# Analysis of different means of transport in the operation and maintenance strategy for the reference DOWEC offshore wind farm

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**ABSTRACT**

The DOWEC project aims at implementation of large wind turbines in large-scale offshore farms. A baseline wind farm has been determined consisting out of 80 wind turbines of 6 MW each and is located 43 km off the Dutch coast. The following access systems for O&M crew have been investigated in the paper: a rubber boat (zodiac), the offshore access system and a helicopter. For these access systems the operational limits, expressed as maximum mean wind speed and significant wave height, have been established. On the basis of the NEXT database the statistics of the corresponding weather windows are been determined. These statistics together with the failure statistics and the regular maintenance demand of the wind turbines and the other offshore wind farm components determine its availability at the specific site. Estimates of the availability of the offshore wind farm have been obtained with a sophisticated Monte Carlo simulation model of the operations within the wind farm. The simulations show that use should be made of access systems with an accessibility of at least 82%; this rules out simple options as a rubber boat in order to maintain a farm availability of above 90%.

## 1. INTRODUCTION

The ability to maintain offshore wind turbines is very much dependent upon the access system used. The actual weather conditions at the site, and its forecast are important for planning transport of maintenance crews and landing using vessels. And for landing the crew at the wind turbines the access system chosen will be a decisive factor for the ability to perform maintenance activities. For the determination of the operation and maintenance (O&M) strategy of offshore wind farms a forecast of the expected weather windows at the actual site are thus required. Within the scope of the DOWEC (Dutch Offshore Wind Energy Converter) project [1], the required weather windows are determined on basis of the NEXT/NESS (North European Storm Study) database. An estimate of the availability of an offshore wind farm can be realised in an advanced way using a Monte Carlo simulation model of the O&M operations within the wind farm. From several Monte Carlo realisations it is possible to extract a trend line of the availability of the wind farm as function of the accessibility of the farm, which depends on the means of transport / access system. In the following section a general treatment of the O&M problem offshore will be given first. Next the above outlined method will be applied for the DOWEC reference wind farm.

## 2. ANALYSIS OF THE O&M PROBLEM

### 2.1 Introduction

Apart from the size of future offshore wind farms there is another evident and important difference with on shore wind farms. Not only the installation is more difficult and more expensive but also building wind turbines offshore has a major impact on the accessibility for maintenance purposes. It may well be that the complete wind farm is inaccessible by boat or helicopter for a period of one or two months because of harsh weather conditions (wind, waves and visibility). And even when weather permits access to the turbines, the cost of offshore maintenance is far higher than the equivalent job on shore. Lifting actions are performed relatively easy on land, but in an offshore environment, require special and therefore expensive and sometimes scarce equipment.

### 2.2 The availability of offshore wind farms

The availability of a wind farm, defined as the percentage of time it is able to produce electricity, is a function of the reliability, maintainability and serviceability of the hard- and software used in the whole system. For an offshore wind farm however the accessibility of the site for O&M hardware equipment as well as the adopted maintenance strategy are of an equal importance for the achieved availability level [3]. In figure 1 this is shown in a schematic way.

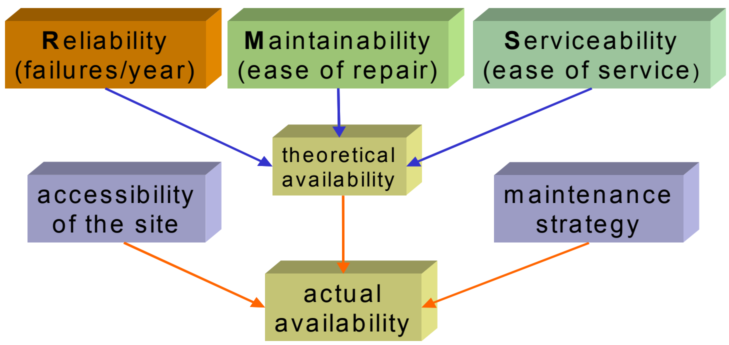


**Fig 1:** Theoretical and actual availability as a function of machine properties, site accessibility and maintenance strategy

