maintenance actions, it should be clear afterwards which group of actions belong to one event.

2. The events need to be sorted in chronological order. This means that the list with alarms and information from vessel transfers, use of crane ships, weather information and personnel needs to be integrated into one list.

It was concluded by the authors that the different data sources with information on logistics (equipment and spare parts) cannot be analysed straight forwardly. An intermediate step is necessary to structure the data before it can be processed by the BB "Logistics". Within the

[1] In parallel to the development, construction, and operation of the wind farm a measurement and monitoring program is carried out (called MEP-NSW) in order to learn lessons on technical and environmental aspects that can be used for the development of new offshore wind farms. The logistics data of the OWEZ wind farm has been submitted by Noordzeewind to ECN as part of this monitoring program. The MEP-NSW program is mainly funded by SenterNovem.

OMCE development this structured list with events is called and "event list" and will be discussed in more detail in Chapter 6.

Although the data analysis appeared to be labour intensive, meaningful results have been obtained to demonstrate the usefulness of the BB "Logistics". It was not possible due to limitations in budget and time to analyse the data of all 36 turbines. The examples below are based on four turbines only.

1. CUSUM plots have been constructed for the different events and alarms, ranging from remote resets to events where crane ships are used to replace large components. As an example in Figure 5.3 a CUSUM plot is given for a certain event type. The CUSUM plots of the individual turbines strongly differ from that representing all turbines. E.g. turbine A only suffers from this event at the beginning of the measurement period whereas turbine B suffers from this event type continuously. If the annual occurrence frequency of major repairs needs to be determined as input for the OMCE-Calculator, the slope of the fitted curve for all turbines could be used.

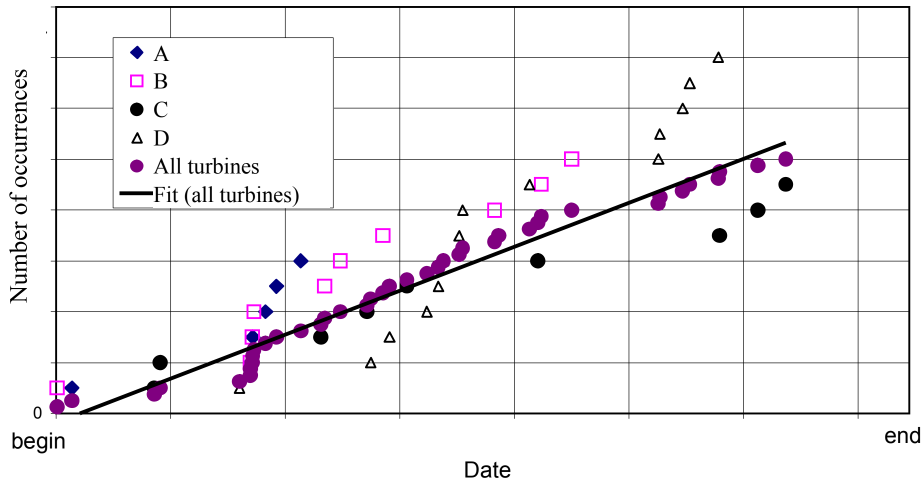

Figure 5.3: *CUSUM plot of a certain event type of 4 individual turbines compared with the average of all 4 turbines*

2. In Figure 5.4, an example of a CUSUM plot is shown for another event type. The CUSUM plot clearly shows that the failure rate of the entire population is decreasing whereas that of a single turbine is below average but not improving.

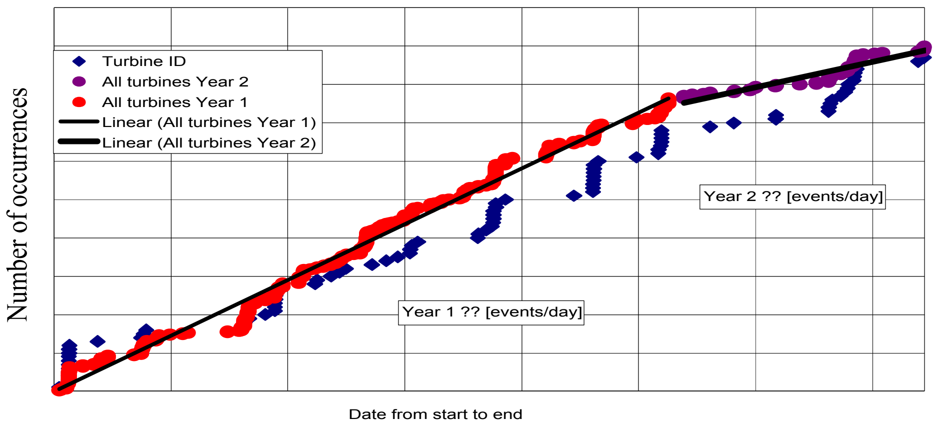

Figure 5.4: *CUSUM plot of a single turbine compared with the average of 4 turbines. The failure rate of total population is decreasing in year 2 whereas the failure rate of the single turbine is lower, but remains constant in year 2*

