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Estimating costs of operation & maintenance for offshore wind farms

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ESTIMATING COSTS OF OPERATION & MAINTENANCE FOR OFFSHORE WIND FARMS

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Summary

The operation and maintenance (O&M) costs of offshore wind farms contribute significantly to the energy generation costs. Reliable estimates of these costs are required during planning and operation of the wind farm at several stages. Such estimates however have a large spread and are uncertain.
ECN is developing the O&M Cost Estimator (OMCE) with which owners and operators of offshore wind farms are able to better estimate and control the future O&M costs for the next coming 1 to 5 years. The OMCE uses data and experience generated by the wind farm under consideration during the first years of operation. The OMCE consists of so called 'OMCE Building Blocks' in which large amounts of data generated by the wind farm, such as O&M data, data from SCADA systems, or data from (load) measurements and condition monitoring are being processed into useful information. Furthermore the OMCE consists of the so called 'OMCE-Calculator' which is the core of the OMCE, which uses the output of the building blocks to make cost estimates for the next 1, 2, or 5 years.

Keywords: Operation and Maintenance, Offshore Wind Energy, Cost Estimation

1. Introduction

The Dutch Government has defined the target to install and operate 6000 MW offshore wind energy in the Dutch part of the North Sea. With an average turbine size of about 5 MW, 1200 turbines with 3600 rotor blades should be transported, installed, operated and maintained. When not only the Dutch plans are considered, but all international developments as well, these numbers are much higher. So worldwide the effort of operation and maintenance (O&M) of offshore wind farms is enormous, and control and optimisation of O&M during the lifetime of these offshore wind turbines is essential for an economic exploitation. To improve the economics of offshore wind farms, more and more emphasis is put on reducing the costs over the total life cycle instead of only reducing investment costs. It is recognised within the wind energy community that O&M costs of offshore wind farms contribute substantially (2 to 4 ct/kWh) to the energy generation costs. So it is a prerequisite to control the O&M costs during the lifetime and further it might be worthwhile to check periodically whether the O&M costs can be reduced so that the total energy generation costs can be reduced over the lifetime.

ECN is developing the O&M Cost Estimator (OMCE) [1] with which owners and operators of offshore wind farms are able to better estimate and control the future O&M costs for the next coming 1 to 5 years. The OMCE uses data and experience generated by the wind farm under consideration during the first years of operation.
This paper will give an introduction on modelling the O&M aspects of offshore wind farms, explain the structure of the OMCE, and demonstrate the first results of applying building blocks (1) to analyse O&M data and (2) to analyse load measurements for O&M optimisation.

2. Modelling O&M Costs

Before explaining the specifications and the structure of the O&M Cost Estimator the reader will become familiar with relevant terms and definitions commonly used in 'the O&M community'. First the different types of maintenance are discussed. Secondly it is discussed how the maintenance effort related to these different types of maintenance are distributed over the lifetime of an offshore wind farm.

2.1 Different types of maintenance

In the CONMOW project [2] it is shown that when considering wind turbine technology the following maintenance categories can be distinguished:

1. <u>Calendar based maintenance:</u> 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.

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.
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.

2.2 Maintenance effort

In Figure 1 the contribution of the three different types of maintenance to the total O&M costs are schematically drawn for the lifetime of an offshore wind farm.

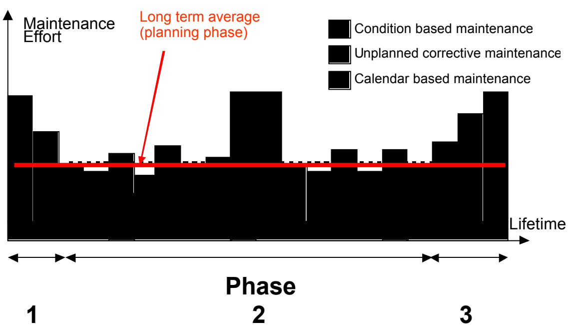

Figure 1: *Schematic overview of the maintenance effort over the lifetime of an offshore wind farm.*

The calendar and condition based maintenance can be planned in advance and the associated costs and downtimes can be determined straightforwardly with minimum uncertainties. The costs related to unplanned corrective maintenance are much more difficult to predict and are covered with large uncertainties. Determining the corrective maintenance costs of an offshore wind farm is similar to the approach for asset management and risk analyses being used in many branches of industry. It can be stated that:

Annual O&M costs =
*Annual failure frequency * Repair costs*

The repair costs consist among others of: labour costs, material costs, costs for access vessels and or crane ships, and revenue losses.