Nowadays commercial onshore wind turbines show very high availability levels. With a proper service organisation and by ensuring that regular maintenance actions are quick and can be performed in time the operators of modern wind turbines show actual availability levels of 98% and beyond. It must be stressed however that this is achieved through visiting a wind turbine about four to six times a year, either for regular service (usually twice a year) or for curing (repair) actions. In situations where both limited access and limited availability of maintenance equipment are at stake, such as for the offshore environment, this may easily lead to an unacceptable down time level. This makes it inevitable to assess the O&M demand of an offshore wind farm in conjunction with the other design parameters in order to achieve the required availability level against optimal cost expenditure. The latter being a trade of between investment costs in order to increase the reliability and the cost of maintenance actions to boost the availability to a high level. Since site accessibility always has a level below 100% for offshore conditions it is paramount to focus first on the decrease of the failure frequency of an offshore wind energy system.

Vestas cite a comparison between availability rates for their Fjaldene onshore wind farm and Tunø Knob offshore wind farm [9]. The average availability for Fjaldene is quoted as 99.3% mainly due to the proximity of this windfarm to Vestas' Central Service Department. Tunø Knob average availability is quoted as; 97.9%, 98.1%, and 95.2% for the years 1996 to 1998 respectively [9]. However it must be stressed that these figure are from a rather small wind farm located close to the coast and in the inland waters of Denmark. The targeted availability level for the recently completed Horns Rev wind farm in the North Sea in front of Esbjerg (DK) is 95% [3].

## 3. SITE CONDITIONS ANALYSIS OF THE DOWEC REFERENCE WIND FARM

### 3.1 Operational limits of different access systems

Operation and maintenance actions for an offshore wind farm involve hoisting actions of e.g. complete nacelles or rotor blades; this will require some means of transport (e.g. barge) and lifting equipment (e.g. jack-up or crane vessel). In this paper the focus will not be on these kind of O&M operations but on the transport of the maintenance crew (including small spare parts and tools only) and especially on the access system to the individual turbines. Some of the crew access systems, currently considered for offshore wind farms, are rubber boats ('Man Over Board'; 'Zodiac'), OAS and helicopters. The OAS is a specially designed gangway developed by P&R systems [6]. The maximum significant wave height and mean wind speed for the considered access systems are summarized in table 1. These limits have been gathered from public available information and private communication, and some of these values are still subject to discussion. In order to study the influence of these operational limits on the availability of an offshore wind farm a fictitious access system is added as well as an optimistic assumption for an OAS.

| No | Access system | Significant wave height (m) | Average (1-hour) wind speed (m/s) |
|---|---|---|---|
| 1 | Fictitious | 0.75 | N.A. |
| 2 | Rubber boat, jump onto ladder | 1.5 | 10 |
| 3 | Offshore Access System (OAS) | 2 | 11.5 |
| 4 | Offshore Access System + (optimistic assumption) | 3 | 15 |
| 5 | Helicopter | NA | 20 |

**Table 1:** Preliminary wind speed and wave height criteria for different access systems.

### 3.2 Determination of weather windows from the Next database

Within the scope of the DOWEC study a reference location, about 43 km off the Dutch coast (indicated as NL7 in figure 2), has been selected for further study. Use is made of the NESS/NEXT (North European Storm Study) database to determine the wind, wave and current characteristics for this site. The NEXT data are given on a 30 km by 30 km grid, see figure 2.

The database consist of hindcast data and are given in a 3-hour interval covering the winter months of the period October 1964 to March 1995. For 9 years also the data of the summer months is included; thus for these years the complete data is available.

