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Including Realistic Vessel and Human Behaviour in Simulations of Offshore Wind Farm Operations

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Since April 1st ECN and TNO have joined forces.

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Executive Summary

During the Offshore Maintenance Joint Industry Project (OM JIP), the offshore wind farm simulation tool ECN O&M Access has been upgraded from version 1.0 to 2.0, enhancing the modelling of wind farm accessibility by incorporating vessel hydrodynamics and motion-induced human fatigue.

Case studies are performed using the new version of ECN O&M Access, to evaluate the added value of this new approach. Previous case studies from an earlier phase of this project determined the optimal operation and maintenance (O&M) strategies for five European wind farms and evaluated the O&M effort in terms of costs and time [1]. These five wind farms and their optimal O&M strategies are now used as the starting point for the current case studies. The differences in O&M effort and effectiveness for these five wind farms between the old and new accessibility modelling methods are evaluated.

The case studies show that vessels generally spend a longer time transiting between the port and wind farm when incorporating hydrodynamics and motion-induced human fatigue. This is because access vessels can now adjust their thrust level: reducing thrust in fierce weather (hence reducing the transit speed) in order to maintain the motion-induced fatigue of the technicians on board below a threshold. However, this also makes access vessels more capable of transiting in fierce weather, resulting in higher transitability in this new approach.

The transferability when using small CTV and large SOV vessels is also explored. A particularly important finding is that SOVs are able to orient themselves flexibly to reduce motion when transferring technicians, and the extent to which this is possible heavily affects the percentage of time when transfer is possible.

The case studies demonstrate that determining wind farm accessibility is a complex task, depending not only on the independent percentages of time when an access vessel can transit to and from the wind farm or transfer technicians: but also on the alignment of these transit and transfer windows in time.

In general wind farm availability appears to be increased (by 0-2%) when simulating with the new approach, while costs – and resulting costs of energy – are sometimes increased and sometimes decreased, depending on the weather conditions and O&M strategy. Taking vessel hydrodynamics and motion-induced human fatigue into account models wind farm accessibility more realistically than was previously possible, and has significant benefits for planning over simple statistical analysis of historical weather data.

Contents

1 Introduction

The offshore wind industry has been operating wind farms since 1991 (Vindeby's 11 450kW Bonus turbines in Denmark). By the end of 2016, there were 3,589 offshore wind turbines operating in Europe, with a rated power generation capacity of 12,631MW [2]. Operation and maintenance (O&M) costs account for 25% of the life cycle costs of offshore wind farms, with the majority of costs associated with unplanned corrective maintenance actions. Therefore, it is of great importance to accurately estimate the O&M costs of the wind farm and then design the optimal O&M strategy.

ECN has therefore developed several software tools which can simulate the O&M activities for an offshore wind farm and evaluate O&M strategies in terms of the costs and time. ECN O&M Access is one of these tools. It is specially developed to evaluate the impact of different access vessels (including helicopters) on the wind farm O&M costs. In the previous version (version 1.0) of ECN O&M Access, wind farm accessibility was modelled in a rather simple way, in alignment with standard industry practice. Only the threshold value of significant wave height and wind speed were considered while assessing the workability. Following the Offshore Maintenance Joint Industry Project (OM JIP), a new version of O&M Access (version 2.0) is now available to improve the modelling of wind farm accessibility, by incorporating vessel hydrodynamics and motion-induced human fatigue. Case studies are performed using the new version of ECN O&M Access in order to evaluate the added value of the enhanced modelling of wind farm operability.

In this report, Chapter 2 first describes new features developed in version 2.0 of ECN O&M Access. The setup, results and conclusions of the case studies are then presented in Chapter 3, followed by concluding remarks in Chapter 4.

2 ECN O&M Access

2.1 O&M Access v1.0

ECN O&M Access is an operation and maintenance (O&M) cost estimator specifically developed for the designers and developers of maintenance vessels and access systems for the offshore wind industry. Through this tool, vessel and access system designers and developers are able to investigate the impact of their designs on the wind farm availability and maintenance costs. This enables the effect of design assumptions and the business case for new developments to be properly evaluated.

