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Estimating costs of operations and maintenance of offshore wind farms

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ECN-M--07-045

This report has been presented at the EWEC2007 conference,
7-10 May, Milan, Italy

ESTIMATING COSTS OF OPERATIONS AND MAINTENANCE OF OFFSHORE WIND FARMS

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Summary

The contribution of the O&M costs of offshore wind farms to the cost of electricity is relatively large. The O&M effort in the wind farm is therefore one of the issues to optimise. ECN develops the 'Operations and Maintenance Cost Estimator'. This tool can assist owners and operators of offshore wind farms to better estimate and control the O&M costs of offshore wind farms. Since cost estimating of the operation and maintenance will be especially important during operation of the wind farm, all information, experience and data from the wind farm should be used to optimise this task. It is therefore necessary to collect information of the wind farm, the turbines, the operation and the maintenance in order to analyse trends. Since a main part of the O&M costs are determined by unexpected failures and corrective maintenance, the task is to determine trends that indicate if failures will occur, how many and what costs are associated to these failures on the longer term. The O&M cost estimator consists of a core that is able to calculate the failures, repairs, logistics etc. of the wind farm in order to estimate the time-varying O&M costs. The input into this core should be updated by the wind farm operator based on the wind farm data. In order to do so, several tools (decision support) are under development. In this report the structure of the O&M cost estimator is presented and the underlying tools are highlighted.

Introduction

The Netherlands have defined the target to install and operate 6000MW 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. The effort of operation and maintenance (O&M) of these turbines is enormous and optimisation of O&M of these offshore wind farms is essential for an economical exploitation. More and more emphasis is put in reducing the lifetime operational costs of offshore wind farms to improve their economics. For many reasons accurate cost estimates of O&M for a wind farm could be required. Examples are: at expiration of guarantees, changes in O&M strategies, or when a wind farm is sold to another investor. In these cases accurate estimates are required of the O&M costs for the longer term. Cost estimates for O&M of offshore wind farms for longer periods of time tend to be uncertain and have a large spread. Therefore the inclusion of information and experience of the wind farm should improve the reliability of the estimate.

The operation of a wind farm gives the operator the opportunity to collect a multitude of information. The sources of information include

- Turbine SCADA system
- The wind farm control
- Condition monitoring vibration systems
- Oil monitoring
- Maintenance or service reports
- Meteorological and hydrological measurements
- Dedicated measurements such as mechanical load measurements or blade monitoring systems
- Contractual information
- Power performance
- Environment

The various sources of information and the large amounts of information require efficient and effective tools. Knowledge management systems or decision support systems filter and reduce the information to manageable sizes. A decision support system is a computer algorithm that analyses the measured data and presents it in a way that users may make their decisions more easily and with reduced uncertainty.

The development of the O&M cost estimator relies heavily on the development of these decision support systems. These tools are essential for the assessment of the trends and key performance indicators required to update the O&M cost estimates, since the estimates must be based on the vast amount of collected wind farm information.

Project Overview

The project 'Operations and Maintenance cost estimator' is carried out under a research grant of the Dutch WE@SEA program. The aim of the project is to develop a methodology with which owners and operators of offshore wind farms are able to better estimate and control the future O&M costs. In the project both O&M cost estimates for the short term as for the longer term are addressed. In many cases, the costs of O&M is defined to include all normally recurring costs associated with routine operation of the wind farm excluding for example major overhauls. The O&M Cost Estimator described here intends to estimate all future costs, thus also includes extraordinary or infrequently incurred costs, such as major overhauls of the wind turbines and other systems. The O&M costs are limited to the costs of the turbines. For example, the costs of cables, transformer station etc. are not included in the estimator (at present). The majority of the O&M costs are associated with maintenance. Maintenance costs are traditionally grouped into three categories:

- unscheduled maintenance to repair wind turbine malfunctions;
- scheduled preventive maintenance for the wind turbines;
- scheduled major overhauls and subsystem replacements of the wind turbine.

Unscheduled maintenance visits as well as scheduled preventive maintenance are included in the O&M cost component. Including scheduled major overhauls in the estimator is important. After the major overhaul, failure rates of the newly installed components should be assessed to update the O&M cost estimate.

Overview of the O&M Cost Estimator

The O&M Cost Estimator is different from the ECN O&M cost model [2, 3]. The Cost Estimator includes the experience and data of existing wind farms to update O&M cost estimate [6]. Where the O&M Cost Model determines the long-term averaged yearly cost of operation and maintenance of offshore wind farms and is applied in the planning phase of a wind farm, the O&M Cost Estimator uses the experience and data from the wind farm to update the time-varying O&M cost estimates and can best be applied during the operational phase of the wind farm.