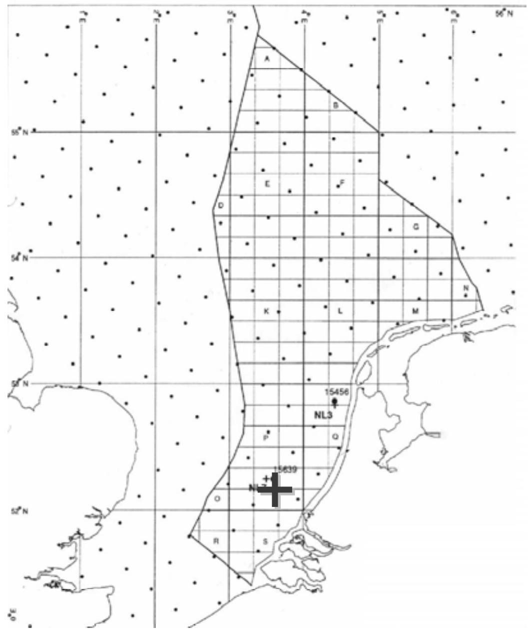

**Fig 2:** The locations of the NEXT grid points (dots) and the NL7 site (cross)

The unique feature of the NEXT database is that the correctly correlated wind and wave data is available. In this paper the following 2 variables from the NEXT database are used:

- (1-hour) mean wind speed V (m/s) at 10 m height
- significant wave height $H_s$ (m)

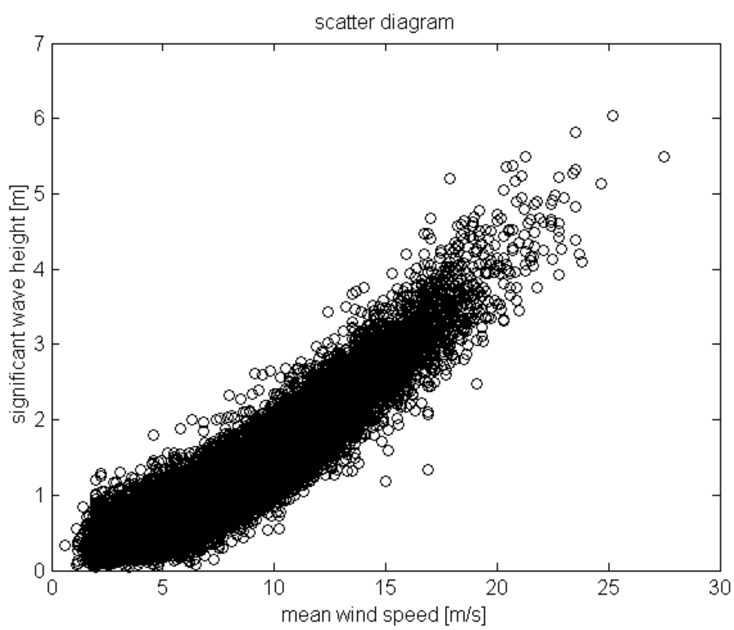


**Fig 3:** Scatter diagram of wind and waves for the NL7 location

The NEXT database also includes wind and wave direction, mean zero crossing period and the significant wave height, wave direction and peak period from wind sea state and swell separately. Furthermore the current and some directional spreading variables are available. In NEXT no information is given on visibility.

For a detailed description of the NEXT database the reader is referred to [4]. The database has been used, in scope of the DOWEC project see [4], to determine the:

- wind rose (required for the energy yield calculation of an offshore wind farm);
- extreme values for several return periods (in order to determine the extreme loading of an offshore wind turbine);
- combined (3D) scatter diagram of the significant wave height, zero crossing period and mean wind speed (required for the fatigue analysis of the support structure);
- weather windows (for the installation as well as for O&M operations)

This paper deals with the last item. A first impression of the variability of the wind and waves for the NL7 location is given by means of a so-called scatter diagram, see figure 3. Such a diagram already provides some insight in the effects of enlarging the operational limits of an access system in order to increase its workability. From figure 3 it follows that, concerning an access system (for application at a wind farm at NL7) with limits $H_s < 2$ m and $V < 10$ m/s, it makes not much sense to extend the wave limit without extending the wind limit at the same time.
The statistics of the weather windows for the access systems from table 1 can be determined in a straightforward manner from the NEXT database for 9 complete years (26288 time points in total), see figure 4. A distinction is made in this figure between percentages in the winter (Oct-Mar) and the summer (Apr-Sep) period. Note that the overall accessibility of a given access system can be estimated by extrapolation of the lines toward the y-axis (for a weather window of 0 hours). Since the NEXT data are given in a 3-hour interval the overall accessibility cannot be determined directly.