ECN O&M Access consists of three independent modules, written in MATLAB:

1. Input
In this module the maintenance model is set up and the required input data are imported. The maintenance model and the corresponding input data are stored in a number of so called libraries, i.e. MAT-files, in such a way that the other two modules can extract all required information from these libraries straightforwardly.

2. Processing
The processing module consists of consecutive execution of three steps: pre-processing, simulation and post-processing:

- Pre-Processing: to facilitate the simulation process a pre-processing step is executed in which a number of MAT-files are generated, which can be loaded in the simulator module. An important part is the processing of the weather data.

- Simulation: the simulation process is the second step of this module. The results of the simulations are stored in a number of MAT-files which can be loaded in the post-processing step. At the start of a simulation, a number of control parameters have to be specified such as the number of simulations and length of the simulation period. In each simulation a new weather time series is simulated based on the historical weather data, and random failures on the wind farm components are generated based on the defined MTTFs. Therefore, each simulation is different, with the distribution of results after a large number of simulations representing the possible future outcomes. The more simulations are conducted, the higher the confidence in the estimates of the median (“P50”) costs and downtime.

- Post-Processing: after the simulations are finished, the results can be post-processed to obtain the required tables and graphs.

3. Output
The output module is illustrating the post-processed data of previous module using cumulative distribution functions (CDFs), bar and pie charts. Additionally, it is also possible to compare the results of two different projects together.

The execution of these four modules is organised by a graphical user interface (GUI), where these modules can be executed independently of each other. In Figure 1 the interface of the original ECN O&M Access is depicted.

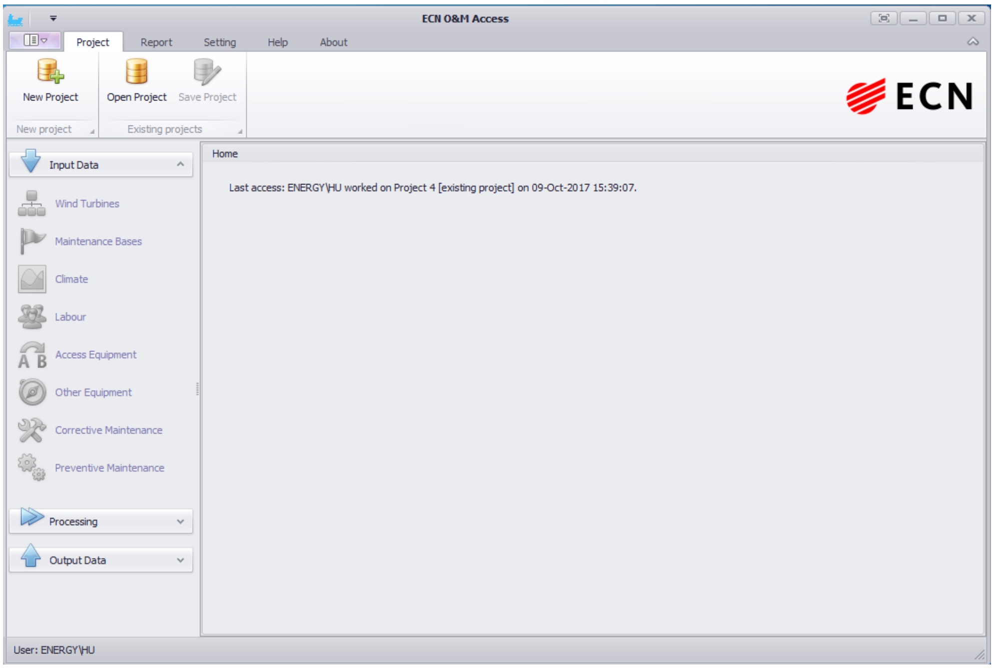

Figure 1 Graphical user interface of ECN O&M Access v1.0.

2.2 Change in v2.0: Interpolator for the Vessel Hydrodynamics Database

The vessel hydrodynamics database is a look-up table which determines the vessel responses from a combination of weather parameters and thrust settings. For a given thrust level, ten different weather parameters form a 10-dimentional discrete input space for the vessel hydrodynamics database. The weather input data at the wind farm site is unlikely to always fall on the discrete grids of this input-space. Furthermore, sometimes the weather data does not even contain all the 10 parameters specified in the vessel hydrodynamics database. Therefore, an interpolator has been developed for the vessel hydrodynamics database, in order to obtain an output from any combination of inputs. In general, the interpolator finds the nearest[1] entry in the database for each weather input data point. In case the weather input data contains fewer parameters (i.e. the weather input data is not a 10-dimensional vector), a default value is assigned to the missing parameters by the interpolator. The default value of the missing parameter is chosen as the most common value in the database in that dimension.