3. Table 5.2 shows an example of the statistical data that have been obtained from one turbine. (Similar tables have also been made for the other three turbines, together with the totals and averages of all four turbines.) It was possible to identify the number of events, to categorise the event, to determine the downtime and duration, the number of visits needed, and per visit also the crew size and the vessels used. Not only average values could be determined but also minimum and maximum values in case uncertainty analyses need to be performed with the OMCE-Calculator.

Indeed it is possible to determine input parameters for logistic aspects; however the currently used format for data collection is very labour intensive. Please note that at all times "engineering judgement" is needed to assess if the events showed up in the measurement period are representative for the (near) future. If not, (e.g. a retrofit has led to a reduction of the number of failures, or faster repair strategies will be applied) the values automatically obtained from the BB "Logistics" should be adjusted manually.

Table 5.2 *Example of a format to report results of statistical analyses of logistic data (original data have been altered for reasons of confidentiality)*

Reporting period from …. to ….

Turbine ID	#		Total downtime							
Total number of alarms reported	1000	[-]	10000	[hr]						
Number of relevant events	**650**	**[-]**	**11000**	**[hr]**						
								Dowtime per event		
1. Resets (auto or remote)	**500**	**[-]**	**1500**	**[hr]**			**Min**	**Average**	**Max**	
1.1 Errors	280	[-]	1000	[hr]			0,1	3,6	25,7	[hr]
1.2 Control, ambient	220	[-]	500	[hr]			0,1	2,3	5,3	[hr]
	#		**Total downtime**		**# of visits**			**Dowtime per event**		
2. Visit required	**150**	**[-]**	**9500**	**[hr]**	**264**	**[-]**	**Min**	**Average**	**Max**	
2.1 Preventive	40	[-]	250	[hr]	40	[-]	5	6	8	[hr]
2.2 Planned corrective cond. based)	40	[-]	250	[hr]	40	[-]	5	6	8	[hr]
2.3 Paint	4	[-]	140	[hr]	8	[-]	20	35	60	[hr]
2.4 Corrective small	50	[-]	2000	[hr]	100	[-]	20	40	80	[hr]
2.5 Corrective crane ship	16	[-]	6860	[hr]	76	[-]	200	429	1000	[hr]

5.3 BB Loads & Lifetime

The purpose of the Building Block "Loads & Lifetime is to process and analyse the mechanical loads measurement data from one or more turbines in the offshore wind farm in order to determine whether differences in accumulated mechanical loading exist between the turbines in the offshore wind farm. Such differences may be caused by e.g. the amount of time turbines are operating in (half) wake conditions, or the different number of transitions like emergency stops. The different (fatigue) loading could be a reason to adjust maintenance and inspection schemes according to the observed loading, 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 can result in important O&M cost savings.

The results of the BB "Loads & Lifetime" should be combined with the results of the BB "Health Monitoring" to provide information on the expected time to failure of components, as indicated in Figure 3.1. With the information derived from the two BB's, the user of the OMCE-Calculator should be able to make an estimate of what kind of failures will occur and what kind of components need to be replaced and when.

The development of the BB "Loads & Lifetime" appeared to be too ambitious to fully develop within the OMCE project. Therefore the developments were renamed as "*Flight Leader Concept for Wind Farm Load Counting and Performance Assessment*" and carried out in a separate project, partly funded by We@Sea. The Flight Leader developments are reported extensively in e.g. [9], [10], and [11].

The concept of the Flight Leader is shown in Figure 5.5. It is a low cost solution to determine the loads on all turbines in a wind farm by making use of the measured data from two fully instrumented turbines (the flight leaders) and the SCADA data of all turbines. Firstly, relations are determined between the SCADA data of the flight leaders and the measured "load indicators" under various operating conditions and wake conditions. Secondly, these relations are "translated" to determine what their load indicators are. Their SCADA data gives information about e.g. how often the turbines run under similar conditions as the flight leaders (e.g. no wake, full wake, shutdown at high wind speed, etc.) and the flight leader relations can then be used to determine the load indicators.