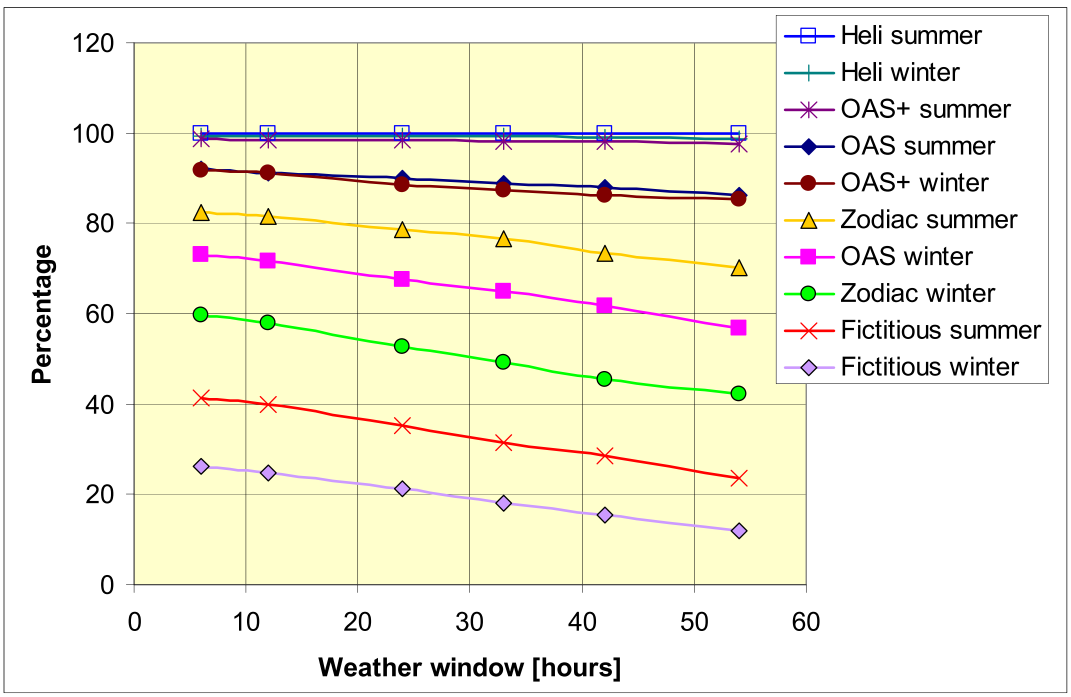


**Fig 4:** Percentage of time that the operational limits (maximum significant wave height and wind speed) are not exceeded for several access systems versus the (minimum) length of the (uninterrupted) time interval.

The calculated weather window percentages for access by helicopter have to be interpreted with care, because they are based on the wind speed restrictions only. Reduction of the percentage of time that a weather window cannot be used due to i.e. fog is certainly perceivable, but is not included in the estimates of figure 4.

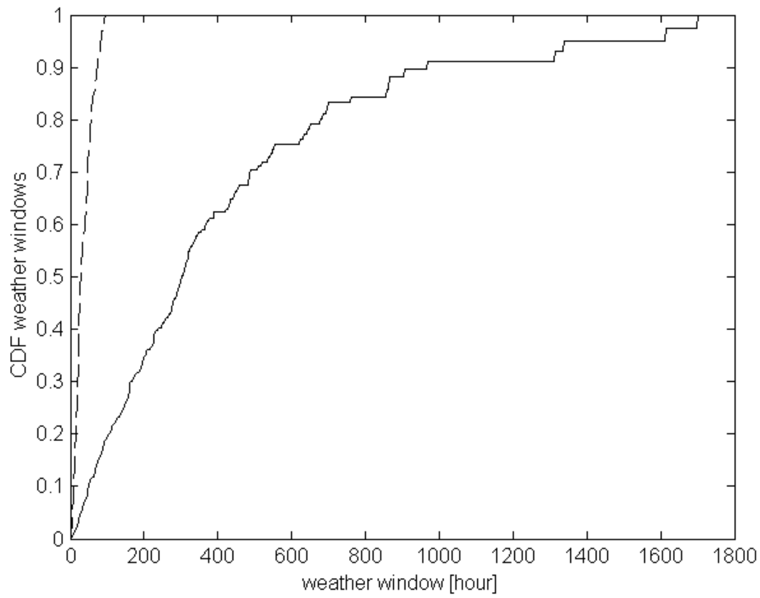


**Fig 5:** Cumulative distribution functions of the weather windows for the OAS (total year) at the NL7 location.
Solid line: CDF of weather windows which do not exceed the operational limits;
Dashed line: CDF of windows which exceed limits