2.3 Change in v2.0: Modelling of Wind Farm Accessibility

In version 1.0 of *ECN O&M Access*, the accessibility of the offshore wind turbines is assessed by thresholds on the significant wave height (Hs) and wind speed (Vw). The operational limits of the vessel are defined separately for transit, positioning and transfer. In the pre-processing step of the calculation, exceedance of the

[1] It is measured by the Euclidean distance in the normalised 10-dimensional input space between the data point and the weather input data.

operational limits is checked for the time series of weather data. An operation can only be conducted when both weather parameters are below threshold during all steps of that operation.

In version 2.0 a new approach is added, that takes the hydrodynamics of the vessel and the motion sickness of the technicians into account. The new approach utilises a database of vessel/human responses to the metocean conditions (hereafter referred to as a ‘vessel hydrodynamics database’) and requires more weather data parameters as input to be most useful. The wind farm accessibility is further broken down into two parts:

- The vessel transitability, indicating if the vessel can transit from the port to the wind farm (or vice versa) for the entire trip if it sets out at a particular timestamp. The travelling speed of the vessel also varies depending on the weather and thrust setting (to be elaborated in Section 2.3.2). Therefore, the transitability and the required transit time changes depending on when the vessel sets out.
- the vessel transferability, showing if the technicians can transfer from the vessel to the wind turbine (or vice versa) once the vessel is positioned at the wind turbine (to be elaborated in Section 2.3.3).

2.3.1 *Access Windows*

This section describes how the pre-processing in the new approach works, namely that the transferability, transitability and transit time of the vessel for an operation are calculated for each time step, after which all the possible access windows are determined.

In both version 1.0 and 2.0 of *ECN O&M Access*, it is assumed that the access window consists of the following consecutive phases:

1. Vessel transits from port to wind farm
2. Technicians transfer from the vessel to the wind turbine
3. Technicians work on the wind turbine
4. Technicians transfer from wind turbine back to the vessel
5. Vessel transits from wind farm back to port

While this general concept is retained, there are differences between the two versions in the approach used to determine the access windows.

The old approach in version 1.0 is shown in Figure 2. In this approach the phases of transfer of technicians are combined with the phase of working on the wind turbine. The duration of transfer is not specified (assumed to be negligible) and it is assumed that technicians should be able to transfer at any time during the working phase. An access window can be formed if the weather allows to carry out these three phases continuously.

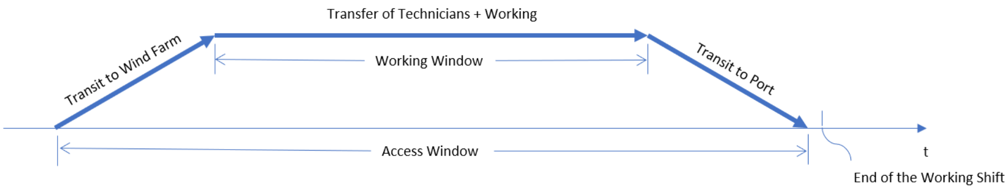

Figure 2 Illustration of the old approach used to determine an access window

On the other hand, the approach in version 2.0 is shown in Figure 3. The transfer phases are separated from the working phase, and the duration of transfer (constant per access vessel) is defined. Furthermore, the transit time of the vessel is not constant as in version 1.0, but variable depending on the time step to set out.