As is indicated in the table below, the ECN O&M cost model [2, 3] is a model that determines the long-term averaged O&M costs of offshore wind farms. The O&M Cost estimator will determine the time-varying costs. Where the first model uses average values for the input parameters that are based on historical generic data, the cost estimator uses time dependent input parameters that are based on experience and data from the wind farm itself. Where the cost model applies the design loads to also determine the average failure rates for the turbines, the cost estimator includes a wind farm model, measured loads and dynamic turbine models to estimate loads (and failure rates) for each turbine in the offshore wind farm.

Planning Phase Wind Farm: O&M Cost Model	**Operational Phase Wind Farm: O&M Cost Estimator**
Long-term averaged O&M-Costs	Time-dependent O&M costs
• Average values	• Values time depend
• Historical generic data	• Actual specific wind farm data
• Design (calculated) loads	• Measured loads
• Same loading and O&M for all turbines	• Loading and O&M turbine specific
Results	**Results**
• Long term annual average values	Values time dependent
• Based on 'design' data	• Wind Farm data and experience included

In addition, the typical outputs of the two models are different. Where the output of the Cost Model exists of long-term averaged values based on the 'design' data, the outputs of the Cost Estimator are time dependent and include data and experience of the wind farm. Furthermore, the Cost Estimator includes decision support tools to assist the wind farm operators in assessing their wind farm data.

The above might lead to the impression that the Cost Model is obsolete. This is absolutely not the case. The O&M Cost Model is successfully applied with different developers and operators of offshore wind farms. Furthermore, the model is an essential part of the O&M Cost Estimator, where it will be used as the base case for the cost estimates.

Structure O&M Cost Estimator

The schematic overview of the O&M cost estimator is indicated in Figure 1. The O&M Cost Estimator is designed to be able to either perform a stochastic or a time series analysis of the wind farm. The stochastic analysis will result in time-varying yearly averaged O&M costs, the time series analysis uses a random realisation of the wind turbine failures from which the logistics of material and devices can be determined. It is obvious that the O&M Cost Estimator requires input data, including the turbine breakdown, O&M strategy, failure rates, wind farm model etc. etc. Using the input data set, the O&M Cost Estimator can estimate the operation and maintenance effort of the offshore wind farm.

The operator receives a multitude of information from its wind farm. The production per turbine, the SCADA data, maintenance information, possible dedicated measurements from meteorological masts or load measurements and others. Ideally, this information should be used in the update of the O&M cost estimate.

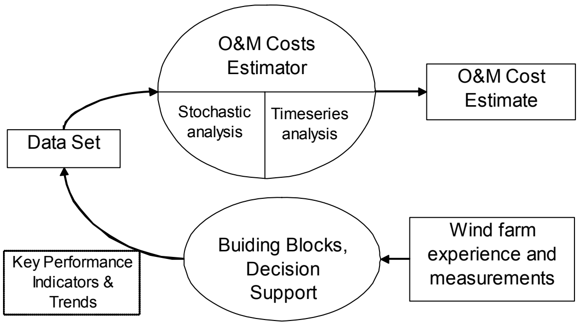

Figure 1. Schematic overview O&M Cost Estimator.

Wind Farm data and experience

The O&M Cost Estimator primarily depends on the input data of the offshore wind farm. The measurements and experience of the wind farm under operation are essential for the reliable update of the O&M cost estimate. All wind farm operators know that the amount of data from a wind farm is huge. The extraction of key parameters and trends is not an easy task. The operator should be assisted by the proper and reliable analysis of the wind farm data in order to be able to update the cost estimate. For that purpose the O&M Cost Estimator is equipped with decision support tools. These tools are referred to as 'Building Blocks' of the O&M Cost Estimator. Since the data have many origins and serve many purposes, the number of building blocks is large. At present building blocks are defined for

- Initial O&M Cost Model
- Wind Turbine Breakdown Model
- Wind and Wave Model
- Devices Model
- Wind Farm Model
- Decision Support System
- Contracts
- Environment
- Fatigue and Extreme Loading Model
- Dynamic Turbine Model

These building blocks are defined to analyse the monitored wind farm data in order to find key parameters to update the cost estimate. These key parameters range from trends of degradation of the turbines or any of their sub-systems. The failure and maintenance data (number of failures, repair actions and use of equipment), load measurements and condition monitoring data may indicate degradation before actual failures occur and may increase the reliability of updated estimates of costs of the wind farm.

In the following sections some of the building blocks are described in more detail. The reader is reminded that these building blocks interact with the input data of the cost estimator. The update of the input data will be performed by the operator of the wind farm; therefore the building blocks must be regarded as decision support tools.