From the data in the NEXT database it is also possible to determine the cumulative probability density function (CDF) of the weather windows for the various access systems. In figure 5 the CDF's are shown for the weather windows of the OAS system. The solid line shows the CDF for weather windows in which the operational limits for the OAS are not exceeded. This figure must be read with care: it expresses the probability that an operational weather window of N hours or less length is met, provided an operational weather window is present. From figure 5 it can e.g. be read that the probability of a weather window of at most 400 hrs long is about 60%. Furthermore the probability that the window is between 200 and 400 hours long is about 60% - 30% = 30%.

Apart from the CDF for the non-exceeding windows there is also a CDF for exceeding windows shown in fig 5 (dashed line). This function tells e.g. that the probability of a window of at least 200 hours exceeding the operational limits is 0. All the windows in which the operational limits are exceeded are less than 100 hours long. This thus means that waiting time for the start of an O&M action is always less than 100 hours. It does not say anything about the total length of the O&M action. In section 3.4 this will be discussed in more detail, based upon the results of Monte Carlo simulations.

## 4 O&M SIMULATIONS FOR THE DOWEC REFERENCE WIND FARM

### 4.1 CONTOFAX simulations of the O&M operations of the DOWEC wind farm

The statistics of the weather windows, together with the failure statistics and the regular maintenance demand of the wind turbines and other farm components determine the availability of an offshore wind farm at the specific site. A sophisticated way to calculate this is by means of a Monte Carlo approach in which realistic maintenance actions are determined under random simulation of wind and wave conditions, random wind turbine failures, predefined maintenance crew deployment and given availability of maintenance equipment. At TU Delft the code CONTOFAX [2] was developed for this purpose. It determines the necessary and possible operations in an offshore wind farm for a given maintenance strategy. Furthermore spare part logistics can be assessed with the program. In the code the number of crews, number of shifts per 24 hours and the days worked per week have to be specified, also the kind and quantity of equipment available for the crews, e.g. the number of vessels. Different maintenance strategies can be evaluated by changing, for example, the input parameters for the time intervals of the year where preventive maintenance (PM) and/or corrective maintenance (CM) is carried out. At the end of a simulation the total O&M costs, the achieved availability and the produced energy of the wind farm are determined. Simulations performed with CONTOFAX immediately made clear that the present failure rate for onshore wind turbines is insufficient for offshore wind farms: the onshore availability of about 97% would drop to about 70% at an offshore location [2].

The stochastic weather simulation has an ‘inaccessibility percentage’ and an average wind speed as input parameters, for both summer and winter season. With these parameters a two-parameter Weibull representation is constructed of the length of the inaccessibility intervals and the length of accessibility intervals. This way of modelling was taken from a study performed by Havers [7] on the provisioning of drilling platforms at the North Sea and was implemented in a weather simulation code which is a part of the CONTOFAX code [5]. For the combination of site parameters and operational limits the distribution of the corresponding weather windows can be are established, in a similar way as the CDF distributions shown in figure 5. The resulting stochastic weather simulations then match, in a statistical way, the desired “inaccessibility” percentages. The advantage of such an approach is that simulations can be performed without detailed information of the wind and wave conditions for a considered site. In the present situation the CDF of the weather windows are available, i.e. figure 5, which could be fitted directly to the Weibull distributions, but such direct fitting has not yet taken place. Instead it is assured that the overall accessibility percentage for the summer and the winter season in the simulations is the same as the levels derived from the NEXT hindcast date for the location NL-7.

