1. INTRODUCTION

Recent studies, for example [4] and [6], have shown that the costs for operation and maintenance of offshore wind turbines will be substantially higher than for onshore turbines. Typical figures for the offshore situation are (including costs for maintaining the park infrastructure, civil structures, etc.):

- preventive maintenance, 0.003 to 0.006 €/kWh
- corrective maintenance, 0.005 to 0.010 €/kWh

The costs for corrective maintenance are a factor of 2 higher than for preventive maintenance, whereas for onshore turbines the costs for preventive and corrective maintenance are in balance. The large range in the O&M costs is caused among others by the following aspects:

1. size and reliability of the turbines (small onshore turbines vs. large turbines optimised for offshore applications)
2. maintenance concept chosen (access systems, hoisting facilities, etc)
3. distance to the shore, water depth, size of the wind farm; and
4. wind and wave climate.

According to [6], the contribution to the kWh price is approximately 25 to 30% whereas onshore the contribution is in between 10 and 15%.

The figures above show the necessity to carefully deal with the O&M aspects of offshore wind farms. Within the DOWEC project (Dutch Offshore Wind Energy Converter) [1] special attention has been given to determine the annual average O&M costs, the annual unavailability, the critical items (cost drivers), and the uncertainties and risks. To quantify these items, both TU Delft and ECN have carried out analyses with their own cost models.

2. COST MODELS OF TU DELFT AND ECN

The approach for modelling the costs and unavailability due to corrective maintenance of offshore wind farms is given in Fig. 1. Three types of input can be distinguished:

1. failure behaviour and repair actions of the turbines
2. access systems, their workable weather windows and their costs
3. the weather windows at the intended site, mainly wind and wave conditions.

Since all input parameters are covered with great uncertainty, a probabilistic calculation method is needed to take this into account and to determine the uncertainty bounds of the output parameters. The costs and unavailability due to preventive maintenance can usually be estimated in a straightforward deterministic manner. The results of the cost model may give reason to optimise the initial O&M strategy. This can be done for example by improving the reliability or maintainability of the turbines, or by choosing different repair strategies, access systems, or hoisting equipment.

Fig. 1: Approach for modelling and optimising O&M aspects of offshore wind farms

Both ECN and TU Delft have developed an analysis tool for modelling the O&M aspects of offshore wind farms, with a distinctly different mathematical basis. TU Delft has developed the program CONTOFAX. Error! Reference source not found. By means of Monte Carlo simulations, the CONTOFAX program simulates the O&M aspects over a period of time by following the state of each “component” in the wind farm, e.g. the turbine itself, the maintenance crew, or the access and hoisting equipment. The failures of components are generated stochastically, complying with the mean time between failures and distribution functions provided by the wind farm developer. Before each simulation, a random realisation of weather windows is generated from the given summer and winter storm percentages at the specific site. The O&M aspects are simulated for several realisations of weather windows and failures and the results are averaged.

The ECN model is based on analytic expressions for the long term annual average O&M costs and downtimes [7], [8], [9]. As the scatter and uncertainty of the input variables will lead to scatter in the annual costs and downtimes, the model is extended with a probabilistic
module, which can handle stochastic inputs. The model has been implemented in MS Excel with the add-in module @Risk [5] to perform probabilistic calculations. The core of this model is the determination of the distribution functions for the waiting times, based on statistics for wind speed and wave height and workable weather windows of various access and hoisting systems. Although the programs are based on essential different approaches, the common focus of the two tools enables direct comparison of the results, and thus providing a means for verification. At the same time complementary analyses can be performed. The simulation tool CONTOFAX is particularly suitable for analysis of non-linear effects, such as combined occurrences of failures and accumulation during inaccessibility with respect to occupation of crew and equipment. The ECN program is notably applicable for probabilistic analyses including the quantification of the uncertainty in the calculated O&M costs and the determination of the source for these uncertainties. In the next sections, the authors will show that the results of both programs do compare fairly well.

3. INPUT PARAMETERS FOR DOWEC BASELINE

The baseline configuration of the DOWEC wind farm consists of 80 turbines with a rated power of 6 MW each. The wind farm is a case study for the North Sea at the location known as “NL?” which is approximately 50 km offshore. The DOWEC turbine is equipped with a 50 MT internal crane for replacing large components like generator, gearbox, or single blades. In the baseline configuration, this 50 MT crane is assumed to be mobile. The mobile crane has to be mounted in two steps with the help of a permanent 1MT crane in the nacelle. This 1 MT crane is also used to hoist smaller spare parts. The spare parts first have to be hoisted on the platform above the splash zone before they will be hoisted with one of the nacelle cranes. In all cases a supplier with an Offshore Access System (OAS) [2] is used for the transportation of personnel and small components. Replacement of the nacelle or entire rotor has to be done with an external crane, e.g. a jack-up.

