<Session No.>, <Paper No.> Accessing offshore wind turbines for maintenance – calculating access probabilities, expected delays and the associated costs using a probabilistic approach

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Abstract

There are ambitious plans in place for the expansion of offshore wind-power capacity in the EU and elsewhere. However, the cost of energy from offshore wind is much higher than that from land-based generation and anything between 15% and 30% of this cost is attributable to the cost of operation and maintenance (O&M). For exposed UK round three sites these costs could be higher still. The stochastic nature of the occurrence of faults, down-times due to adverse weather and sea-state and the associated losses in energy production, as well as vessel and personnel costs, all add to the potential risk to the finance of an offshore wind farm project. There is a clear need to estimate these effects and the risks associated with them when planning and financing a wind-farm. Key to all such calculations are the restrictions on safe access for maintenance associated with vessels and access methods and the consequent delays caused by adverse sea-state and weather. A computational approach has been developed at University of Strathclyde, based on an event tree and closed-form probabilistic calculations, enabling very fast estimates to be made of offshore access probabilities and expected delays using a simple spreadsheet. Examples are presented for calculations of accessibility. Turbine availability and loss of energy production are calculated based on given turbine component reliability data together with an agreed maintenance scheme. Direct maintenance cost and revenue lost due to down-time can also be calculated with suitable data on the costs of personnel, components, and vessel hire as well as electricity unit and ROC prices, and examples are given. Sensitivities to some of the key parameters are also presented.

Keywords – Offshore Wind, Operation and Maintenance, Risk, Accessibility, Availability, Sea-state, Probabilistic Analysis

Introduction

Operation and maintenance can strongly affect the financial and technical risk of offshore wind energy, largely through uncertainties in the repair process and particularly constraints on access to the turbines. Access for maintenance, particularly in adverse sea-states, can be challenging and will have a major impact on turbine availability. There is a pressing need for improved understanding of this effect. A probabilistic event-tree model has been developed as an alternative to conventional Monte Carlo methods that require repeated extensive simulations. Expected values of delays due to sea-state can be expressed as closed form expressions depending on the probability distributions of sea-state ‘storm’ and ‘calm’ duration.

Using records of significant wave height, sea-state duration distributions for a given threshold wave height can be computed directly from level-crossings and ‘storm’ and ‘calm’ durations. Weibull distributions are generally a good fit for these distributions and relevant parameters can be calculated using maximum likelihood methods. The contribution from each branch of the event-tree to the expected delay time is a function of a small set of parameters calculated from the duration probability distributions. If these distributions are used in Weibull form, they can be calculated directly from the calm and storm duration Weibull parameters for the particular wave-height.

Using subsystem reliability and repair time data, a simple spreadsheet can then be used to estimate annual expected delays due to each subsystem as well as the sensitivities of delays to site, turbine and access parameters. In this work, subsystem reliabilities and repair times are based on operational data from Danish and German turbines based on land. Assumptions are also made about access methods for repairing different subsystems and consequently permissible sea conditions.

Calculations for wind turbines located at North Sea sites for which wave data are available indicate that annual down-times are dominated by repairs to the blades, generator and gearbox. These are not necessarily the subsystems with the highest failure rates but those requiring long repair windows and whose repairs currently require large crane vessels, the use of which is severely restricted by sea-state. The greatest influence on down-time and availability is found to come from changes in the access conditions for repairs, by reducing reliance on ‘sensitive’ vessels, by reducing repair time at the turbine and by reducing vessels’ sensitivity to sea-state.

The advantage of the approach developed is that it is possible to explore the impact of changing access thresholds, reliabilities or site parameters quickly and easily without having to run a long series of simulations for each new situation.

Using suitable data on the costs of personnel, components, and vessel hire as well as electricity unit and ROC prices, the cost implications of maintenance and lost revenue (due to down-time) can also be calculated using the probabilistic methodology outlined above.

Methodology for estimating access delays

The aim of the work undertaken was to arrive at estimates of non-availability of wind turbines recently and/or currently being installed offshore, overall and broken down by sub-system. The approach adopted is that of a probability ‘event tree’ to facilitate rapid assessment of a wide range of input data and scenarios. The paper is concerned with unplanned repairs and the problem of whether access is possible immediately or only after a delay. No attempt has been made to model regular, planned maintenance. Access conditions have been somewhat simplified: for any given fault, it has been assumed that the necessary repair requires the use of a certain vessel type that has known access limits that can be expressed in their simplest terms as a threshold wave height, Hth. It has further been assumed that the repair takes a certain time to complete, and that the wave height restriction applies throughout that time period. The availability of suitable vessels, spares, and personnel are assumed ideal in the analysis presented here, but this could be generalized in future work.

A. Requirements for model

There are several possible approaches to modelling offshore access and its effect on operation and maintenance and thereby on turbine availability. Any such approach will always require certain key elements: wind and wave data; failure rate data for each relevant component or sub-system and each type of failure; actions required in response to each type of failure, particularly materials, personnel, tools and plant and time needed and by implication the vessels to be used; limiting operational conditions, expressed as threshold wind speeds and wave heights for safe operation (characteristic of the vessel required and the transfer systems); travel and operating times required.

How these elements fit together is shown schematically in Figure 1.