### 4.2 Definition of DOWEC reference wind farm and maintenance categories

The baseline configuration of the DOWEC offshore wind farm consists out of 80 turbines of 6 MW nominal power. For the O&M analysis all the different O&M activities are put into a limited number of maintenance categories, see table 2. For each category the failure rate is specified (or equivalently, the mean time between failure), as well as the required repair time (and if applicable the mobilisation/demobilisation time) and the required repair tool (e.g. internal or external crane). In references [3] and [8] several possible turbine concepts have been investigated with respect to O&M; the failure rates were estimated to range from about 0.9 yearly failures for a ‘Robust concept’ to 1.2 for a ‘Smart-stall concept’. These values are well below the rates currently experienced at onshore wind turbines. But it must be bared in mind that the DOWEC project refers to a future well adapted 6 MW wind turbine design that has not yet been realised.

| Maintenance categories |
|---|
| Cat. 1: Heavy components, external crane |
| Cat. 2: Large components internal crane |
| Cat. 3: Small parts, 48 hrs repair time |
| Cat. 4: Small/no parts 24 hrs repair time |

**Table 2:** Maintenance categories for the DOWEC reference turbine

The simulations carried out are based on the reliability figures of the present DOWEC baseline wind farm. The total farm requires at least 40 PM operations per year (maximum PM interval of two years) and the average number of CM visits is 120 per year (1.5 failures per year per turbine). Furthermore it is assumed that the maintenance crews work in one shift of 12 hours per 24 hours (i.e. crews work only by daylight) and per shift there are always 2 crews available.

### 4.3 Consequences for the planning and duration of successful O&M actions

The CONTOFAX simulations deliver a large amount of information regarding the desirability and adequacy of the adapted O&M strategy. Within this paper we well restrict ourselves to the impact of the chosen means of transport upon the planning of the O&M actions. At first the results have been analysed with respect to the probability that direct action can be taken when there is a need to perform an O&M activity. In figure 6 below the results of Monte Carlo simulations for different accessibility percentages are shown (symbols), for varying lengths of the required O&M window.
The respective windows are 12, 24, 48, 168 (one week) and 336 (two weeks) long. The solid lines show a linear approximation of the simulation results. Note further that the various simulations for a given accessibility percentage (read weather simulation) are generated with the same realisation of the weather conditions. Although there is a significant amount of scatter, which might be reduced by repeated weather simulations with a different "seed" in the random generation, there seems to be a linear decrease of the probability that direct action can be taken with the decrease of accessibility, which is also a plausible relation.

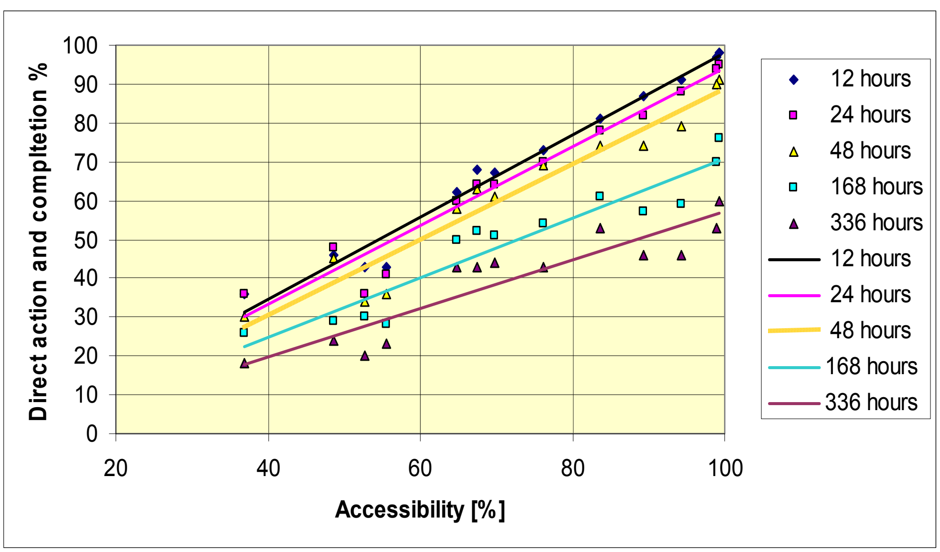


**Fig 6:** The percentage of O&M actions that can be performed and completed immediately after a request for O&M is established.