3.1 Failure Behaviour and Repair Actions

Failure rates were determined based on available information in the market. As this paper aims at the exploration of factors that influence the O&M costs, the absolute failure rate, \( \lambda \), is not determinative, thus the failure rate of the wind turbines is set to 1 failure per year per turbine, while preventive maintenance is not taken into account. The consequences of all failures are not equal. The failure modes determine what type of repair strategy is required and thus determine the costs. E.g. a generator may fail in various modes (failure of bearings, burned windings, unbalance, etc.) and the repair actions can vary between replacement of carbon brushes and replacement of the entire generator. Within the DOWEC O&M studies, all failure modes and their resulting repair actions have been described in great detail. To parameterise this as input for the cost models, four maintenance categories have been defined:

- **Cat. 1:** Replacement of rotor and nacelle with external crane;
- **Cat. 2:** Replacement of large components with internal crane;
- **Cat. 3:** Replacements of small parts;
- **Cat. 4:** Inspection and repair.

The failure rates of the individual components have been distributed over the four maintenance categories. For each category a number of input parameters was specified, such as the costs of materials, the costs of labour and the costs of the equipment needed. Furthermore the time to repair, the logistic time of spare parts and the equipment were specified. As these parameters deal with large uncertainties, they can be treated as stochastic variables. For the categories 1 and 2 distinction has been made between high, medium and low priced parts. An example of how the failure behaviour of the turbine has been parameterised is shown in Table 1 for a certain component.

Table 1: Annual failure rate of certain component per maintenance category and the assigned fault type classes to quantify the consequences and uncertainties

<table>
<thead>
<tr>
<th>Annual Failure Rate</th>
<th>Maintenance Category</th>
<th>Probability of occurrence</th>
<th>Conditional Annual Failure Rate</th>
<th>Fault Type Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Cat. 1</td>
<td>Cat. 2</td>
<td>Cat. 3</td>
<td>Cat. 4</td>
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3.2 Access and Hoisting Equipment

For the baseline, a supplier with the OAS system has been selected to transfer personnel, consumables and smaller spare parts. Internal cranes (permanent and mobile) are available to hoist larger parts. To replace the nacelle or rotor, an external crane, for example mounted on a jack-up, is needed. In collaboration with the DOWEC team data relevant for the O&M aspects have been collected, e.g.:

- costs for renting or costs per day, including estimated uncertainties;
- costs for mobilisation and de-mobilisation (MOB-DEMOB);
- weather windows, maximum significant wave height, \( H_{\text{max}} \) and maximum wind speed, \( V_{\text{Wmax}} \);
- expected logistics time.

<table>
<thead>
<tr>
<th>Transportation of Personnel</th>
<th>Component Positioning</th>
<th>Hoisting Equipment</th>
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</thead>
<tbody>
<tr>
<td>Supplier with OAS</td>
<td>Supplier with OAS</td>
<td></td>
</tr>
<tr>
<td>Internal crane (1MT)</td>
<td>Jumping Jack</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Supplier with OAS</th>
<th>Jumping Jack with crane</th>
</tr>
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<table>
<thead>
<tr>
<th>Maintenance Category</th>
<th>Frequency</th>
<th>Probability of occurrence</th>
<th>Conditional Annual Failure Rate</th>
<th>Fault Type Class</th>
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<tbody>
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<tr>
<th>Annual Failure Rate</th>
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<table>
<thead>
<tr>
<th>Material Costs [% of Investment]</th>
<th>Crew Size</th>
<th>Repair Time [hours]</th>
<th>Logistics Time [hours]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Mid</td>
<td>Max</td>
</tr>
<tr>
<td>0.02% 0.03% 0.06%</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>0.40% 0.80% 1.60%</td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>3.00% 6.00% 9.00%</td>
<td>4</td>
<td>8</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Supplier with OAS</th>
<th>Jumping Jack with crane</th>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Supplier with OAS</th>
<th>Jumping Jack</th>
</tr>
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</table>
In the input part of the ECN and TU-Delft models, certain access and hoisting equipment have been assigned to the failed components as is illustrated in Table 1.

3.3 Weather Windows
Each repair equipment has its own maximum wind and wave conditions [10]. For instance, the OAS is assumed to operate up to $H_{\text{max}} = 2.0 \text{ m}$ and $V_{\text{wmax}} = 12 \text{ m/s}$ for transferring personnel, and $1.5 \text{ m}$ and $8.0 \text{ m/s}$ respectively for transferring spare parts. Both ECN and TU-Delft have processed time series of wind and wave data at the NL7 location to determine:

- the waiting time as a function of the duration of the repair, $H_{\text{max}}$ and $V_{\text{wmax}}$;
- the uncertainties of the waiting time and repair actions.