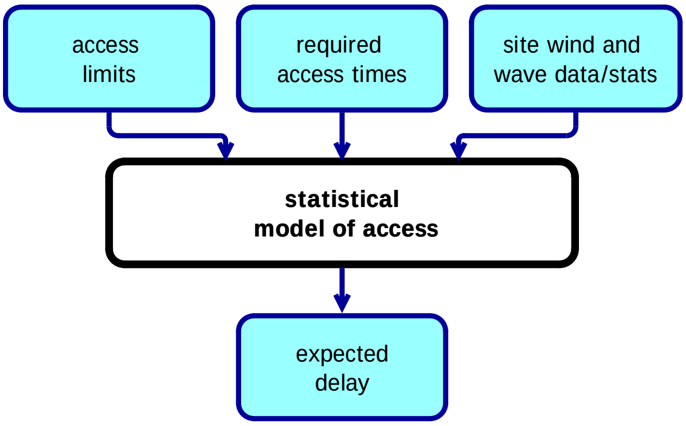

Figure 1: Schematic diagram of offshore access delay calculation

Monte Carlo methods are most commonly used for estimating offshore delays and system down-time. Their main disadvantage is that many runs are required for convergence. A more direct approach to modelling delays is to construct an ‘event tree’. This describes every conceivable event and its alternatives, prerequisite conditions and consequences, with probabilities assigned to each ‘branch’. The advantages are transparency and speed and simplicity of computation and these make it straightforward to explore trends by varying input parameters.

B. Probabilistic delay model

The probabilistic model of operational delay developed here is based on a number of simplifying assumptions that, for the sake of clarity, allow the presentation of a very simple event tree and the derivation of relatively simple expressions for expected delay. For any given offshore operation, the starting point is to define the wave statistics of the given site, the operational limits, which may be expressed as a limiting or threshold wave height for the given vessel, as well as the operation time required (consisting of travel time plus repair time). The expected or mean delay time can then be calculated and thereby down-time.

A number of assumptions are made: faults occur randomly and independently; offshore, repairs are completed in a single visit, which may however last several days; a single operational limit applies to each operation (significant wave height); short term forecasts of sea state are available corresponding to the length of the required operation.

A simplified event tree is shown in Figure 2 below; this accounts both for the threshold wave height and the required time window.

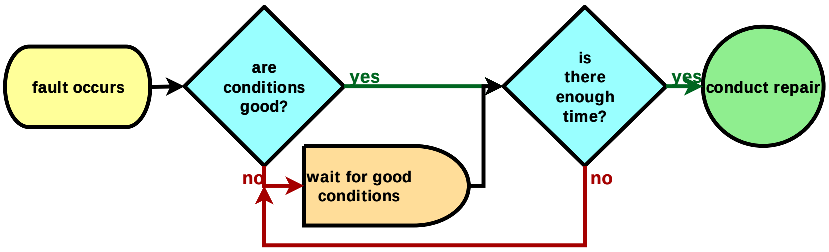

Figure 2: Simplified event tree for offshore repairs

It is possible to identify 4 distinct situations when a fault occurs (see Figure 3):

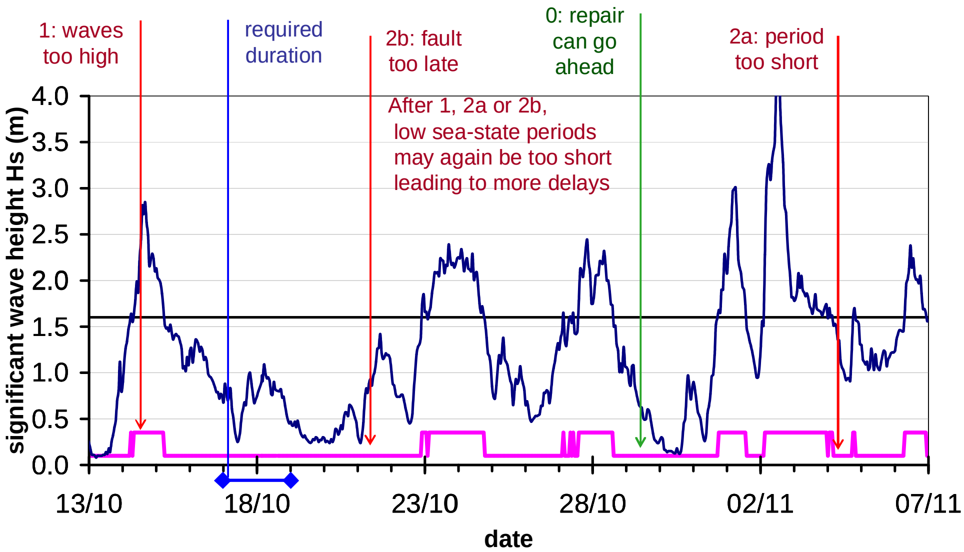

Figure 3: Example wave-height time-series with illustration of types of delay

0: the sea state is low enough and there is sufficient time left to carry out the operation (no delay)

1: the sea state is too high to gain access. The next period of low sea must be waited for. (1st order delay)

2a: the sea state is low enough but is predicted to be too short to effect repair. This period and the subsequent period of high sea-state must be waited through. (2nd order delay, type a)

2b: the sea state is low enough and the predicted period is long enough but there is insufficient time left in the current period to complete the operation, i.e. the fault occurred too late in the weather window. As above, this period and the subsequent period of high sea-state must be waited through. (2nd order delay, type b)

A period of high waves preventing access will eventually be followed by a period of suitably low wave height to allow access, but this may not be long enough to effect the repair and would then lead to a further cycle of delay. Similarly, after a 2nd order delay, there will be a period of high waves followed by a period of low waves and, again, this may not be long enough.