It can also be seen that there is not too much difference between the probability that a 12 hour O&M action can be performed an that a 48 hour action can take place.
But whenever an O&M activity takes one week or more, the probability of performing and completing an O&M action at first instant reduces significantly, say to a level of 10% less than for a significantly shorter action. Thus would suggest a deployment of O&M teams, which are so large that the required maintenance action can always be taken within 48 hours. This stresses the importance of future offshore wind plant to be designed for "touch and go" maintenance. Furthermore it can be seen that there is an important effect of the level of accessibility upon the percentage of O&M actions that can be performed and completed upon demand. Increase of accessibility level from e.g. 60% to 80% does increase the number of successful O&M actions (without interruption) with about 20%. Apart from the percentage of O&M actions that can be carried out immediately and without interruption, it is also interesting to take a look to number of waiting hours before an action can be taken and/or continued. This is shown in figure 8. From this figure it can be seen that above an accessibility level of 80% the number of waiting hours is limited, and a fairly small portion of the nominal hours required for the O&M action. Let's take the 48 hours nominal O&M time (category 3) as an example. From figure 6 we know that the probability of completing an O&M action of 48 hours directly after the demand for such action has been monitored is 70%. From figure 7 it can be seen that the average waiting time for the remaining 30% is around 24 hours. This means that within 24+48=72 hours at least 70% + 0.7* 30% = 91% of the demands for such action is successfully handled, and within 24+24+48= 96 hours the percentage of completed actions is at least 97%.

But as soon as the accessibility decreases towards 70% the picture changes quite drastically. With the same category 3 maintenance action as an example: In this case the percentage of direct action and completion is reduced to 60%, and for the remaining 40% the waiting time is 56 hours. Thus after 48+56 = 104 hours the number of successful operations is 60% + 0.6* 40% = 84% and after 160 hours (about a week!!) some 10% of the problems is still not cured. How important this is for the ultimate availability of an offshore wind farm depends evidently upon the maintenance characteristics of the anticipated wind turbines and other components in the considered wind farm.

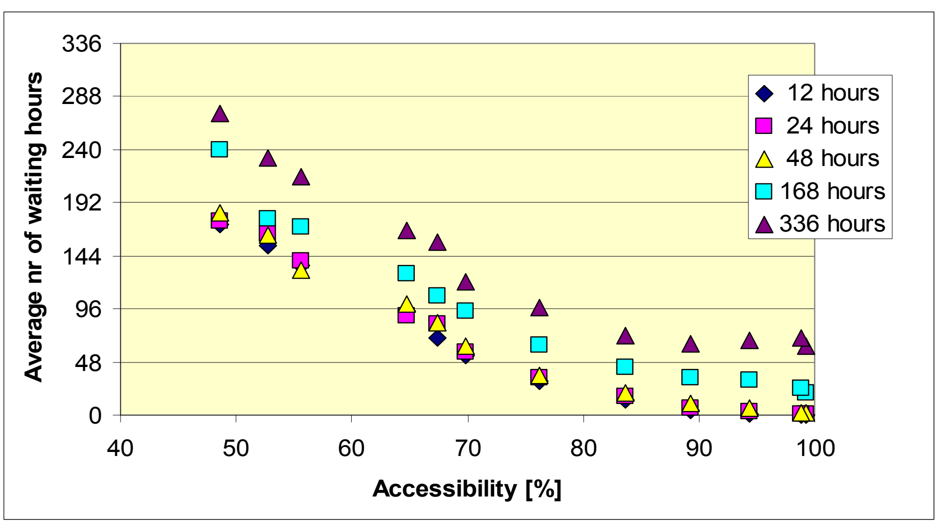


**Fig 7:** The average nr of waiting hours after a call for an O&M action as a function of accessibility and required operational window.

### 4.4 Results for the DOWEC wind farm

The results of the CONTOFAX Monte Carlo simulations in terms of wind farm availability as function of accessibility are shown in figure 8 (symbols); a trend line of the results is also given.