4. RESULTS OF DOWEC BASELINE
Considering corrective maintenance only and assuming a normalised annual failure rate of 1 for the entire turbine, the technical availability is 97.1 % according to CONTOFAX and 94.6% according to the ECN program. This difference is mainly caused by the fact how the built-up crane for maintenance category 2 is treated in both programs. In maintenance category 2 three stages can be distinguished. First the mobile crane is transported to the turbine and is hoisted and mounted into the nacelle. Next the exchange of the failed component can be done and finally the mobile crane has to be dismounted. During all these phases parts are hoisted outside the tower. This means that the weather conditions should be suitable, notably the wind speed has to be less than 6 m/s. The long maintenance activity needed a continuous weather window in the ECN study, whereas an intermittent procedure was allowed in the CONTOFAX simulation.

Considering the lower downtime when interruptions in the procedures are allowed and the impossibility to predict a good weather window of 6 days on beforehand, it is highly recommended to break down long repair actions into smaller steps that can be finished off in case of bad weather. Mobilisation and idle times of offshore equipment must be considered in the breakdown, to avoid large additional costs. When these differences are settled in both models, the results of both programs do agree fairly well.

An annual unavailability of 5.4 % together with a capacity factor of 0.43 and a kWh price of 8 €cents, corresponds to a financial loss of 98 k€ per turbine due to revenue losses. For the entire wind farm of 80 turbines, the revenue losses are 7.8 M€. The total maintenance costs per turbine (direct costs without revenue losses!), consisting of material costs, labour costs and costs for equipment are 80 k€ per turbine or 6,5 M€ for the entire wind farm. It should be remembered that these numbers are based on a normalised annual failure rate of 1. Note that the revenue losses contribute approximately 55 % to the total costs! In other words, the revenue losses are more or less equal to the direct costs.

In order to suggest improvements, e.g. in the design or in the selection of cranes and supply vessels, it is necessary to obtain insight in the cost drivers. It appears that maintenance category 2 contributes the most to the downtime and the costs. Looking into more detail into maintenance category 2 it can be concluded that the downtime is by far dominated by the waiting time.

5. OPTIMISATION OF O&M STRATEGY
Based on the baseline results, several alternatives were analysed to reduce the O&M costs or downtime. The alternatives have been categorised according to the following objectives:

- improvement of deployment of crew and equipment (maintenance strategy)
- reduction of failure rate, including redundancy
- fault tolerant operation
- improvement of accessibility.

In this paper only the alternative where a permanent 50 MT crane is used instead of the mobile crane is presented. It is expected that a permanent crane will lead to lower downtime but higher investment costs. Furthermore, the robustness of the conclusions has been investigated by means of sensitivity studies. Some doubts existed about the exact workable weather windows of access and hoisting equipment. As an example, the influence of the weather windows on the unavailability is presented for access systems for personnel and small parts (the OAS in the Baseline configuration).

5.1 Permanent Crane vs. Mobile Crane
For maintenance category 2, the replacement of large components like the generator, gearbox, or single blade, a 50 MT crane is needed. In the baseline configuration, this crane is a mobile crane. In the nacelle a small crane (< 1
MT) is permanently present. This crane first has to hoist
an intermediate crane that is able to hoist the actual 50
MT crane. These mobile cranes (the intermediate crane
and the 50 MT crane) are brought to the wind turbine
together with the spare part and next both the cranes and
the spare part are hoisted to the platform by a crane ship.
In the costs analysis of the baseline it is assumed that the
assembly of the two mobile cranes and the replacement
of the component takes about 5 working days. During
this whole period the weather conditions should be
suitable for hoisting components outside, which means
that the wind speed should be less than 6 m/s (guiding
systems to prevent the spare parts from colliding the
tower were not foreseen in the baseline). A considerable
part of this period of 5 days is used to hoist and to set up
the 50 MT crane.

In order to reduce the actual repair time and the time that
the top of the nacelle should stay open, it has been
proposed to install a permanent 50 MT crane. Especially
the waiting time for a period of 5 days good weather will
be reduced. As was expected the costs analyses show that
shortening the number of “crane-days” mainly leads to a
reduction of the waiting time. Two days of workable
weather conditions occur more often than five days. For
the baseline, the waiting time is 424 hours per unit of
failure rate, whereas for 4, 3, and 2 crane days, the
waiting time reduces to 198, 83 and 39 hours
respectively. The higher availability leads to additional
income that can be spend on the investment of the
permanent crane. Moreover, the direct costs are also
somewhat lower because personnel and equipment needs
to be hired for a shorter period of time. Assuming a kWh
price of 8 €cents, the annual savings due to the permanent
crane can be up to 80 k€ for the two crane-days with a
normalised failure rate of 1. For the situation considered
a permanent crane of say 150 k€ can be made profitable
within a couple of years. In case the actual failure rate is
higher than 1 this period will even be shorter. Note that
these conclusions strongly depend on the expected occurrence frequency of maintenance category 2. The
reduction of the O&M costs per kWh relative to the
baseline is given in Fig. 3.