The event tree can also be expressed in a more detailed form as shown in Figure 4 below.

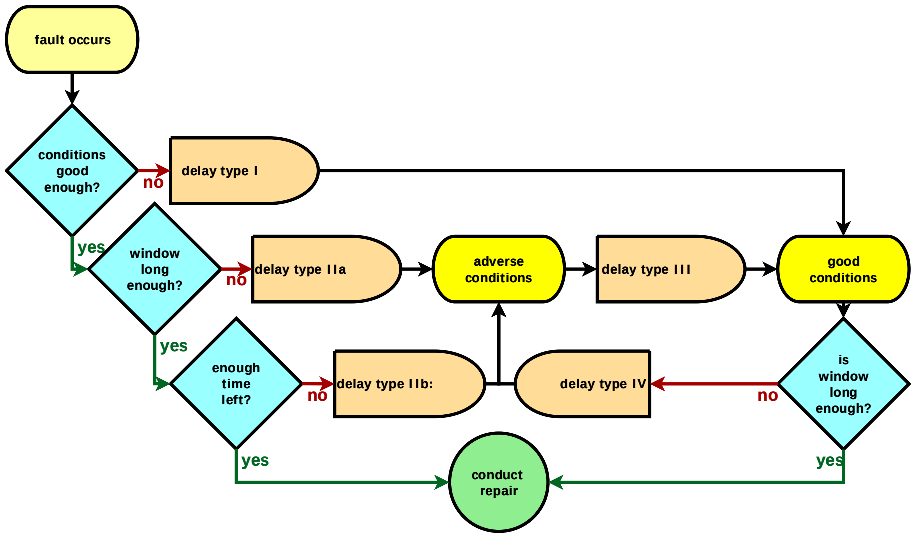

Figure 4: Full event tree for offshore repairs

The probabilities of occurrence of periods of different duration as expressed in the probability distribution are based on numbers of occurrences expected in, say, a year or alternatively a season. In contrast a fault is more likely to occur in a long period than a short one so whether an initial fault occurs in period of type 0, 1, 2a, or 2b, must be time biased. Thus, the expectation of delay resulting from the fault is determined by the 'time-biased' 'storm' (exceedence) and 'calm' (non-exceedence) duration probability distributions. On the other hand, the probability of a subsequent period being long or short is not biased in this way and, assuming independence , follows the original unbiased occurrence probability distribution.

The derivation of the relevant expressions for the probabilities of each of the above and the respective expected values of delays is omitted here but summary equations are presented below.

$\mathrm{P}_0(H_{th},t_{req})$ gives the probability that the wave height will be below a given threshold, H_{th}, and remain so for a clear window of time, t_{req}:

$$\mathrm{P}_0(H_{th},t_{req}) = [1-\mathrm{P}_\mathrm{H}(H_{th})]\cdot[1-\mathrm{M}_\mathrm{qn}(H_{th},t_{req})-\mathrm{Q}_\mathrm{n}(H_{th},t_{req})\cdot t_{req}/\tau_n(H_{th})] \quad (1)$$

where $\mathrm{P}_\mathrm{H}(H_{th})$ is the probability that wave height exceeds the threshold H_{th}

$\mathrm{q}_\mathrm{x}(H_{th},t)$ and $\mathrm{q}_\mathrm{n}(H_{th},t)$ are the storm and calm duration probability density functions for a threshold wave height of H_{th}

$\mathrm{Q}_\mathrm{n}(H_{th},t)$ is the probability that a calm with $H_S < H_{th}$ has a duration longer than t_{req}, and is found by integrating $\mathrm{q}_\mathrm{n}(H_{th},t)$ up to t_{req}

$\mathrm{M}_\mathrm{qn}(H_{th},t_{req})$ is the normalised partial 1st moment of $\mathrm{q}_\mathrm{n}(H_{th},t)$ up to t_{req}

$\tau_n(H_{th})$ is the mean calm duration

$\tau_x(H_{th})$ is the mean storm duration

$\mathrm{M}_\mathrm{qqx}(H_{th})$ is ½ the normalised complete 2nd moment of $\mathrm{q}_\mathrm{x}(H_{th},t)$

and $\mathrm{M}_\mathrm{qqn}(H_{th},t_{req})$ is ½ the normalised partial 2nd moment of $\mathrm{q}_\mathrm{n}(H_{th},t)$ up to t_{req}.