Initial O&M Cost Model

Models of O&M of offshore wind farms have been studied in detail in the past [2, 3]. The ECN cost model is in use at ECN and is in use by several project developers around the world [2]. It includes a breakdown of the turbine with failure classes and failure rates, includes a maintenance strategy that takes into account the choice of vessels, the cost and availability of vessels, weather periods in which O&M can be performed on the turbine and the loss of energy due to unavailable turbines after failures have occurred. The O&M cost model is used to have a base case (from the planning phase of the wind farm) in the calculation in order to quantify the added value of the O&M cost estimator. The input for the Cost Model exists of long-term average values of

- A breakdown of the turbine with failure classes and 'design' failure rates
- An initial maintenance strategy including a specification of the choice of devices (vessels) for the specific repair
- The cost and availability of devices
- The wind and wave requirements on the devices

Together with time series of wind speed and wave height the waiting times of the devices can be determined. Together with the breakdown, the costs of maintenance, loss of energy due to unavailability and costs of repairs are calculated thus leading to a long-term yearly averaged O&M cost estimates.

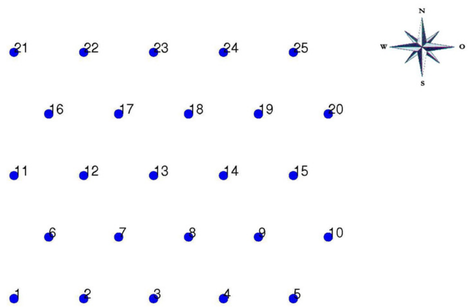

Figure 2. Example of a wind farm layout.

Wind Farm Model

The assessment of O&M of offshore wind farms cannot be performed without a proper and reliable wind farm model. The wind farm model should be used to assess

- travel times in between turbines
- wake losses for production assessments
- added turbulence for mechanical loading of turbines under wake conditions

Figure 2 shows an example wind farm of 25 turbines of the multi-MW class. The wind farm model uses the output of dedicated wind farm calculation models, such as the FluxFarm model [5] that has been developed by ECN. The FluxFarm model includes the Wakefarm [8] model and calculates both the wind speed deficits as well as the added turbulence due to the wakes in the wind farm. The added turbulence will have the largest effects under offshore conditions where the ambient turbulence is small.

Decision Support

Offshore wind farms, consisting of many turbines will require maintenance. Maintenance is usually reported using the maintenance reports. At present maintenance information often are handwritten paper reports that are usually collected and stored by the wind farm operator. In order to extract useful information the reports need to be digitalized and stored in a database. Based on the ECN maintenance manager [4] 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. One of the building blocks of the O&M Cost estimator is a postprocessor on the database. It analyses and presents the data that is stored in the database structure in an easy and accessible way in order to assess whether the failure rates implemented in the O&M Cost Estimator are similar to the experienced failure rates.

In figure 3, an example is presented from the analysis of maintenance reports. The data from the database are analysed to determine the percentage of failures for each component (upper figure). In the lower figure, the largest contribution to the failures is analysed. The cumulative number of failures is plotted as function of operation time of the wind farm. The derivative to this curve is by definition the failure rate. By assessing yearly derivatives to this curve, it is easy to see the variation in failure rates over the three years. In addition, the decision support system presents confidence levels to the operator whether or not the failure rates in the O&M Cost Estimator should be updated.

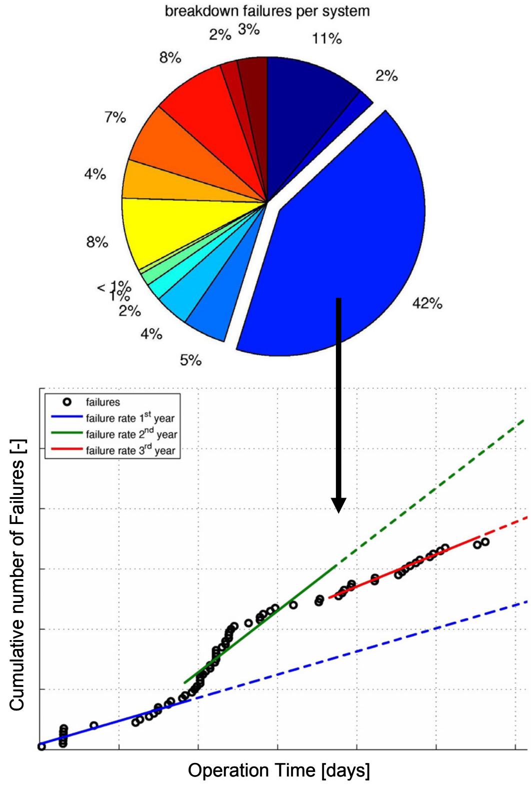

Figure 3. In the upper figure, the percentage of failures per component is presented. For the largest contribution, the cumulative number of failures as function of operation time is presented.

The decision support tool assists the operator in assessing the information from the maintenance reports. The results of the analysis are:

- estimated failure rates of the various wind turbine components
- estimated failure rates depending on turbine location in the wind farm
- confidence interval in order to assist the decision whether the original estimate of the failure rate is still valid or should be updated.

The tool 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. An example is presented in Figure 4 where the total number of times that a certain component needed to be serviced per turbine is plotted. From the analysis, two distinct sets of turbines are distinguished. From further questions it was found that the two sets of turbines in the wind farm were equipped with components from different manufacturers.