At present the Flight Leader software is ready and validated to a large extent. The software makes use of artificial neural networks to establish the flight leader relations between load indicators and SCADA data. The validation has been performed onshore first by making use of flight leader measurements performed at ECN's test infrastructure EWTW [2]. Recently, the flight leader software has been validated with data from the OWEZ wind farm. The results of both validations showed that the flight leader concept indeed works and is able to quantify the differences in loading.

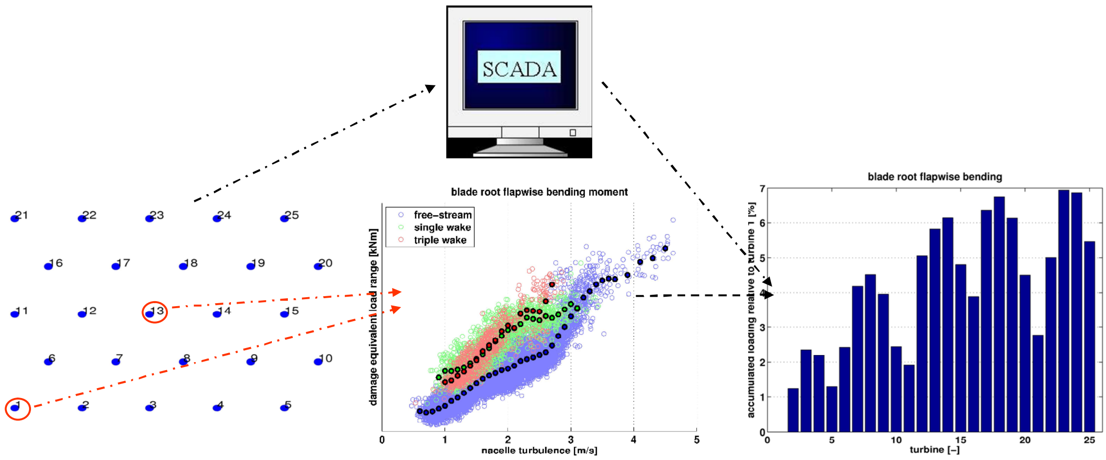

Figure 5.5: *General structure of the flight leader computer model*

5.4 BB Health Monitoring

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.

Within the OMCE project, but especially within the CONMOW project [14] 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] 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.

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 5.6. 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.

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 stand alone 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.

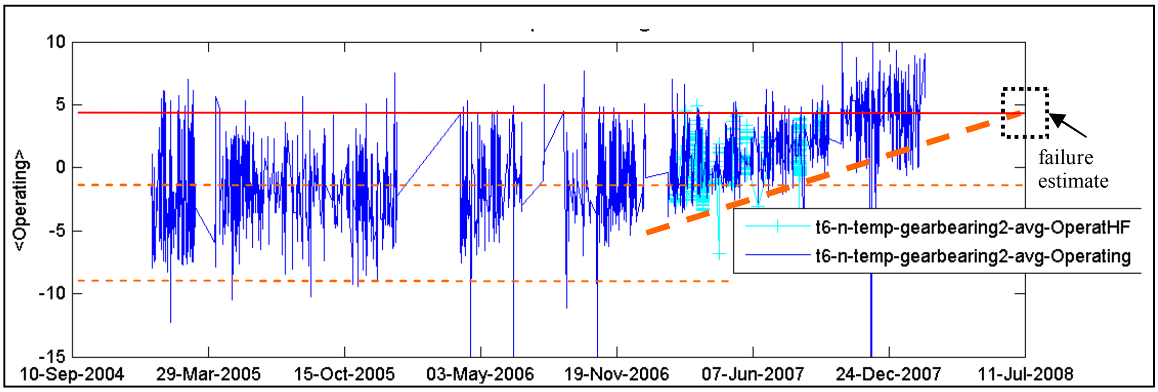

Figure 5.6: *Example of a visualisation from de-trended SCADA statistical data; slow increase of the bearing temperature indicating wear*

6. Event List

As mentioned already in Section 5.2, the format used by most wind farm operators for storage of data is not suitable for automated data processing by the BB's "Operation & Maintenance" and "Logistics". Usually, operators collect the data as different sources e.g.: overviews of alarms, lists with vessels transfers, MS Excel sheets with production figures, losses, and down-time, reports of scheduled maintenance, etc., and make overviews on a monthly basis.

After some time it is not always clear how different alarms, maintenance actions, downtimes, etc. are linked with each other. Therefore within the OMCE the so-called "Event List" was introduced. An even list can be best visualised as a list with events per turbine in a chronological order, including all fields with data and information that are relevant for further processing by the BB's. (*In practice such an event list will probably consist of a query on top of a relational database system*.) The lists are not limited to one month which is common practice. Within the context of the OMCE, an "event" is considered as one (or a series of) maintenance action(s) to prevent turbine malfunctioning, or maintenance action(s) following after malfunctioning of the turbine. The total duration of an event is often longer than the sum of the individual maintenance actions. Maintenance actions can be remote resets, visits with technicians only, or the replacement of large parts.