The expected value of delay, taking into account all contributions, and with arguments omitted for clarity, is given by:

$$
\begin{aligned}
\mathrm{E}\left[\mathrm{t}_{\mathrm{delay.total}}\left(H_{th},t_{req}\right)\right] = {} & \mathrm{P}\left(H_{th}\right)\cdot \mathrm{M}_{\mathrm{qqx}}\left(H_{th}\right)\cdot \tau_x\left(H_{th}\right) \\
& + \frac{\left(1-\mathrm{P}\left(H_{th}\right)\right)^2}{\mathrm{P}\left(H_{th}\right)}\cdot \mathrm{M}_{\mathrm{qqn}}\left(H_{th},t_{req}\right)\cdot \tau_x\left(H_{th}\right) \\
& + \mathrm{P}\left(H_{th}\right)\cdot \mathrm{Q}_{\mathrm{n}}\left(H_{th},t_{req}\right)\cdot \frac{t_{req}{}^2}{2\tau_x\left(H_{th}\right)} \\
& + \mathrm{P}\left(H_{th}\right)\cdot \mathrm{Q}_{\mathrm{n}}\left(H_{th},t_{req}\right)\cdot t_{req} \\
& + \left(1-\mathrm{P}\left(H_{th}\right)\right)\cdot \mathrm{M}_{\mathrm{qn}}\left(H_{th},t_{req}\right)\cdot \tau_x\left(H_{th}\right) \\
& + \left[\mathrm{P}\left(H_{th}\right)+\left(1-\mathrm{P}\left(H_{th}\right)\right)\cdot \mathrm{M}_{\mathrm{qn}}\left(H_{th},t_{req}\right)\right]\cdot t_{req} \\
& + \frac{\left[\mathrm{P}\left(H_{th}\right)+\left(1-\mathrm{P}\left(H_{th}\right)\right)\cdot \mathrm{M}_{\mathrm{qn}}\left(H_{th},t_{req}\right)\right]^2}{\mathrm{P}\left(H_{th}\right)\cdot \mathrm{Q}_{\mathrm{n}}\left(H_{th},t_{req}\right)}\cdot \tau_x\left(H_{th}\right)
\end{aligned}
\qquad (2)
$$

C. Sea-State Representation

There are many different sources and types of data that can be used to characterize a local sea-state. For this work it has been assumed that adequate time-series data exist for significant wave height, Hs. These data are used to fit Weibull probability distributions for Hs and for durations of calms and storms corresponding to the threshold wave height under consideration. A combination of the method of moments and maximum-likelihood analysis was used.

An example is shown in Figure 5 and Figure 6 using data from the Barrow OWF site (at 054° 0.0'N 003°18.8'W) from August 1992 to November 1993, and was downloaded from the web-page of the British Oceanographic Data Centre (BODC) *[1]*.

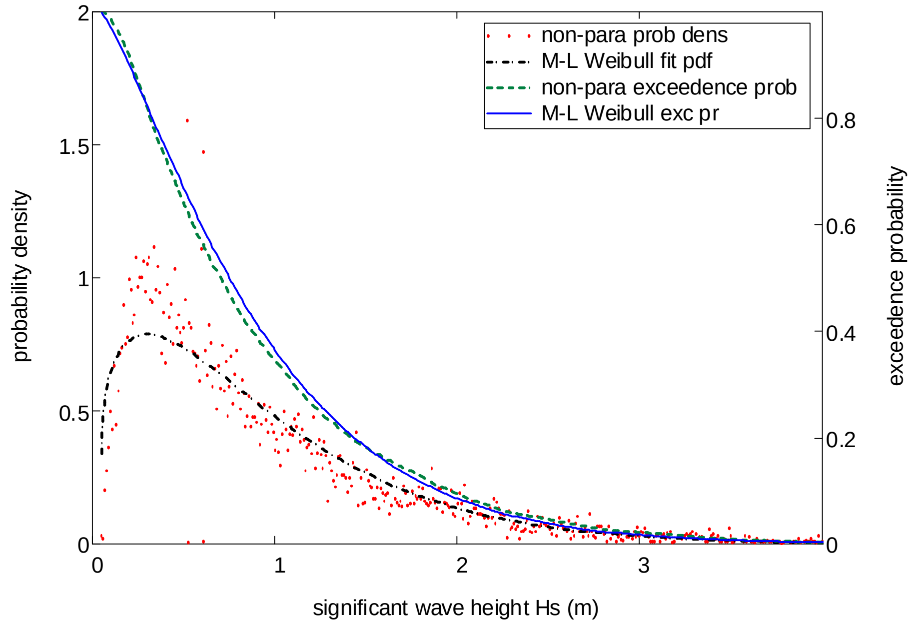

Figure 5: Significant wave height distributions for Barrow OWF

From these distributions, the required moments can be calculated, and from these the expected delay can be estimated as set out above in eqn. (2).
The outcome of the probability tree calculation is a set of curves giving delay time as a function of limiting sea-state (threshold wave height) and operational time required. An example family of curves in Figure 7 is based on the same Barrow OWF site data as in the figures **Error! Reference source not found.**. They show delay time against operation time for a range of threshold wave heights. It can be seen that the delay time is very sensitive to both operation time and threshold. It should also be noted that they are highly sensitive to the specific site's sea conditions.