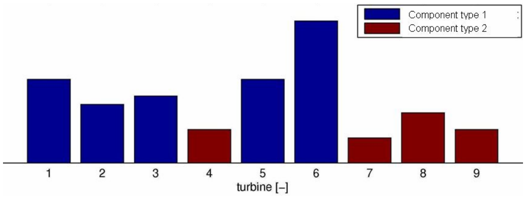

Figure 4. Plotted are per turbine the number of service actions for a certain component. Clearly two sets are distinguished that could be traced to different component manufacturers.

Building block Fatigue and Extreme Loading

In large offshore wind farms the turbulence levels inside the wind farm are significantly larger than the ambient turbulence due to the presence of wakes. In addition, turbines located inside the wind farm will operate more often under partial wake conditions. Therefore, these turbines will experience larger mechanical loads due to 1. the higher turbulence levels and 2. partial wake operation compared to the turbines under free-stream wind conditions. The analysis of these (large) differences in fatigue damage between the wind turbines in the farm can assist the operator to assess the failure information of its turbines. It is not assumed nor expected that all turbines in an offshore wind farm are equipped with load measurements. However, it is reasonable to expect that mechanical loads are measured at one or two turbines. Using the decision support models (farm model and load model) the relative mechanical loads can be assessed on the other turbines in the wind farm. The main impact of these analyses on the O&M cost estimate is through the assessment of failure rates. The required detailed wind farm model that includes the added turbulence due to wake effects is included in the O&M Cost Estimator.

Here an example is included from a calculation performed on a fictitious wind farm of 25 multi-MW turbines. The lay-out is indicated in figure 1 and the wind climate that is used is the one at the North Sea. The dominant wind is therefore from the South-West. An analysis has been performed to determine the relative fatigue damage. In order to assess the various components, from blades, main bearing, gearbox bearing and the gearbox itself, a model of the drive train has been made. This simplified model of the drive train calculates the load measurements on blades and tower to loads on the gearbox, main bearing and gearbox bearing.

From detailed and extensive measurements at the ECN wind turbine test site in the Wieringermeer, The Netherlands [1], relationships between wind conditions and the characteristic fatigue loading parameters are established for blades, tower, gearbox, main bearing and gearbox bearing. Primarily the loading conditions under wake operation are essential for the further analyses. These relationships are generalised, and when the turbines of the wind farm are modelled using aerodynamic codes, these relationships could be verified. As an example, the blade root bending moment in the flap-wise direction are taken. From literature it is known that the blade root bending moment in the flap-wise direction depends heavily on turbulence level. Therefore, the wakes that add turbulence to the relatively low ambient offshore turbulence will dominate the loading.

The wind farm evaluation program FluxFarm is used to calculate the wake effects in the farm (decreased wind speed and increased turbulence). Using this output together with the established relationship the differences in fatigue damage between the turbines in the farm are determined. The results are presented in Figure 5. For the blades (flap wise direction) significant differences in fatigue damage are found between the lighter and heavier loaded turbines in the farm. The differences can be up to 45% in the case the ambient turbulence level is 6%. When the ambient turbulence level increases, the relative differences between the turbines in the wind farm decreases. For the components for which large differences in fatigue damage exist between the turbines in a large offshore wind farm, different failure rates should be implemented in the O&M Cost Estimator.

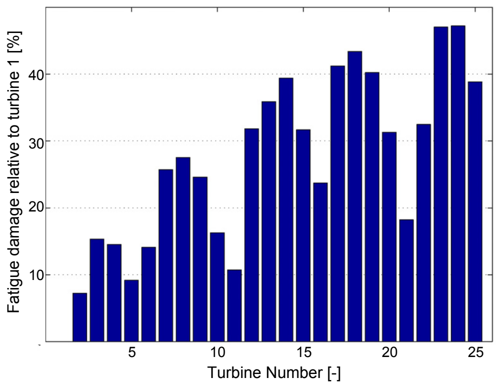

Figure 5. Relative fatigue damage of the 25 turbines in the wind farm for the blade root bending moment in the flap-wise direction.

Another application is the correlation of measured loading and measured failure rates with these analyses. The operator should expect the highest failure rates with the turbines that have the largest loads. Decisions must be made whether the measured loading exceeds the design assumptions. Inspection could be altered or components may be replaced earlier, of course in connection to the experienced maintenance.

Other Building Blocks

Building blocks still under development are:

- **Environment.** Additional information on noise restrictions, bird restrictions and others could have implications on the maintenance strategy.
- **Dynamic Turbine Model.** The assessment of the impact of parameters (wind, wave, wake) on fatigue characteristics could require results from dynamic turbine models.
- **Contracts** The wind farm model and the wind climate are used to assess the wind farm performance. The measured wind resource can be compared to the estimated one and in addition, the nacelle power performance assessment technique can be applied to assess individual turbines.
- **Wind and waves [7].** The wind speeds and wave heights at the wind farm location are essential to assess the periods where maintenance is possible.