The location of the event list within the OMCE concept is in between the raw data and the BB's and schematically presented in Figure 6.1.

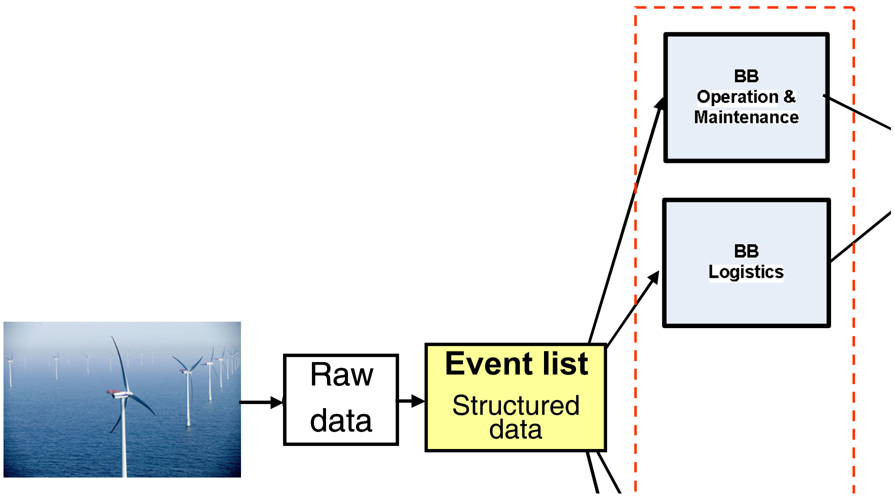

Figure 6.1: *Event list to structure raw data be-fore it can be analysed by the BB's*

Four requirements are relevant when constructing an event list suitable for the OMCE:
1. It should provide insight how individual maintenance actions are related to the total event.
2. Each event should be classified as one of the Repair Classes relevant for O&M modelling (see also Section 3.2.2);
3. It should contain all details about the event relevant for analyses with the OMCE calculator (see also Figure 6.2).

Ad 1) It should become clear from the event list what kind of maintenance actions have been performed to fix a problem. Within the OMCE-Calculator, the modelling of the following event types is foreseen:
- preventive maintenance;
- unplanned corrective maintenance;
- condition based maintenance;
- shutdown with automatic reset

A preventive maintenance event may consist for example of three visits with each a duration of 8 hours. An unplanned corrective maintenance action may consist for example of: several alarms with a remote resets, on site visits to better understand the problem, replacement of a component with a large vessel, and additional visits for commissioning and the total downtime is longer than the duration of the individual maintenance actions. The present situation is such that operators receive data and maintenance sheets from service providers and manual effort is needed to establish the relations between the individual actions. If however, the operators become in charge of the repair actions they can define a repair job with a unique code after the first trigger (alarm or observation) and close the job after the problem is solved. The unique code could ensure the relation between the individual actions.

Ad 2) To classify the different events it is necessary to subdivide the four above mentioned event types. For example, the event "unplanned corrective maintenance" can be subdivided into:

- visit with personnel only (small boat);
- visit with personnel only (helicopter);
- ……;
- replacement of large parts (supply vessel and crane barge).

Ad 3) Items to be reported per event are among others number of maintenance actions, use of equipment, spares used, personnel, downtime, duration etc. (see also the definition of Repair Classes in Section 3.2.2). Time stamps of the events enable easy data processing to generate e.g. CUSUM plots, failure rates, and other statistical data. This is especially relevant for events which start at the end of a month and last until the next month.

An example to illustrate how an event could be reported and what kind or fields are relevant is presented in Figure 6.2. It is an example how the event "Shutdown with visit" could be reported. The event consists of 4 maintenance actions. An alarm led to an immediate shutdown which required three on-site visits after a remote reset has been tried first; the downtime is equal to the total duration of the event. (The yellow rows summarise information of the event whereas the brown rows contain information about the individual maintenance actions.