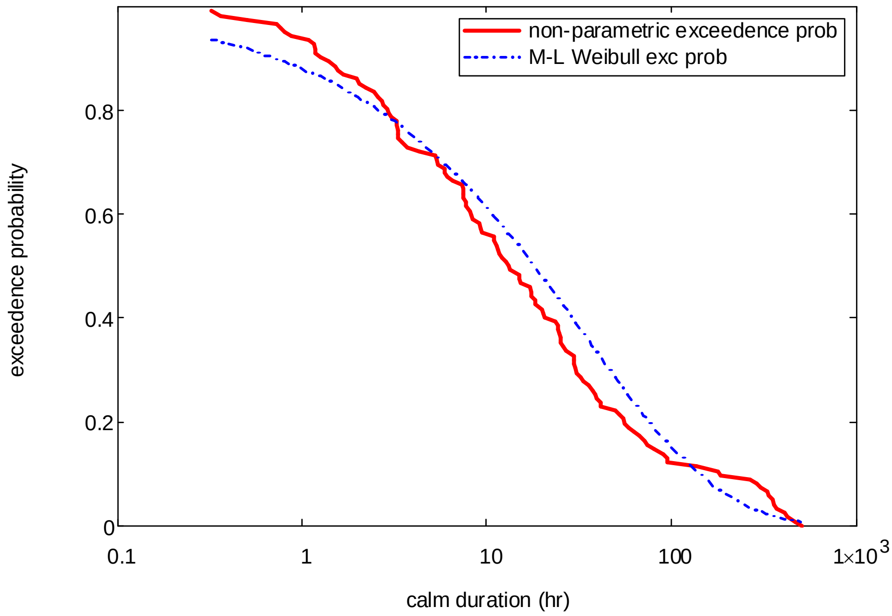

Figure 6: Calm duration exceedence distribution for Barrow OWF

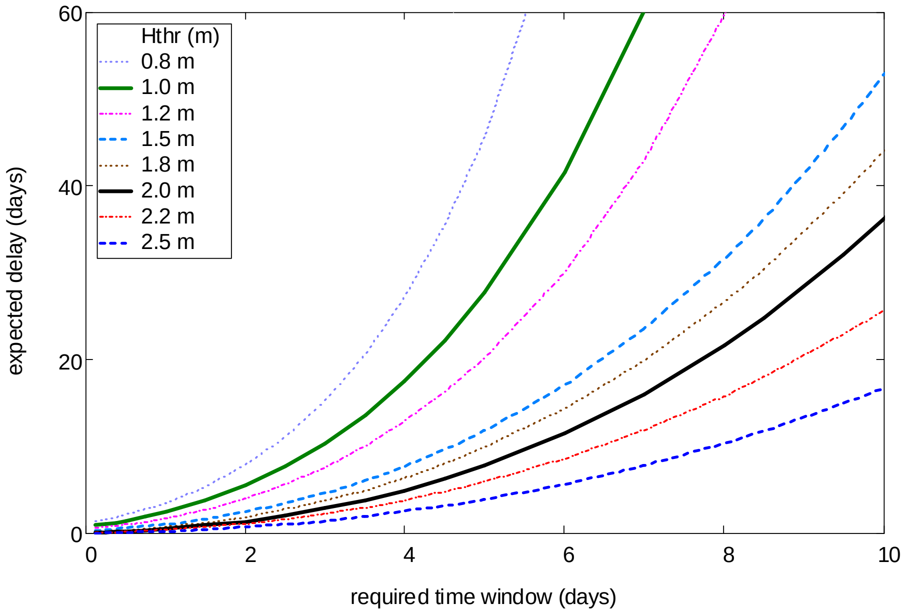

Figure 7: Expected delay time vs. repair time, for different wave height thresholds at Barrow OWF site

Example application of model: assessing influences on turbine availability and costs

A. *Reliability and maintenance data sources*

In order to estimate the impact of maintenance access on revenue, it is necessary to estimate total down-time. Ideally, data are needed for each fault type on failure rate, operation type and time required, 'muster time', vessel required and its operational limits and speed.

There are virtually no detailed data in the public domain regarding offshore wind farms so data from land-based wind farms have been used. Numerous sources of data are available, each with strengths and weaknesses. For our purposes, we have derived a baseline description of component reliability and repair times synthesized from a number of published reports and shown here in Figure 8.

For this study, an overall whole-turbine failure rate has been derived from *[2]*, where a trend can be observed of failure rate increasing with turbine size. A baseline turbine with 3.2 MW rating was chosen and an appropriate figure of 3.5 failures per year was assumed. The subdivision of that failure rate between subsystems was derived from *[3]* (where only percentages are given). Proportions of failures were allocated to different severities of repair category, where the categories themselves and the parameters associated with them are largely derived from *[4]*. The relative proportions allocated were checked against *[5]*, where a loose division is made between major and minor repairs, i.e. longer or shorter than 24 hours respectively. The process of creating the baseline dataset is discussed in greater detail in *[6]* (though some figures used in this paper are more recent). There is also an explanation of sources of cost data and of how cost calculations are carried out *[ibid]*.