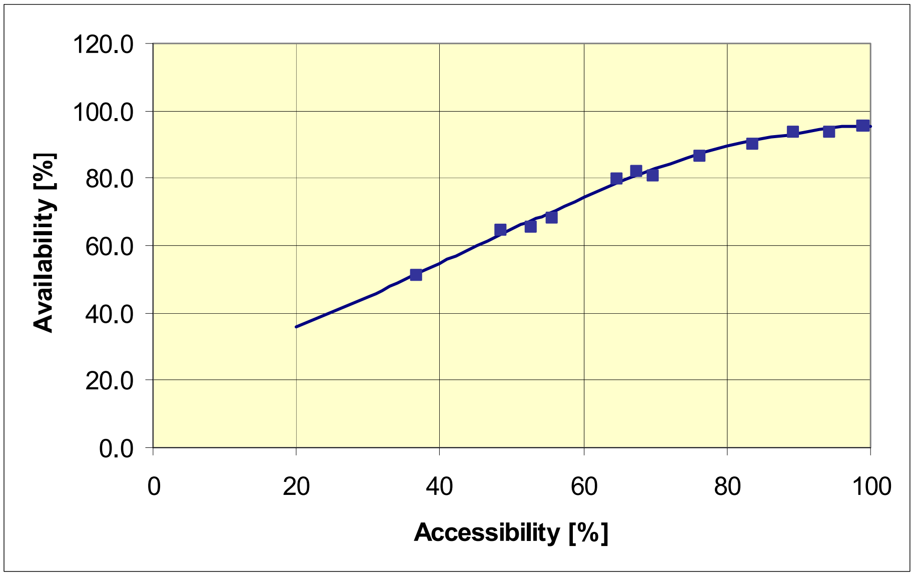


**Fig 8:** Availability of the DOWEC base line offshore wind farm as function of the accessibility. Wind and wave data represent Dutch NL7 North Sea location. The symbols indicate calculated values from the CONTOFAX simulations. The solid line is a 3rd degree polynomial curve fit.

The results for the considered types of access systems are summarised in table 3 below, together with an overall value of the accessibility of the NL-7 site by these access systems. The overall accessibility of an access system over an whole year, as given in table 3, is determined as the average of the limiting accessibility values for the winter and summer periods, for the weather windows going to zero length, as can be determined from figure 4. These accessibility levels are then used in the polynomial fit of the CONTOFAX simulations shown in figure 8. The result is shown in the right column of table 3.

| No | Access system | Accessibility [%] | Availability [%] |
|---|---|---|---|
| 1 | Fictitious | 34 | 49 |
| 2 | Rubber boat, jump onto ladder | 71 | 83 |
| 3 | Offshore Access System | 84 | 91 |
| 4 | Offshore Access System + (optimistic assumption) | 95 | 95 |
| 5 | Helicopter | 100 | 96 |

**Table 3:** The accessibility of the NL7 location for different access systems and the resulting estimated farm availability

From figure 8 and table 3 it follows that in order to maintain a farm availability of above 90% use should be made of access systems with an accessibility of at least 82%. This rules out the straightforward options as using a rubber boat (zodiac) for landing crew at the wind turbines. And also with the lower limiting criteria for the OAS, this access system will be just suitable to obtain such a minimum availability level of 90%. Furthermore remember that such an availability level is the average of a summer and a winter availability, and hence the winter availability will be less then 90%.

The final choice of an access system have to be made with respect to the overall offshore wind farm and will e.g. also depend on safety and practical issues.

## 4. CONCLUSIONS

- Analysis so far has showed that an availability of more than 90% can be achieved for the reference DOWEC wind farm at a rather remote location in the North Sea (NL-7). This level cannot be achieved when use is made of rubber boats (zodiacs) for landing crew at the wind turbines.
- The OAS system, in which a flexible gangway is used to facilitate the maintenance crew access to the wind turbines from a more or less standard pilot vessel, does provide a good opportunity to obtain good availability levels for the reference DOWEC wind farm (>90%) provided it will be able to operate beyond its present lowest values for the limiting conditions.
- Onshore availability levels are not feasible for remote offshore locations. Even with the highly optimistic assumptions made here with respect to access by helicopter the simulated availability level is 96%. Apart from this it is questionable whether this is the most economic solution. Probably a hybrid O&M strategy, allowing different means of access in different seasons, will turn out to be favourable, but this is part of future research.
- The CONTOFAX simulations indicate that a limitation to a maximum nominal repair/maintenance time of 48 hours is favourable for an efficient O&M strategy. I

## 5. ACKNOWLEDGEMENT

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