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	3.3	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	Code/text n	Code/text n	Code/text n
Crew size		2	4	2
Vessel personnel		Windcat 2	Windcat 2	Windcat 1
Travel time (one way)		0,75	0,75	0,75
Mobilisation time [hr]		0	0	0
Supply vessel	n.a.	n.a.	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

Figure 6.2: *Example of report of an event "Shutdown with visit" consisting of 4 maintenance actions.*

7. Status and Future Developments

Since 2004, ECN is developing the OMCE (Operation and Maintenance Cost Estimator) in collaboration with developers and operators of offshore wind farms. The OMCE is intended to make an estimate of future O&M costs of offshore wind farms making use of data generated by the wind farm during the first years of operation. The OMCE consists roughly of two parts: (1) the OMCE Calculator to determine and assess the future costs, and (2) the OMCE Building Blocks to process the operational data.

Based on experiences of ECN with cost modelling in the planning phase of a wind farm with the software “ECN O&M Tool”, the specifications for the OMCE Calculator have been made and from the specifications the models for the OMCE Calculator have been derived. As opposed to the ECN O&M Tool which determines the long term average values of downtime and costs, the OMCE Calculator will become a simulation tool which takes into account the variations in downtime and costs over time.

To process all available data generated by an offshore wind farm in such a way that useful information is obtained, five OMCE Building Blocks (BB) have been specified, each covering a specific data set.

- BB *Operation and Maintenance*
- BB *Logistics*
- BB *Loads and Lifetime*
- BB *Health Monitoring*
- BB *Weather Conditions*

The specifications for the BB “Operation & Maintenance” have been based on ECN’s long term experience with the collection and analysis of operation and maintenance data of onshore wind farms. The essence is to collect the data in a structured way and avoid free format for reporting failures and repair activities. The BB “Operation and Maintenance” is intended to determine failure rates of component which can be used to estimate the costs for corrective maintenance.

The specifications for the BB “Logistics” have been derived mainly from the reports and data obtained from the OWEZ wind farm. It has been concluded that the information relevant to determine the logistics aspects for cost estimation is present in the collected data. However, the format used to store the data leads a very labour intensive analyses process. The specifications include recommendations to structure the raw data first before they can be processed with the BB “Logistics”. The results of the BB “Logistics” can be used among others to estimate the costs of repair actions.

The BB “Loads and Lifetime” specifies how measured data can be used in combination with the BB “Health Monitoring” how mechanical load measurements can be used to assess the degradation of components and make estimates for condition based maintenance. It was concluded that the research for this BB was too ambitious for the OMCE project. Therefore a new project was initiated, called the “*Flight Leader Concept for Wind Farm Load Counting and Performance Assessment*” from which the BB specifications have been determined.

The BB “Health Monitoring” is needed to determine the remaining lifetime of components to estimate the effort for condition based maintenance. The BB uses results from among others condition monitoring programs, inspections, and analyses of SCADA data and PLC data. Extensive research has been done by analysing the data of ECN’s wind farm EWTW with five Nordex N80 turbines.

The BB “Weather Conditions” in fact has not lead to a research task within the OMCE project since it only requires the collection of wind and wave data on site.

The project has resulted in updates of the already existing ECN O&M Tool and to specifications for the OMCE Calculator and the OMCE Building Blocks. The results have been presented at various conferences and workshops. Many of the results are already being used by project developers and operators.

In the next coming years a continuation of the OMCE development is foreseen. Firstly the models of the OMCE Calculator will be implemented in a software programme. Next, the specifications of the different BB’s will be disseminated to potential users of the OMCE Calculator (viz. operators of offshore wind farms) so they can implement these specifications in their data capture procedures. ECN will not implement the specifications of the BB’s in software since they should be implemented in maintenance management systems or works management systems of which many are on the market already.

The commercial introduction of the OMCE Calculator and the dissemination of the specifications of the BB’s is foreseen from 2010 on.

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Appendix A OMCE Project

In this appendix, the original project plan is summarised and per work package the results, adjustments, and deliverables will be mentioned.

Summary of project plan

Objective

The overall objective of this project is to develop methods and tools with which owners and operators of offshore wind farms are able to estimate and control the O&M costs for the next coming years. By doing so, budgets that should be reserved for O&M can be determined more accurately.

Summary

This project focuses on estimating the O&M costs that can be expected on the longer term, say 1 to 10 years. In order to do that, it is necessary to monitor all data that could indicate degradation of the turbines or any of its sub-systems. Data that will be considered in this project deals with *failure and maintenance data* (number of failures, repair actions and use of equipment, wind and wave conditions), and data from *load measurements and condition monitoring* systems that may indicate degradation before actual failures occur. In the project, it will be especially relevant to determine trends that indicate if failures will occur, how many and what costs are associated to these failures on the longer term. With such information, farm owners can make decisions on what repair strategies or major overhauls should be planned and what costs can be expected. It is the ambition of this project to identify a limited number "key-parameters" that should be monitored in order to obtain an estimate of the near future O&M costs.