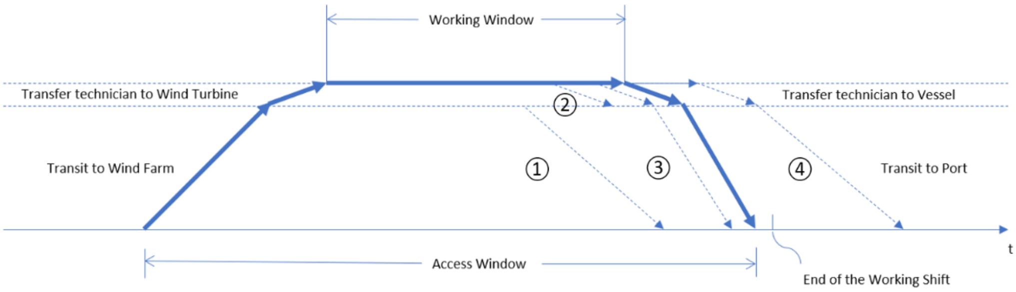

Figure 3 Illustration of the new approach used to determine an access window. The dotted lines represent options that are not selected.

First, starting at a particular time step, the transitability and transit time of the vessel from port to wind farm are determined. Then it is checked whether the technicians can be transferred to the wind turbine immediately after the vessel reaches the wind farm. Subsequently, the possible time steps when the technicians can transfer back to the vessel are found, as well as the time steps that the vessel would have reached the port if it starts to transit back to shore immediately after the transfer of technicians. Finally, the *latest*[2] time step that allows the technicians to transfer back to vessel *and* transit to Port before the end of the working shift is determined as the end of the working window. The access window is stored only if all the steps mentioned above can be achieved.

Figure 3 shows also four causes for an access window *not* being available:

1. At the time when the vessel wants to go back to port, the technicians cannot be transferred to the vessel
2. After the technicians are transferred to the vessel, the vessel cannot transit to port.
3. Both transfer and transit are possible and connected, but it is not the longest possible working window.
4. Both transfer and transit are possible and connected, but the vessel cannot reach the port before the end of the working shift.

In pre-processing, all the possible access windows in the period defined in the weather data are determined and stored. Based on this, the amount of time required for a given task is calculated later in the simulation.

2.3.2 *Transitability*

The new approach to assess the transitability of the vessel is illustrated in Figure 4. The core of this approach lies in the vessel hydrodynamics database, delivered by MARIN in the OM JIP project, which translates the weather conditions into the vessel response, and further to the motion induced fatigue of the people on board.

First, the time series of the weather data is loaded. A one-hour or three-hour resolution is currently accepted in the tool for weather data. The weather data contains up to ten different parameters, as shown in Figure 4. For each time step,

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[2] The purpose of choosing the latest time step is to make the working window as long as possible.

the nearest metocean state in the vessel hydrodynamics database is found. Then for each thrust setting the following outputs from the database are retrieved:

1. Vessel travelling speed, used to determine the transit time between the port and the wind farm.
2. Vessel accelerations or motion induced human fatigue, used as the criterion to determine the transitability. The vessel accelerations consist of acceleration in x, y, and z direction at various vessel locations (accommodation area, bow, etc.). On the other hand, the motion induced human fatigue can be represented by three different indicators, namely Motion Induced Interruptions (MII), Motion Sickness Incidence (MSI) and Motion Illness Rating MIR[3]. The user can select any one of the vessel accelerations or human fatigue indicators as the criterion for the transitability, although MSI is recommended as the most meaningful.