Results

The results from the O&M cost estimator are the time-varying cost estimates for operation and maintenance of the offshore wind farm. By running the decision support tools, the operator will have more information on the state of its turbines and is able to redirect priorities etc. In addition to the time-varying estimates, realisations of failures of the wind farm can be modelled, thus giving insight in the logistics of material and devices.

Conclusions

Estimating the time-varying cost of operations and maintenance of offshore wind farms for a longer period of time is essential. For the operator, there are many opportunities to collect a large variety of information from the wind farm. However, efficient and effective use of the huge amount of data of the wind farm is a challenge and requires decision support tools. The O&M cost estimator under development at ECN determines the long-term time-varying O&M cost estimates and enables the operator with decision support tools to reliably update the input data based on the wind farm experience and data. Furthermore, the tools support analyses of revised O&M strategies.

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Acknowledgement. This study is carried out and co-financed in the context of the Bsik-programme: "Large-scale wind power generation offshore", of the consortium We@Sea (www.we-at-sea.org).

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O&M Cost Estimator

Estimating Cost of O&M for Offshore Wind Farms

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Objective O&M Cost Estimator

- Development of methods and tools to better estimate O&M costs for offshore wind farms based on operational data
- Horizon: medium to long term (2-15 years)

- **Partners**: ECN, KEMA, TUD, SHELL, NUON, Fabricom, Vestas

This project is co-financed in the context of the Bsik-programme: Large-scale wind power generation offshore, of the consortium we@sea (www.we-at-sea.org)

Planning Phase ↔ Operational Phase

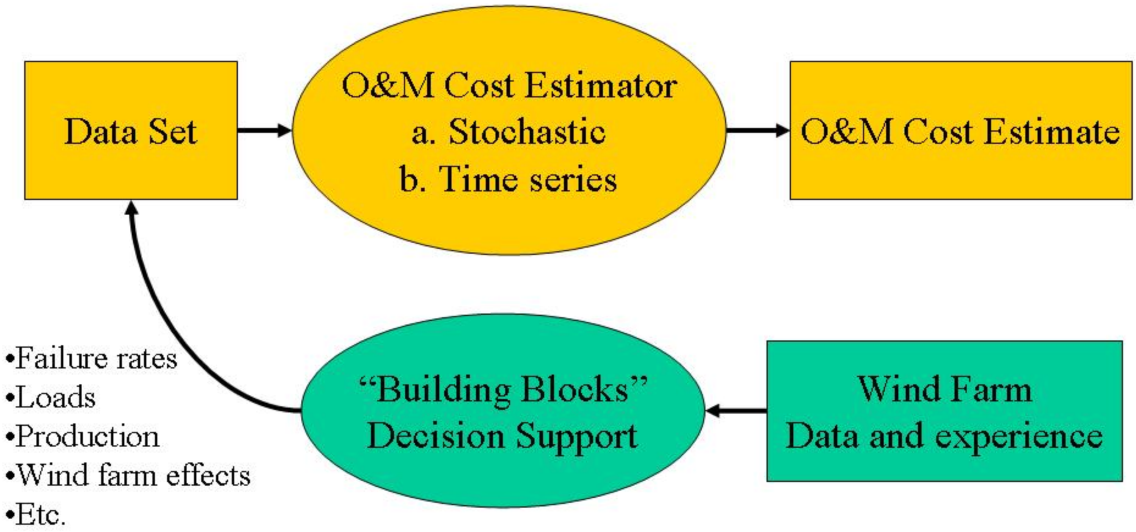
Planning Phase

- Long-term averaged O&M-Costs
  - Average values
  - Historical generic data
  - Design (calculated) loads
  - Same loading and O&M for all turbines
- Results
  - Long term annual average values
  - Based on 'design' data

Operational Phase

- Time-dependent O&M costs
  - Values time depend
  - Actual specific wind farm data
  - Measured loads
  - Turbine specific Loading and O&M
- Results
  - Values time dependent
  - Wind Farm data and experience included

Overview of O&M Cost Estimator



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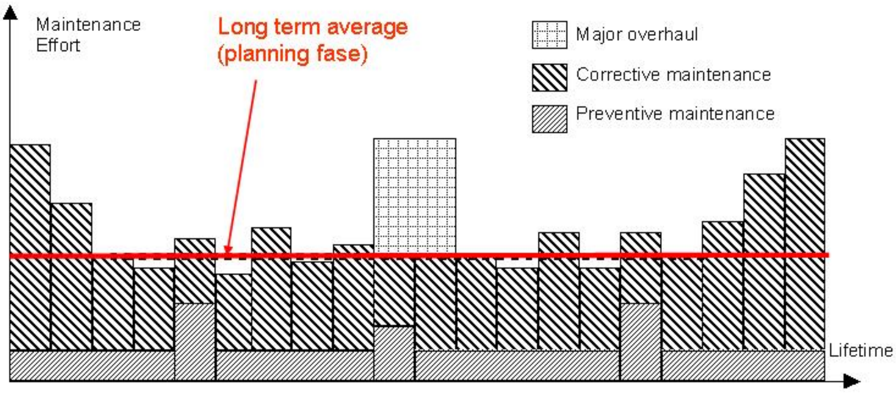
O&M Cost Estimator Stochastic