Apart from the data that will be collected and analysed during the operational phase, it is relevant to compare these data with the assumptions that have been made during the planning phase of the wind farm. This is valid for the cost aspects as well as the loads and condition monitoring aspects. As a first step in this project, it is therefore relevant to model the O&M aspects of a (ficticious) offshore wind farm as a base case. Similar to the cost model, wind farm models should be applied to model the loads on the wind turbines at different locations in the wind farm on forehand. The second step in the project is to analyse the data collected during the operational phase and periodically compare them with the results of the base case during the planning phase.

In order to develop the Operations and Maintenance Cost Estimator (OMCE) it is necessary to use an actual wind farm as a case and to have access to databases with relevant wind farm information. It will be necessary to monitor a wind farm with large turbines and to get maintenance information from this wind farm as well as from other wind farms (this includes failure and repair data, cost and performance data). ECN has available a research wind farm existing of five Nordex N80 turbines which could be used for this project. The ECN Wind Turbine Test farm Wieringermeer (EWTW) includes a research infrastructure including large meteorological masts. In this project the research wind farm at EWTW will be equipped with a condition monitoring system in the five turbines. Furthermore, a limited load measurement program is foreseen (blade loads, tower bending, etc.) for one or two turbines in the wind farm. In addition, operation and maintenance information of other wind farms will be available to the project for further analysis.

To carry out the project, eight work packages have been defined:

WP 1. Cost modelling (Planning Phase)
The costs of an offshore wind farm are modelled using available cost models and updated information based on existing (onshore) wind farms. The evaluations of the model result in an initial O&M strategy and an estimate of the long-term annual downtime and costs.

WP 2. Wind farm modelling (Planning Phase)
The wind farms are modelled with the ECN model "FluxFarm". The model estimates the production of the turbines in the wind farm and the loads on different turbines.

WP 3. Decision support system for operation and maintenance actions (Operational Phase – Short term)
Maintenance and failure data of existing wind farms are analysed to understand the mechanisms for decision support systems for operation and maintenance actions.

WP 4. Data collection and analyses (Operational Phase – long-term)
The work package concerns the collection and analysis of maintenance and failure data in order to determine any trend in degradation and costs. The data are collected of existing wind farms of NUON and SHELL. In addition, measurements are done on the five N80 turbines of the EWTW. The data analyses show trends in failure behaviour and costs.

WP 5. Contracts (Operational Phase – long-term)
A method is defined to determine whether individual turbines in the wind farm are under performing.

WP 6. Wind farm effects and loads (Operational Phase – long-term)
The condition monitoring data together with the load measurements are analysed to determine deterioration of the turbines. The wind farm modelling in Work Package 2 is used to predict load cases and predict the effect of preventive actions, such as shutting down turbines at certain wind conditions.

WP 7. Development of Operation and Maintenance Cost Estimator
A tool is developed in order to estimate the O&M costs of wind farms on the longer term, say 3 to 10 years. All monitored data are analysed to find indications for degradation of the turbines or any of its sub-systems. The *failure and maintenance data* (number of failures, repair actions and use of equipment, wind and wave conditions), and *load measurements and condition monitoring* data increase the reliability of updated estimates of costs of the wind farm.

WP 8. Project Coordination and Dissemination of Results
Project coordination, presentations at European Wind Energy Conferences and project meetings.

Duration
1 November 2004 until 31 December 2008 (initially 30 June 2007).

WP 1. Cost modelling (Planning Phase)

The original plan was to make an inventory of the existing models for modelling the O&M aspects of offshore wind farms. The inventory led to the following models:
- O2M (Garrad Hassan)
- Contofax (TUD)
- Cost Model of BMT
- ECN O&M Tool (ECN)

Within the project team it has been decided to use the ECN O&M Tool for modelling a fictitious offshore wind farm at the North Sea. Firstly, the wind and wave conditions have been analysed and reported in [H, Braam, P.J. Eecen, *Assessment of wind and wave data measured at IJmuiden munitiestortplaats*, ECN-C--05-060]. Next ECN has sent a document to the project partners as a format to collect input data for cost modelling [H. Braam, P.J. Eecen, O*&M Cost Model Of Offshore Wind Farm; Format Input Baseline Configuration*]. The modelling of the offshore wind farm consisting of Nordex N80 turbines is reported in [H. Braam, L. Rademakers, *Maintenance Aspects at the Planning Phase of an Offshore Wind Farm,* ECN-CX--06-051, Confidential]. The result was an initial optimal O&M strategy for the offshore wind farm assuming generic failure data of components that are publicly available and using equipment that was available in 2005 for transfer of personnel and hoisting of components.