![Fig 3: Reduction of the kWh price, relative to the baseline](image)

5.2 Weather Windows for Accessing Personnel

The accessibility of the DOWEC turbine is strongly
dependent on the weather windows for the equipment to
be used. Depending on the type of equipment, the
weather window is dependent on parameters like wave
height (H_s), wind speed (V_w), visibility etc. In this study
the weather windows are specified by wave height and
wind speed only. The criteria set for the weather window
will influence the costs and the availability and to
determine this influence, the values for H_s and V_w have
been varied for the supply boat with steps of 0.5 m and 2
m/s respectively. To determine the influence of the
weather windows the base line configuration was used as
starting point, where the following adjustments have been
made:

- Only one weather window is chosen for the supply boat
for both types of operations, personnel transfer and
transfer of small parts;
- The wind turbine is equipped with a permanent internal
crane as described before

The calculated unavailability for the different weather
windows is shown in Fig. 4.

![Fig 4: Unavailability as a function of V_w max and H_s max
of the access system for transferring personnel
and equipment](image)

From the analyses and the Fig. 4 the following can be
concluded:

- The unavailability is hardly influenced if access
systems for personnel and small parts that can operate under
more harsh weather conditions does not make sense in
this specific case. The weather limits (H_s and V_w) are
independent of the chosen crane: mobile vs. permanent.

- Using systems that can operate under less harsh
weather conditions only, will drastically influence the
availability. In case the maximum wave height for the
supply boat becomes less than 0.5 m, the unavailability
will increase dramatically.

In order to have some safety margin, an access system for
transferring personnel and small parts with the following
limits are recommended: H_s ≥ 1.5 m and V_w ≥ 12 m/s.

6. Uncertainty Analyses

Based on the results of the analyses for optimising the
O&M aspects, the baseline configuration has been
modified. Some alternatives indeed appeared to be cost
The probability of exceeding the average values is in this case 30%. The uncertainty of the failure frequencies of all components appeared to have the largest influence on the uncertainty of the results, especially the uncertainty in the failure frequencies of the blades, generator, drive train and gearbox. They have in common that the number of observed failures is small so the data are covered with large statistical uncertainty, while at the same time their effect on maintenance costs and downtime are large.

7. CONCLUSIONS

The primary objective of the O&M part of the DOWEC project was the exploration of the factors that influence the operation and maintenance. With the cost models of TU-Delft and ECN Wind Energy, the O&M aspects of the 500 MW DOWEC wind farm have been analysed. This wind farm is case study for the North Sea. The starting point in the analyses was the baseline configuration with a mobile 50 MT crane. Some points for improvement were identified and quantified. This led to recommendations for an improved baseline. It should be noted that not all recommendations will be accepted because minimisation of the O&M costs and downtime does not necessarily lead to minimisation of the levelised production costs (LPC). A good example is the replacement of the mobile crane by a permanent crane. The downtime can be strongly reduced by using a permanent crane for large components, however the uncertainty of the results, especially the uncertainty in downtimes and costs as a function of the uncertainties in the input parameters (failure rates, weather windows, and specifications of the access and hoisting systems) has been quantified.

With these results, the DOWEC project team can take more rational decisions for design modifications or improving their O&M procedures.

A secondary objective of this study is the comparison of the two different modelling approaches. The direct O&M costs obtained with the two approaches were very similar, thanks to the more or less straightforward dominance of average failures rates and service requirements. Downtimes could differ significantly, although not unexpectedly, due to the complex influences of the duration of weather windows and maintenance operations. The complementary analyses contributed to the insight and optimisation in a way that could not as easily have been achieved with any of the tools separately.

ACKNOWLEDGEMENT

The work presented in this paper forms part of the fundamental research work within the DOWEC project. This project is partly funded by the EET-program of the Dutch Ministry of Economic Affairs and is being undertaken by LM Glasfiber Holland, Van Oord ACZ, Ballast-Nedam, ECN and TU Delft under the leadership of NEG-Micon Holland.

REFERENCES


1 Can be downloaded at: http://www.ecn.nl/library/reports/main.html