- Results: detailed and time-varying O&M cost estimates based on wind farm data



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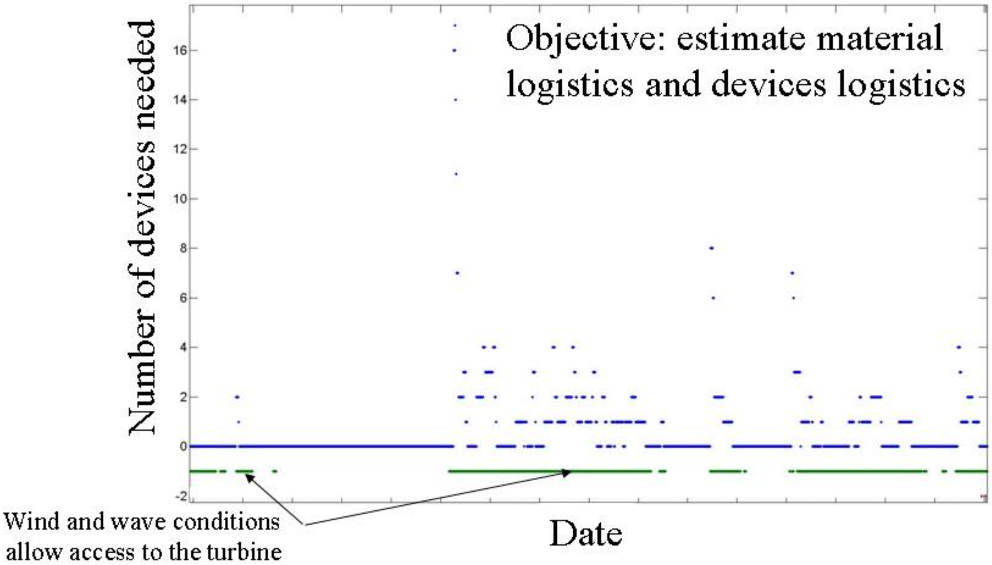
O&M Cost Estimator Time Series

More insight in stochastic results are obtained by analysing the underlying time-series data



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Building Blocks

- The Building Blocks determine the “input parameters” for the O&M Cost Estimator. The Building Blocks can be regarded as decision support systems using wind farm data and experience.

- Examples
  - Determine failure rates from Maintenance Reports
  - Wind farm model: Mechanical Loads on wind turbines

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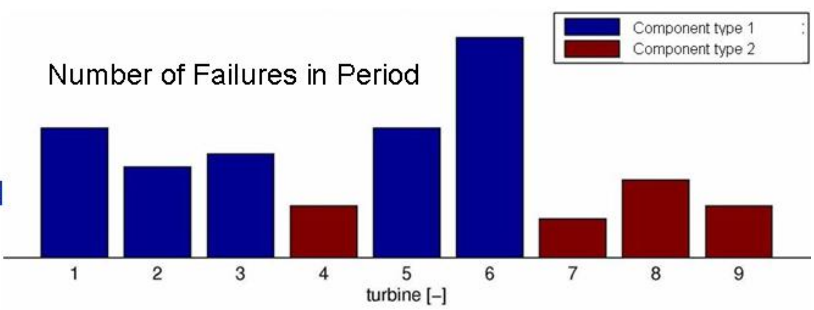
Building Block: O&M data

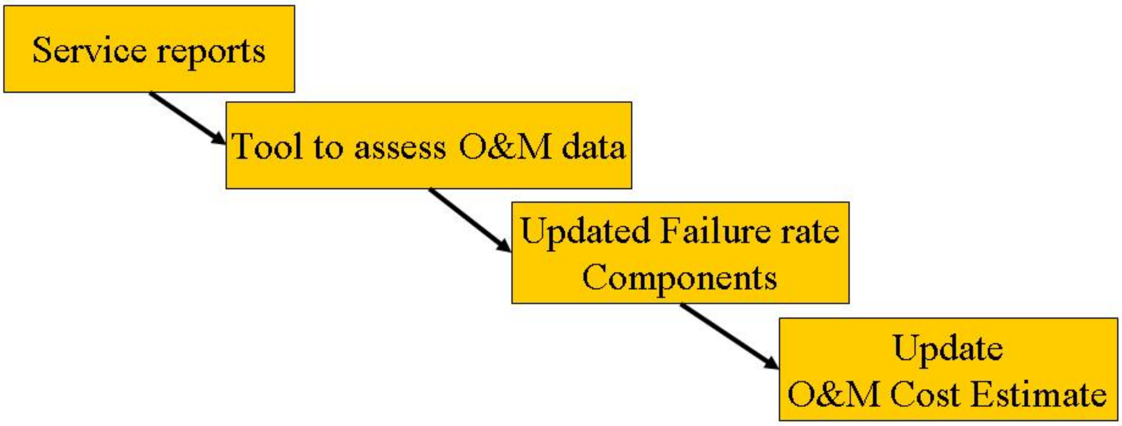
- From wind farms service reports are available
- ECN developed database structure to
  - Organise information in ‘fixed format’
  - Organise according ‘turbine breakdown’