3. The ECN O&M Cost Estimator

ECN is currently developing the O&M Cost Estimator (OMCE). The problem and objectives of the OMCE project are explained in more detail by means of Figure 2 which shows the costs for corrective maintenance over the lifetime from a turbine owner's perspective.

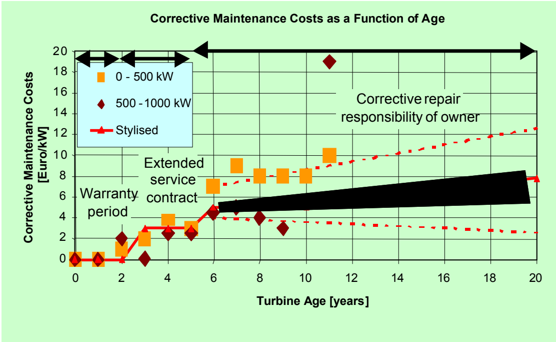

Figure 2: *Development of the costs for unplanned corrective maintenance in the different stages of the lifetime [3].*

During the first period of operation (typically 2 to 5 years) the turbine is under warranty. Any failure will be repaired by the manufacturer as part of the warranty contract. Sometimes the service contracts including the warranties can be extended to five years, or a turbine owner can decide for a contract with only limited warranties. From year 5 on turbine owners need to decide on how to continue with the operation, service and maintenance of their wind farms.

At this point the wind farm operator requires an accurate estimation of the expected O&M costs during the next coming years. The OMCE project has the objective of developing methods and tools for estimating the future O&M effort and associated costs for the coming period, taking the operational experience, acquired during the first years of operation of the offshore wind farm, into account.

The OMCE model can be seen as a further development and refinement of the ECN O&M Tool [4], [5], [6] which is to be used in the planning phase of a project. Logically, both models do have a lot in common, but on certain points both models differ essentially, especially with respect to the following:

3.1 Type of results to be determined

The objective of the OMCE model is to make estimates for a relative short period (1, 2 or 5 years). This implies that an approach based on long term yearly average values is not usable and time-domain simulations are required.

3.2 Feedback of operational data

The OMCE model should provide detailed insight in the actual behaviour of the wind turbine and its components over time, based on operational experience. This means that operational data has to be processed to:

- Quantify and determine trends;
- Assess the input parameters for new cost estimates by combining the latest obtained results with previously determined data and generic data.

4. Functionality OMCE

In this section, the specifications for the OMCE are summarised.

4.1 Types of Maintenance

All three types of maintenance (see section 2.1) are taken into account by the OMCE model. It should be kept in mind that some resources (manpower, equipment, etc.) might be needed for both preventive and corrective maintenance simultaneously. Hence interaction of the different types of maintenance has to be addressed.

4.2 Failure behaviour

The O&M costs of a wind farm are mainly determined by the failure behaviour of the wind turbines and the reliability of their individual components. If turbines are designed and manufactured correctly, they will show few random failures and need little unplanned corrective maintenance. In addition to high quality design and manufacturing, appropriate preventive maintenance (e.g. periodic inspections, lubrication, re-tightening of bolts) is needed to minimise the need for corrective maintenance. In some cases, condition monitoring techniques can be applied to limit the consequences of failures and to minimise the repair costs. But even if turbines are well designed and preventive and condition based maintenance are well applied, unexpected failures will happen.

The OMCE distinguishes failure behaviour that can be measured *directly* and *indirect*. The failure behaviour of components can be measured directly if failure modes occur at the early stage of operation. The OMCE 'measures' the failure rates *directly* by collecting and analysing the amount of observed failures in a structured way[1].

[1] A format for collecting, analyzing and reporting O&M data as presented for example in [6] meets the requirements to a large extent.