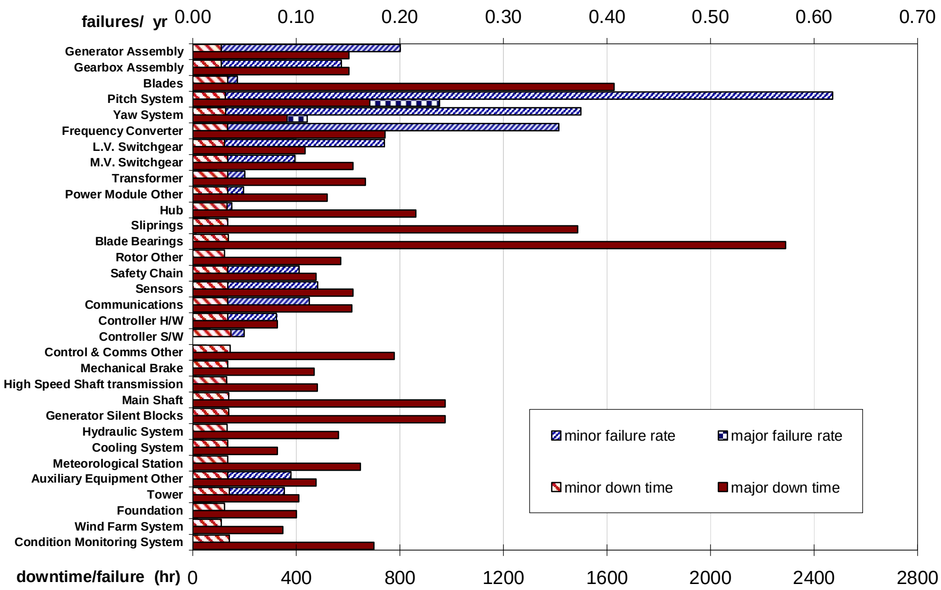

Figure 8: Baseline case subsystem failure rates & down-times per failure

All calculations were performed in a spreadsheet. (A small macro is required to calculate the incomplete gamma function, though there are routines and numerical recipes in the public domain). For any one fault class calculation, an appropriate threshold is set, the total offshore operation time is estimated from a lead time, a travel time, positioning time and a repair time and the corresponding expected delay

time is calculated. The expected annual delay caused by that fault class is the product of failure rate per year with the delay time per fault. The sum of all the subsystems' annual contributions to down-time gives the total expected annual down-time and thereby the (un)availability.
Figure 9 clearly shows that both maintenance and loss of revenue have major impacts on costs and that the former is dominated by vessel costs.

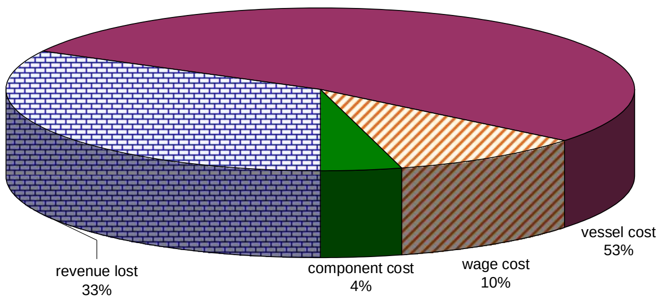

Figure 9: Baseline contributions to cost

Sensitivities to key operational parameters

The base line case gives an expected annual loss of approx. 876 hours or 36.5 days, equivalent to an availability of about 90%. As can be seen in Figure 10, the annual down-time is in the main dominated by the large subsystems, generator, gearbox, and power electronic converter, as well as the pitch mechanisms. This is true to a greater extent than might be guessed just from failure rates and repair times. Of course, these figures must be treated with caution but they illustrate the extent to which delays to repairs on large subsystems are exacerbated by the long operational time needed and the requirement for vessels that are sensitive to sea conditions.
The effect of changing repair times, failure rates, and access thresholds (for large and small vessels separately) was modelled by scaling the baseline case figures by ± 30%. In addition, sensitivity to sea-state conditions is presented. Curves of sensitivity to lead times and vessel speeds have been omitted for clarity as the sensitivities are so low.
It can be seen in Figure 11 that, of the factors that can be influenced at a particular site, the thresholds for minor and major vessels have by far the greatest effect on availability, with the former having slightly more effect. The effect of site conditions is also very strong, but it can not always be influenced – the choice of sites may be limited. Repair time and failure rate have significant but somewhat smaller effects. In the figure, failure rate appears to have a greater effect than repair time but in reality this is not the case as a percentage change in failure rate in this model applies across all repair categories, minor and major.
If lost revenue is examined rather than availability, as in Figure 12, vessel thresholds and site conditions still have the greatest effect, but the differences between major and minor failures seem to be reduced. It should be noted that when energy generated and revenue lost are calculated, a distinction is made between stoppages in high and low wind conditions.

Finally, operation and maintenance cost is shown in Figure 13. Here it can be seen that there is a large difference in the overall cost of major and minor repairs, largely due to the day-rate of heavy lift vessels.

Note that these results are somewhat different from those presented previously *[7]*; this is believed to reflect refinement in the representation of repair times.