Example:
From the service reports of a wind farm, it was found that the turbines were equipped with two types of a certain component



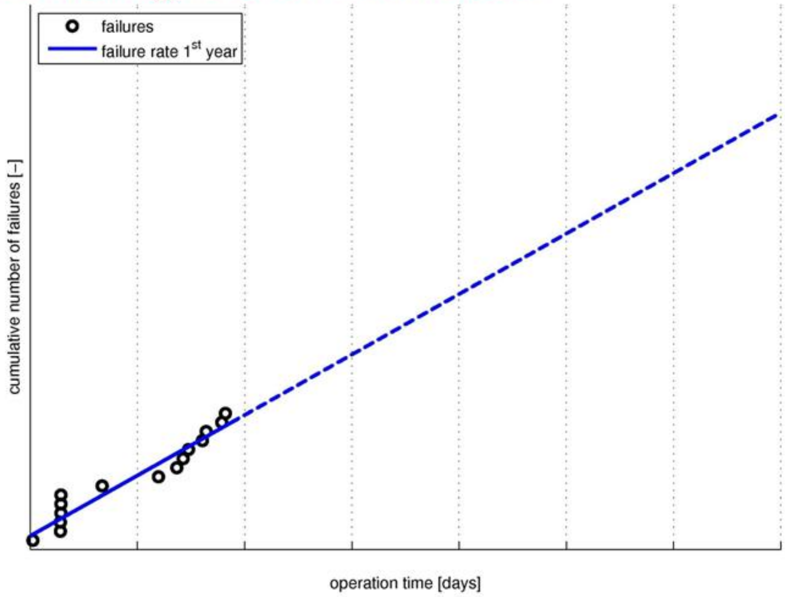
Building Block: O&M data Analysis → Input O&M Cost Estimator

- From the service reports, failure rates can be determined for each (sub)component



Example Building Block O&M data

- Information after 1st year of operating the offshore wind farm.



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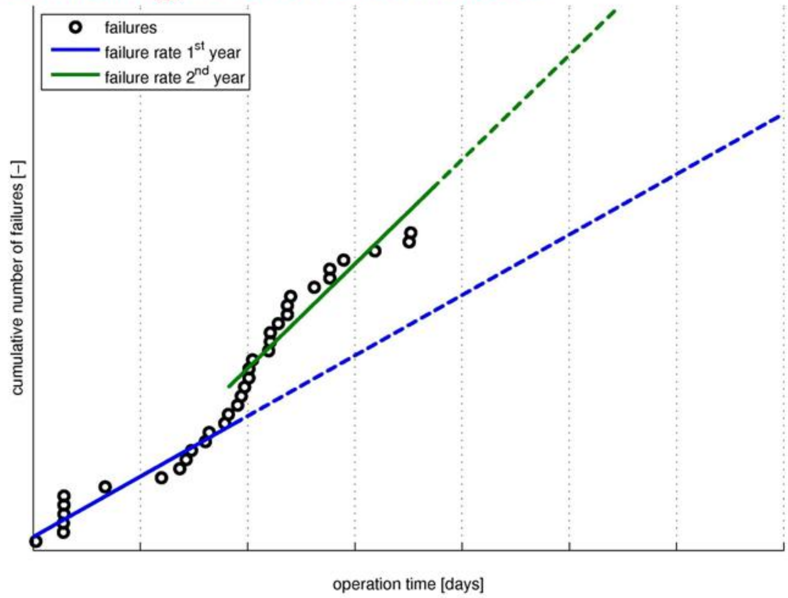
Example Building Block O&M data

- Information after 2^{nd} year of operating the offshore wind farm.
- The failure rate has increased