Some components are designed to have the same lifetime as the turbine and are unlikely to fail early. However in some cases failures occur sooner than expected due to unexpected wear out of these components. In these situations major overhauls will be planned. (These failures are considered as condition based maintenance.) The OMCE will analyse *indirect parameters* that (may) influence the expected lifetime. Such indirect parameters could be:

- External loading on the components. The loads may vary from turbine to turbine and it is likely that the turbines with the highest loads will reach the end of life at first.
- Results from health monitoring (e.g. the amount of warnings given by the SCADA system, trends observed during periodic inspections, or the results of condition monitoring measurements) could indicate the remaining lifetime of components. The remaining lifetime is also dependent on the expected loading.

Combining the indirect parameters and taking into account the quality of manufacturing and service, the OMCE will make an estimate if and how many components will fail in the next coming period(s) and how many overhauls should be planned. By doing so, the effort for condition based maintenance can be estimated.

4.3 Logistics and repair

Once an estimate is made how often components are expected to fail in the next coming period(s), a repair strategy needs to be developed for each different failure mode. Within the framework of cost modelling, the repair strategy includes the:

- Choice whether a component will be repaired or replaced; the latter might be of importance for stock control;
- Types of equipment that will be used for transportation, hoisting etc.
- Weather windows in what the equipment needed is allowed to be operated;
- Crew size and repair time.

The OMCE-model should be able to generate information on logistics and repair from the maintenance activities carried out in the past. For instance an assumption of the average repair time for a certain failure mode is assumed in the planning phase. By recording the actual repair time each time the specific failure mode is repaired, the average repair time can be determined, compared with the initial value and if necessary adjusted for future estimates. The same holds for the type of vessels used, travelling time, crew size, or limiting weather conditions.

5. Structure OMCE

From the considerations given in the previous sections, the first structure for the O&M Cost Estimator has been developed as is shown in Figure 3.