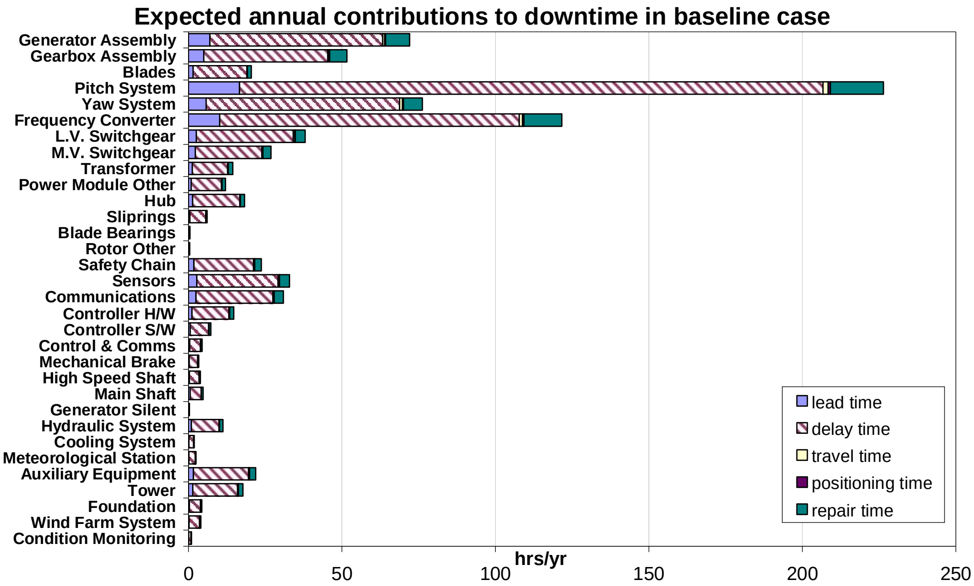

Figure 10: Expected annual contributions to downtime by subsystem

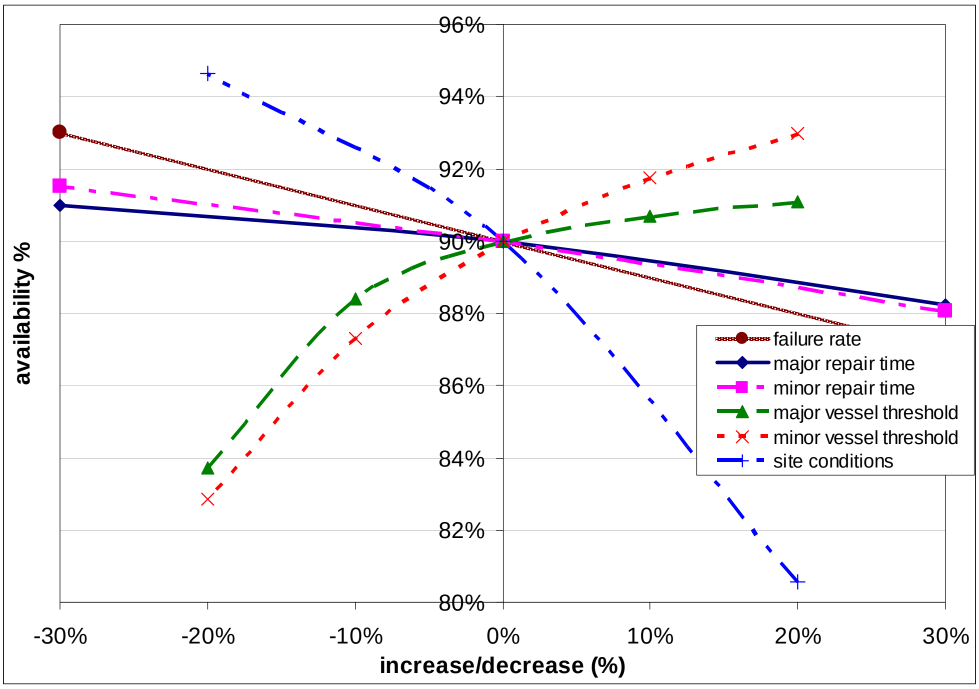

Figure 11: Sensitivity of turbine availability to different factors

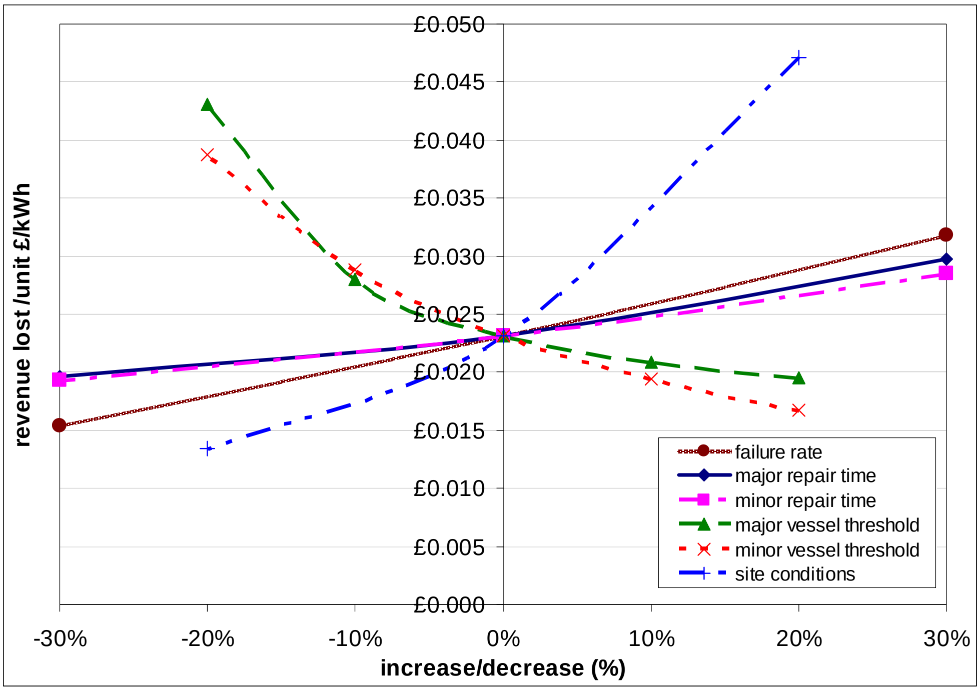

Figure 12: Sensitivity of lost revenue to different factors

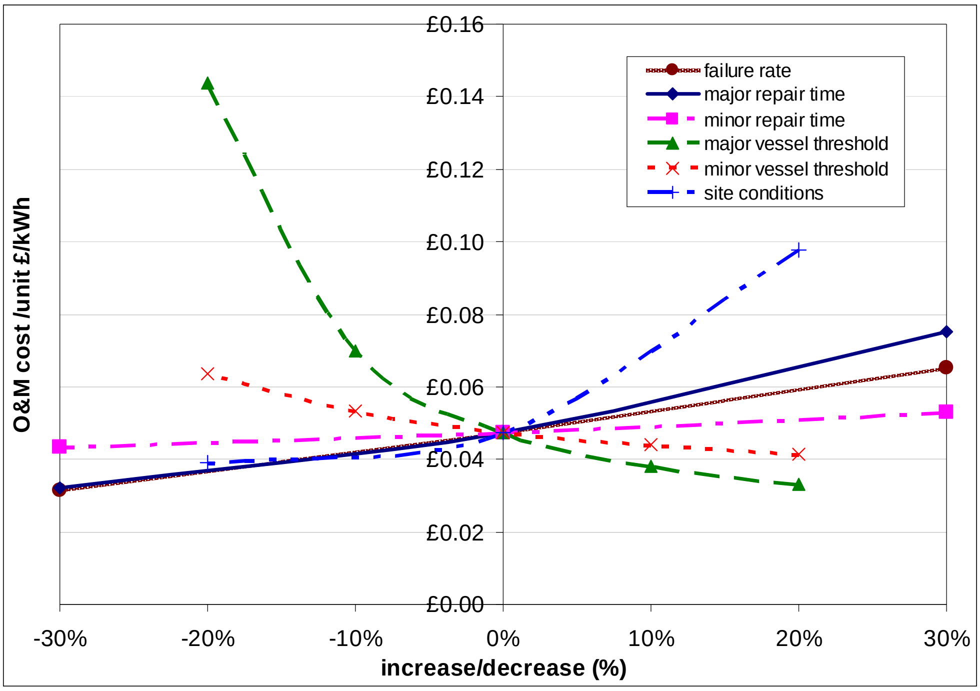

Figure 13: Sensitivity of O&M cost per unit to different factors

Summary & Conclusion

A method has been presented for calculating the expected delays to offshore operations directly from probabilities assigned to the branches of an event tree.

The current lack of data in the public domain regarding offshore wind farms makes validation of the methodology difficult.

The advantage of the approach developed is that it does allow rapid investigation of the influence of various factors on downtime without having to run a long series of simulations for each new situation.

Calculations indicate that annual down-times tend to be dominated by repairs to the generator, gearbox, converter, and pitch mechanism. Not all the critical subsystems have the highest failure rates but they tend to require long repair windows and require large crane vessels, the use of which is severely restricted by sea-state. The greatest influence on down-time and availability is found to come from changes in the access conditions for repairs, by reducing reliance on 'sensitive' vessels, by reducing repair time at the turbine and by reducing vessels' sensitivity to sea-state.