Parallel to the execution of the OMCE project, the ECN O&M Tool has also been used to model the O&M aspects of more than 15 offshore wind farms and more than 10 licenses have been sold to leading project developers. Based on feedback from ECN's customers and on the experiences in this WP1, two updates of the ECN O&M Tool have been made within the OMCE project. [H. Braam, LW.M.M. Rademakers; *Availability and Cost Analysis Model for Offshore Wind Farms; User Guide and Model Description;* ECN-X--07-073; June 2007, Confidential], [H. Braam, LW.M.M. Rademakers: User Guide and Model Description of the ECN O&M Tool version 2; ECN-X—08-059, October 2008, Confidential].

WP 2. Wind farm modelling (Planning Phase)

In WP1, the emphasis was on determining the costs for O&M, in this WP the emphasis was on predicting the energy production of the individual wind turbines and of the entire wind farm. A second objective was to model the loads on the turbines. ECN used the in-house developed model FluxFarm and the WAsP program. The results are reported in [T.S. Obdam, *Validation of wind farm production calculations by WASP and FluxFarm*, ECN-Wind Memo-06-090, confidential].

WP 3. Decision support system for operation and maintenance actions (Operational Phase – Short term)

The maintenance, failure, and SCADA data of several onshore wind farms have been collected and anlysed and it has been assessed if and how they can be used for optimisation of the O&M procedures on the short term (day-to-day). It was concluded that the maintenance and failure data are useful for making decisions on the longer term (next coming years), but has not really added value for the short term. For the short term, the SCADA data can be most helpful if analyses are applied for de-trending and determining component degradation. Unfortunately, only limited proof could be found for this within the framework of the OMCE project. Results of the data analyses are reported in [H. Braam, L. Rademakers, *Failure data collection and processing for N80 wind turbines at EWTW*, ECN-X--07-010, Confidential], [P.J. Eecen and L. Grignon-Masse, *Nordex N80 SCADA data; Fingerprints and Trends*, ECN-X-06-089, Confidential], [P.J. Eecen, *Nordex N80 SCADA data, ECN wind turbine test site Wieringermeer, June 2004 to December 2006*, ECN-Wind Memo-06-052 -- ECN-Wind Memo-06-083, Confidential], [Laurent Grignon-Masse, *Wind farm monitoring for operation and maintenance planning. Data reduction and presentation for decision support systems*, ECN-Wind Memo-06-051, Confidential], [T.S. Obdam, *Methods for using operational experience for optimising O&M of offshore wind farms, MSc thesis*, ECN-Wind Memo-07-034], [P.J. Eecen, *Wind Farm Monitoring. Reduction and presentation of SCADA data for decision support systems*, ECN-X--07-025, Confidential]. The results of WP 3 have been used to develop the Building Blocks "Operation & Maintenance" and "Health Monitoring", see WP 7.

In this WP, also a lot of effort has been put in establishing and maintaining the measurement and data collection infrastructure of the ECN Wind turbine Test site Wieringermeer (EWTW). Results are reported in [P.J. Eecen, L.A.H. Machielse, H. Braam, J.P. Verhoef, *LTVM Statistics Database*, ECN-CX-05-084, Confidential], [M. de Noord, P.J. Eecen, USER MANUAL: *ECN Wind Data Management System WDMS*, ECN-Wind Memo-05-015, Confidential], [P.J. Eecen, EWTW *Meteorological database: Description June 2003 - May 2006*, ECN-E--06-004, Confidential], [P.J. Eecen, M. de Noord, *EWTW Meteorological database: Description June 2003 - May 2005*, ECN-I--05-007], [P.J. Eecen, J.P. Verhoef, *EWTW Meteorological database: Description June 2003 - May 2007*, ECN-E--07-041],

WP 4. Data collection and analyses (Operational Phase – long-term)

In WP3, data were collected of onshore wind farms mainly, whereas in WP4 the focus was on offshore wind farms. Data from offshore wind farms appeared to be very relevant for the development of the OMCE since the logistic aspects (usage of equipment, spare parts, and personnel) really differs from the onshore O&M practices. During the first years of the OMCE project it appeared to be impossible to obtain a data set of an offshore wind farm that was suitable for the OMCE development. In 2007 it became clear that a data set if the Offshore Wind farm Egmond aan Zee (OWEZ) would become available. Therefore the end date of the project was postponed until 31 December 2008. The experiences are reported in [Luc Rademakers, Ad den Ouden: *Background Research to Develop the Specifications of the OMCE BB "Logistics"*; ECN-X--09-020, March 2009, Confidential]. The results of this WP have led to specifications for the BB "Logistics", see WP 7.