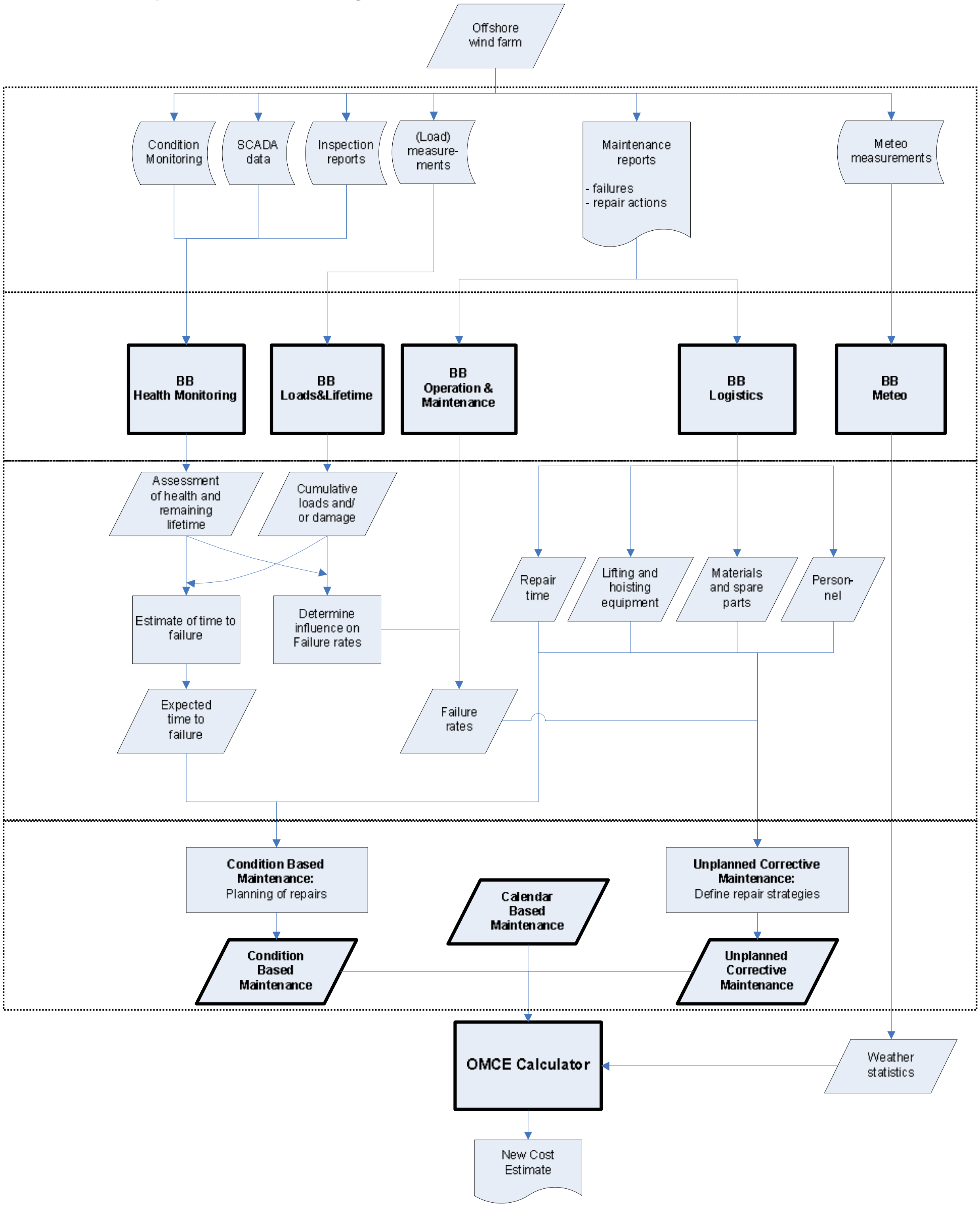

Figure 3: *Structure for the O&M Cost Estimator*

The offshore wind farm generates large amounts of data. These data are being processed by so called ‘Building Blocks’ (BB) to provide information for O&M optimisation and to generate input for the OMCE Calculator. The OMCE Calculator is the tool with which future (1, 2, and 5 years) O&M costs can be estimated. Below, the most important data flows will be explained.

<u>Failure behaviour (direct):</u> The wind farm generates failures and for each repair action a report will be made containing details of the failure but also details about the logistics and repair. A Building Block (BB) ‘*Operation & Maintenance’* has been developed to process the collected information and to quantify the observed failure rates.

<u>Failure behaviour (indirect):</u> If wind turbines are running, reports from inspections (e.g. oil contamination), SCADA data (alarms, error messages), and maybe also data from condition monitoring will become available. A BB ‘*Health Monitoring*’ will process the data and assess the health of components. If turbines are equipped with measurement instrumentation, the loads acting on the different components can be measured and processed by the BB ‘*Loads & Lifetime*’ to determine the cumulative load spectra or damages. The results of both BB should be combined to make estimates if, when, and how many components will fail within the next coming period(s).

<u>Logistics:</u> The maintenance reports on which the failures are reported do also contain data about repair time, equipment, materials, and crew size. The BB ‘*Logistics*’ determines new input values for quantifying the maintenance strategy.

In the next two chapters the functionality of the building blocks ‘Operation & Maintenance’ and ‘Loads & Lifetime’ will be highlighted.

6. BB ‘Operation & 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. This is only possible if the maintenance data is systematically stored in a database for failure collection.

Based on the ECN Maintenance Manager project [7] 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. The registration form of the database for failure collection is shown in Figure 4.

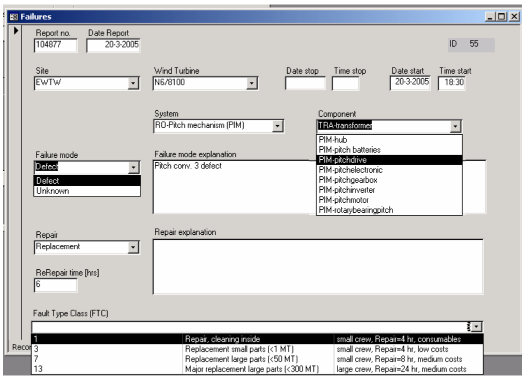

Figure 4: *The database for failure collection. Using a breakdown of the wind farm predefined answers are defined, which enables systematic collection of wind turbine failures.*

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 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.