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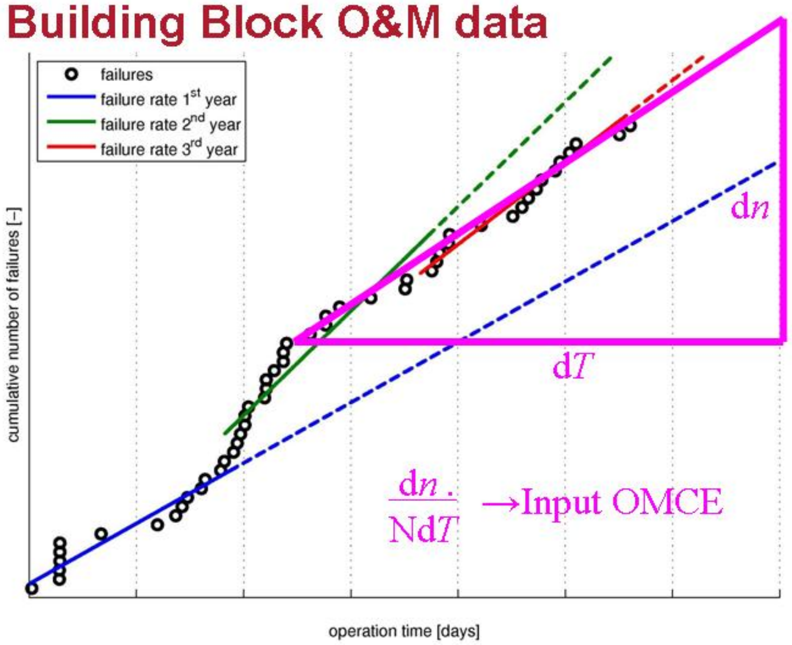
Example Building Block O&M data

- Information after 3^{rd} year of operating the offshore wind farm.



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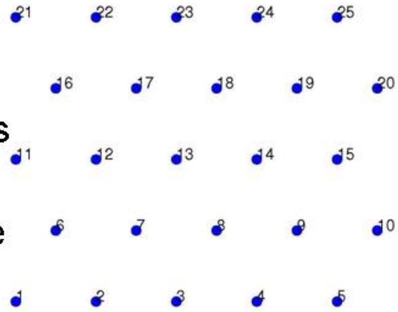
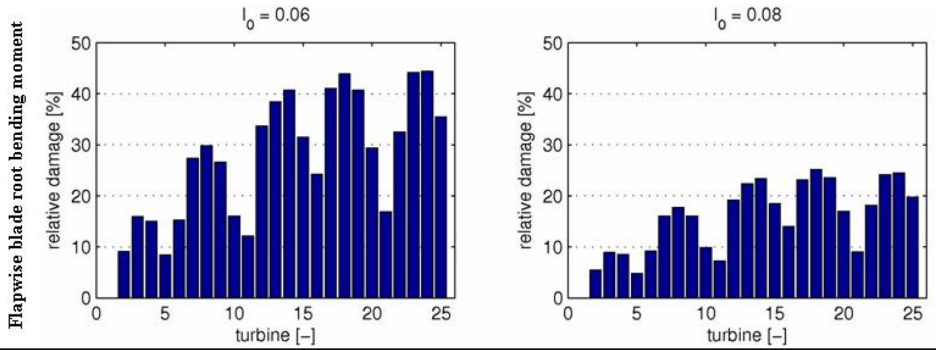
Relative loads in wind farm



- Mechanical loading of some components strongly depends on turbulence
- Significant differences in fatigue damage between turbines in offshore wind farm



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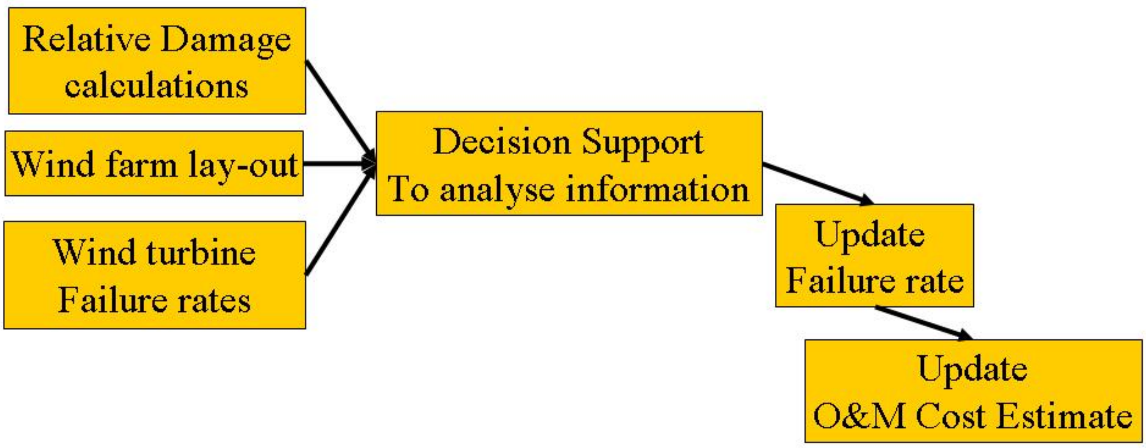
Building Block: Loads Analysis → Input O&M Cost Estimator

- Correlate calculated relative damage calculations with actual failures



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Conclusions

- Time-varying O&M cost estimates for offshore wind farms are essential
- Presented is the procedure to better estimate O&M costs
  - Inclusion of measurements and experience of the wind farm improves the O&M cost estimate
  - In order to use the large amount of wind farm data, decision support is required
- Tool under development to estimate time-varying O&M costs of offshore wind farms