WP 5. Contracts (Operational Phase – long-term)

This WP was defined to determine if contracts (warranties, energy supply, OEM's, ship owners, etc.) have an influence on the operation of a wind farm and on the decision making process for optimal operations. If so, it had to be investigated if the influence can be modelled in the OMCE. Unfortunately, the project partners could not decide on what kind of contracts would be of importance and it was decided not to execute this WP.

WP 6. Wind farm effects and loads (Operational Phase – long-term)

Research has been done to use load measurements complementary to SCADA data and condition monitoring results as a means to determine degradation of components. However, it appeared that this type of research was very fundamental and complex and too ambitious to fully execute within the OMCE project. Therefore the project "*Flight Leader Concept for Wind Farm Load Counting and Performance Assessment*" was initiated within the We@Sea consortium and executed in parallel with the OMCE project. The results of this WP and the preliminary results of the Flight Leader project have led to specifications for the BB "Load Monitoring", see WP 7.

WP 7. Development of Operation and Maintenance Cost Estimator

Based on the extensive research carried out in the WP's 1 through 6, the functional specifications for the OMCE and the technical requirements for the OMCE-Calculator and the OMCE Building Blocks have been developed in WP 7. The results are reported in [L.W.M.M. Rademakers, H. Braam, T.S. Obdam; *Functional Specifications for the O&M Cost Estimator*; ECN-X--07-138, December 2007], [H. Braam, T.S. Obdam, L.W.M.M. Rademakers; *Technical Specifications and Model Description OMCE-Calculator*; ECN-X--08-052, May 2008, Confidential], [Luc Rademakers, Ad den Ouden: "*OMCE Building Block 'Logistics' Technical Specifications*"; ECN-X--09-013, Confidential], [T.S. Obdam, L.W.M.M. Rademakers, H. Braam: "*OMCE Building Block 'Operation & Maintenance' Technical Specifications*"; ECN-X--09-014, Confidential], [T.S. Obdam: "*OMCE Building Block 'Loads & Lifetime' Technical Specifications*"; ECN-X--09-015, Confidential], [E.J. Wiggelinkhuizen, L.W.M.M. Rademakers: *"OMCE Building Block 'Health Monitoring' Technical Specifications"*; ECN-X--09-016, Confidential].

WP 8. Project Coordination and Dissemination of Results

In total 5 plenary project meetings have been held and 9 quarterly progress reports have been submitted to the We@Sea management.

Presentations and papers have been presented at various conferences and workshops.

L.W.M.M. Rademakers, H. Braam, T.S. Obdam, R.P. v.d. Pieterman: "*Operation and Maintenance Cost Estimator (OMCE) to Estimate the Future O&M Costs of Offshore Wind Farms*"; Paper presented at the Offshore Wind Energy Conference 2009, Stockholm, September 2009

L.W.M.M. Rademakers: "*Operation & Maintenance: From near shore to far offshore*"; Presentation held at the We@Sea conference "Essential Innovations", Den Helder, February 2009

L.W.M.M. Rademakers, H. Braam, T.S. Obdam; *Estimating Costs of Operation and Maintenance of Offshore Wind Farms*; ECN-M--08-027, Paper presented at the EWEC 2008, Brussels

Rademakers, L.W.M.M.; Braam, H.; Obdam, T.S.; Frohböse, P.; Kruse, N.: *Tools for Estimating Operation and Maintenance Costs of Offshore Wind Farms: Stat-of-the-art*; ECN-M--08-026; Paper presented at the EWEC 2008, Brussels, Belgium.

T.S. Obdam, H. Braam, L.W.M.M Rademakers, P.J. Eecen; *Estimating Costs of Operation and Maintenance of Offshore Wind Farms*; ECN-M--07-120; Paper presented at the European Offshore Wind Energy Conference 2007, Berlin, Germany[3]

Eecen, P.J.; Braam, H.; Rademakers, L.W.M.M.; Obdam, T.S.: *Estimating Costs of Operation and Maintenance of Offshore Wind Farms,* ECN-M--07-045, Paper presented at the EWEC 2007, Milan, Italy

Eecen, P.J.; Braam, H.; Rademakers, L.W.M.M. *Development of operations and maintenance cost estimator*; ECN-RX--06-058; Paper presented at the EWEC 2006, Athens, Greece

[3] This paper has also been included in the text book"Modern Maintenance management: Concepts and Cases"; ISBN: 978-81-314-2191-8; India, 2009.