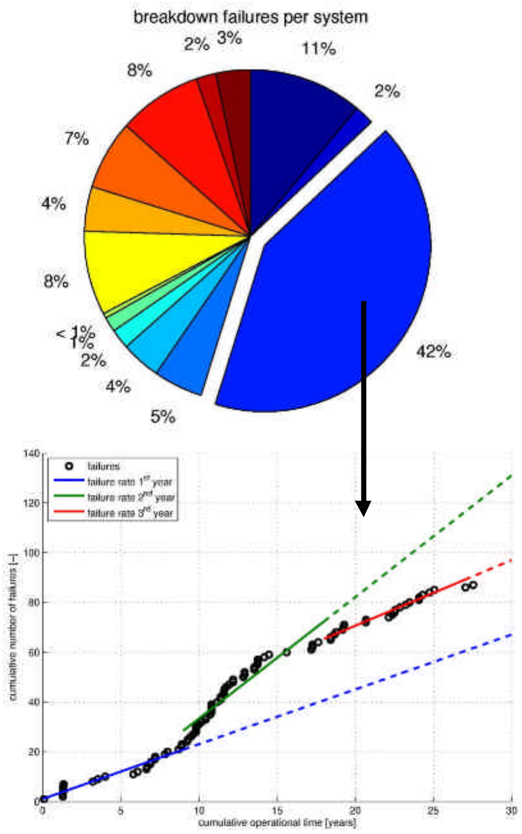

Figure 5: *In the upper figure, the percentage of failures per component is presented. For the largest contribution, the cumulative number of failures as function of cumulative operational time is presented in the lower figure.*

In the example shown in Figure 5 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.

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 symbol a chi-square distribution with a (1-α) confidence.

For the example shown in Figure 5 the following values can be calculated based on a confidence level of 90%:

Table 1: *Future estimate of the failure frequency for the example shown in Figure 7.*

	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.

7. BB 'Loads & Lifetime'

The possibilities of the BB Loads & Lifetime are illustrated by studying the fatigue damage of a fictitious offshore wind farm existing of N80 turbines. The investigated fatigue damage is the damage related to fluctuations in the flapwise bending moment of the blades. The size of the offshore wind farm is 5x5, see Figure 6. The wind resource analysis program FluxFarm [8] has been used to calculate the wake characteristics (turbulence increase and wind speed decrease due to wakes) inside the wind farm. To convert these wind characteristics into fatigue loading (out-of-plane bending of the blades) an empirical model has been developed using measurements on N80 turbines at the ECN Wind Turbine Test Location Wieringermeer (EWTW). Finally, this fatigue loading is combined with a wind speed distribution and wind rose in order to calculate the cumulative fatigue damage.

The goal of this investigation was to study the effect of operation in wake on the fatigue damage of the turbines in an offshore wind farm. Especially the relative loads on the turbines in the wind farm are of interest: are turbines in the middle of the farm (which operate in the wake of the other turbines for a significant amount of time) suffering more fatigue damage than the turbines located at the edge of the wind farm? To investigate this, the following steps have been taken.

7.1 Description of wind farm

Figure 6 shows the layout of the wind farm. The rows are shifted with respect to each other in order to increase the separation between the individual turbines. The spacing between the turbines in one row equals 7·D, the distance between the rows is 8.3·D, which gives a spacing of 9·D on the diagonals. The turbines are Nordex N80's, which have a rotor diameter of 80m, hub height of 80m and a rated power of 2.5 MW. The turbines have active pitch control.

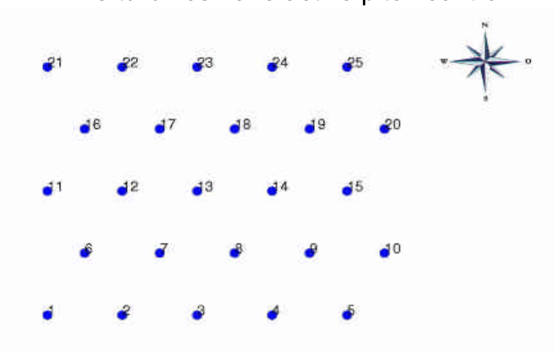

Figure 6: *Layout of the fictitious 5x5 offshore wind farm of N80 turbines.*

7.2 Wind climate

A uniform wind climate has been assumed for all 25 turbines (apart from the wake effects). The wind climate is based on the ECN offshore wind atlas [9] location A at 90m height. For further analysis a Weibull characterization is used using a Weibull shape factor of k = 2.2. As a result, the probability of occurrence of a certain wind direction θ_j and a wind speed bin $U_{free\text{-}stream,k}$ is generated, $p_{j,k}$.