The cost of failures is dominated by day-rates for heavy lift vessels required for major repairs and replacements. The greatest impact on costs would be achieved by reducing the frequency of these types of failures and reducing the repair time needed, as well as by enabling repairs to be carried out in a wider range of conditions.

Future work will concentrate on validation and should include the calculation of confidence limits on the results presented here, these being expected values.

References

[1] British Oceanographic Data Centre (BODC) Wave data series archive http://www.bodc.ac.uk/data/online_request/waves/ (Last accessed on 06/04/2011)

[2] Spinato F, Tavner PJ, Bussel GJW van, Koutoulakos E; 'Reliability of wind turbine subassemblies'; IET Renew Power Gen,2009,Vol 3,Issue 4, pp387–401

[3] Wilkinson M, Hendriks B, Tavner P; Report on Wind Turbine Reliability Profiles; GL-GH for Reliawind FP7-ENERGY-2007-1-RTD Deliverable D-1-3

[4] Rademakers LWMM & Braam H; 'O&M ASPECTS OF THE 500 MW OFFSHORE WIND FARM AT NL7 - (80 × 6 MW Turbines) - Baseline Configuration'; DOWEC Report Nr. 10080 rev 2, 2002, ECN & TUDelft, NL

[5] Faulstich S, Hahn B, & Tavner PJ; 'Wind turbine downtime and its importance for offshore deployment', Wind Energy 2011; Vol. 14; pp327–337

[6] Feuchtwang JB & Infield DG; 'Estimating the cost of offshore maintenance and the benefit from condition monitoring; European Offshore Wind Conference 2011, Amsterdam

[7] Feuchtwang JB & Infield DG; 'The Offshore Access Problem and Turbine Availability - Probabilistic Modelling of Expected Delays to Repairs'; European Offshore Wind Conference 2009, Stockholm