7.3 Correlating wind conditions and fatigue loading

Using measurements on the N80 turbines at the ECN Wind Turbine Test Location Wieringermeer (EWTW) it is investigated whether it is possible to correlate fatigue loading (in terms of damage equivalent load range ΔF_{EQ}) with parameters measured at the nacelle of wind turbines. After reviewing several options it is found that the combination of turbulence (defined as standard deviation of the wind speed) and wind speed deficit (defined as ratio of wind speed relative to free-stream wind speed; 1 in free-stream and <1 in wake) gives a good estimate for the flapwise damage equivalent load range.

Turbulence can directly be measured by the nacelle anemometer, $\sigma_{nacelle}$, and wind speed deficit, U_{def}, can be derived by dividing the wind speed measured at a wind turbine operating in wake, U_{local}, by the wind speed measured at a wind turbine operating in free-stream, $U_{free\text{-}stream}$ (for example in Figure 6 by dividing wind speed measured at turbine 2 by wind speed measured at turbine 1 for western wind). This is shown in the equation below:

$$U_{def} = \frac{U_{local}}{U_{free-stream}}$$

The correlation is depicted in Figure 7. The data for free-stream conditions is depicted in black, the data for single and triple wake is shown in green and red respectively, and the quadratic surface fit is shown in colour.

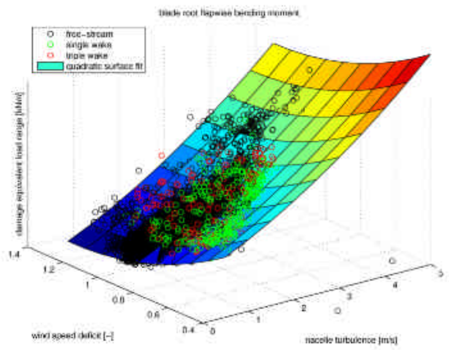

Figure 7: *Correlation between turbulence, wind speed deficit and equivalent flapwise load ranges (using m = 7), measured at ECN wind turbine test site Wieringermeer*

When applying this method for an offshore wind farm, the following should be noted.

- To determine the wind speed deficit, U_{def}, the local wind speed U_{local}, needs to be combined with the undisturbed wind speed, $U_{free\text{-}stream}$. Measurements revealed that the wind speed measured at the nacelle is a good measure for the local wind speed. This undisturbed wind speed can either be determined from (1) an anemometer mounted on a met-mast or on turbines positioned at the edge of the wind farm, or (2) from wind farm simulations as is done in section 7.4.
- The turbulence measured with the nacelle anemometer, $\sigma_{nacelle}$, is not equal to the turbulence of the local wind just in front of the rotor plane, σ_{local}. However, from analysing data measured with the met-mast anemometers and the data measured with the nacelle anemometer it was concluded that the following relationship exists, see also Figure 8.

$$\sigma_{nacelle} = 1.51 \cdot \sigma_{local} + 0.75$$

With this relationship, the values on the 'turbulence axis' in Figure 7 (representing the nacelle turbulence) can be replaced by the turbulence of the local wind speed.

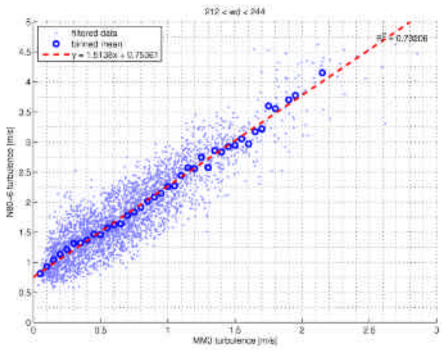

Figure 8: *Correlation between turbulence measured at the nacelle of a N80 turbine and turbulence measured at a meteorological mast*

7.4 Wind Conditions for all individual turbines (FluxFarm calculations)

The resource analysis program FluxFarm has been used to determine the local wind conditions for every turbine i. First of all FluxFarm determined the wind speed deficit, $U_{def,\ i,j,k}$, for every wind turbine i, for all wind directions θ_j and all wind speed bins $U_{free\text{-}stream,\ k}$. Secondly, FluxFarm determined the turbulence caused by the wake effects $I_{add,\ i,j,k}$, for every turbine, wind direction and wind speed bin. This is called the 'added turbulence', To determine the local turbulence intensity in front of the rotor plane for every turbine, $I_{local,\ i,j,k}$., the added turbulence intensity was added to the turbulence of the undisturbed wind speed, I_0, using the equation:

$$I_{local\ i,j,k} = \sqrt{I_0^2 + I_{add\,i,j,k}^2}$$

Subsequently with

$$\sigma_{local i,j,k} = I_{local i,j,k} \cdot U_{free-stream} \cdot U_{def\,i,j,k}$$

the local turbulence $\sigma_{local,\ i,j,k}$, for every wind turbine, direction and wind speed bin has been determined.

7.5 Determining fatigue loads

From the FluxFarm analyses in Section 7.4, the local wind conditions are known for every wind turbine, for all wind directions and all wind speed bins, namely the wind speed deficit $U_{def,\ i,j,k}$, and the local turbulence $\sigma_{local,\ i,j,k}$. The relationship between the 'flapwise bending damage equivalent load range' ΔF_{EQ}, the wind speed deficit and the local turbulence has been determined from the measurements in section 7.3. With this information, the 'flapwise bending damage equivalent load range' has been determined for all turbines, directions and wind speed: $\Delta F_{EQ\ i,j,k.}$

7.6 Damage calculations

Using Miner's rule the fatigue damage has been determined for every turbine by combining the probability of occurrence $p_{j,k}$ from the wind rose with the damage equivalent load range $\Delta F_{EQ\ i,j,k}$.

7.7 Results

Figure 9 shows the fatigue damage of each of the 25 turbines relative to the fatigue damage sustained by turbine 1 for different values of ambient turbulence intensity I_0.

For an ambient turbulence intensity of I_0 = 6% the most heavily loaded turbines suffer a fatigue damage which is about 25% larger than the reference turbine 1.

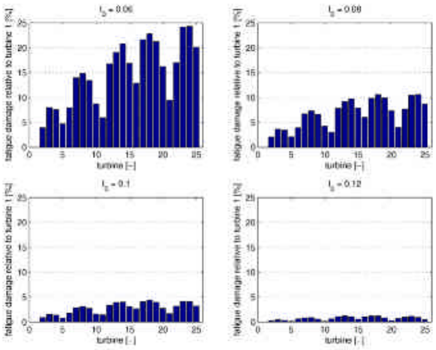

Figure 9: *Relative fatigue damage (turbine 1 = reference) of the 25 turbines for different values of ambient turbulence intensity.*

For higher ambient turbulence intensity the difference in fatigue damage between the turbines decreases. This is explained by the fact that wake effects (increased turbulence and decreased wind speed) are less significant in case of high ambient turbulence intensities. It should be mentioned that, although the difference in fatigue damage between the turbines is smaller for higher ambient turbulence intensity, the absolute value of fatigue damage is higher for higher ambient turbulence intensity.

Similar analyses have been done for different components. It has been concluded that for certain components the loads acting on the individual turbines are dependent on the location in the wind farm. This might be a reason to adjust the O&M procedures for the different turbines based on the observed load patterns. However there is no real prove at present and therefore subject of future work.

8. Status and future work

Detailed specifications for the O&M Cost Estimator are nearly completed. In the near future, on the basis of the detailed specifications, a demo software model for the OMCE Calculator will be developed.

A demo version of the BB 'Operation & Maintenance is ready and has been demonstrated already several times.

The initial research (see chapter 6) for the BB 'Loads & Lifetime' has shown promising results. This BB will be worked out in detail within the We@Sea project 'Flight Leader'. This project has the objective to develop a methodology where based on load measurements on one or two turbines the loads on all turbines in an offshore wind farm can be determined. Using this methodology the wind farm operator has knowledge about the loading of all the turbines in the offshore wind farm at low costs, which can be used monitor the possible degradation of certain components.

BB 'Health Monitoring' has been tested but the results are not sufficient yet to develop a universal procedure and software.

BB 'Logistics' will be developed once operational data from an existing offshore wind farm is going to be analyzed.

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