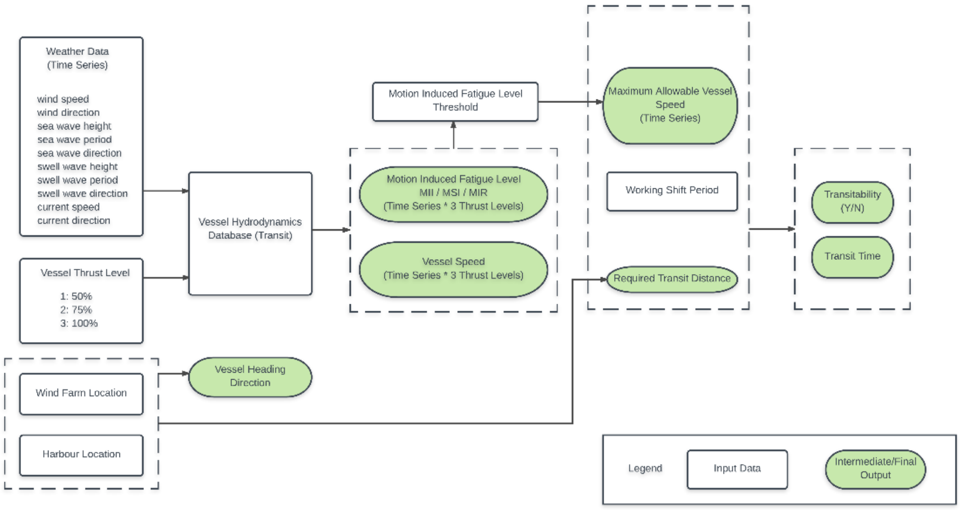

Figure 4 Illustration of the new approach to assess the vessel transitability and transit time

For each time step, the thrust setting of the vessel is selected in such a way that the vessel travels as fast as possible while keeping the vessel acceleration/motion induced fatigue of the technicians within the user-defined threshold. In some very bad weather conditions the sea sickness level of the technicians may exceed the threshold regardless of the vessel thrust setting. If this is the case, then the vessel cannot travel.

2.3.3 Transferability

Figure 5 illustrates the new approach to assess transferability for crew transfer vessels (CTV). For each time step, the nearest metocean state in the vessel hydrodynamics database is found.

[3] The technicians experience different levels of motion induced fatigue when they are situated on different locations of the vessel. In this project, the calculated motion induced fatigue levels correspond to the case that the technicians are staying in the accommodation area of the vessel.

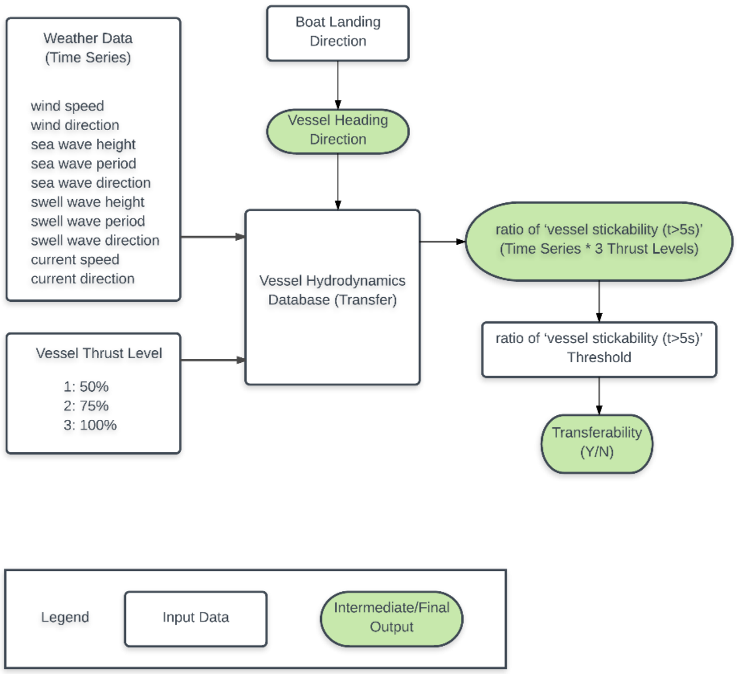

Figure 5 Illustration of the new approach to assess the CTV vessel transferability

The database provides, for each thrust setting, the proportion of time for which the vessel is stationary against the boat landing for a period greater than 5 seconds during a transfer operation (hereafter referred to as “stickability”). During the pre-processing, the transferability of the vessel at each time step is determined by comparing the corresponding vessel stickability at this time with the user-defined threshold. If the vessel stickability in any of the three thrust settings is higher than the threshold, the technicians can be transferred at this time step.

For service operation vessels (SOV), a similar approach is taken as for the CTVs, as depicted in Figure 6. The transferability parameters for a successful transfer from an SOV can be found in [3] and includes acceleration, pitch and roll motion. In order to account for the possible heading adjustments that an SOV with an access gangway can make to reduce induced vessel motions, the tool can also cope with a user-specified heading range. Three effective vessel headings are considered – the default vessel heading (perpendicular to the TP direction, as described in Section 2.5), the default vessel heading minus the heading range, and the default vessel heading plus the heading range. If the vessel response to any of the three effective vessel headings falls within the operational limits, the transfer is possible.

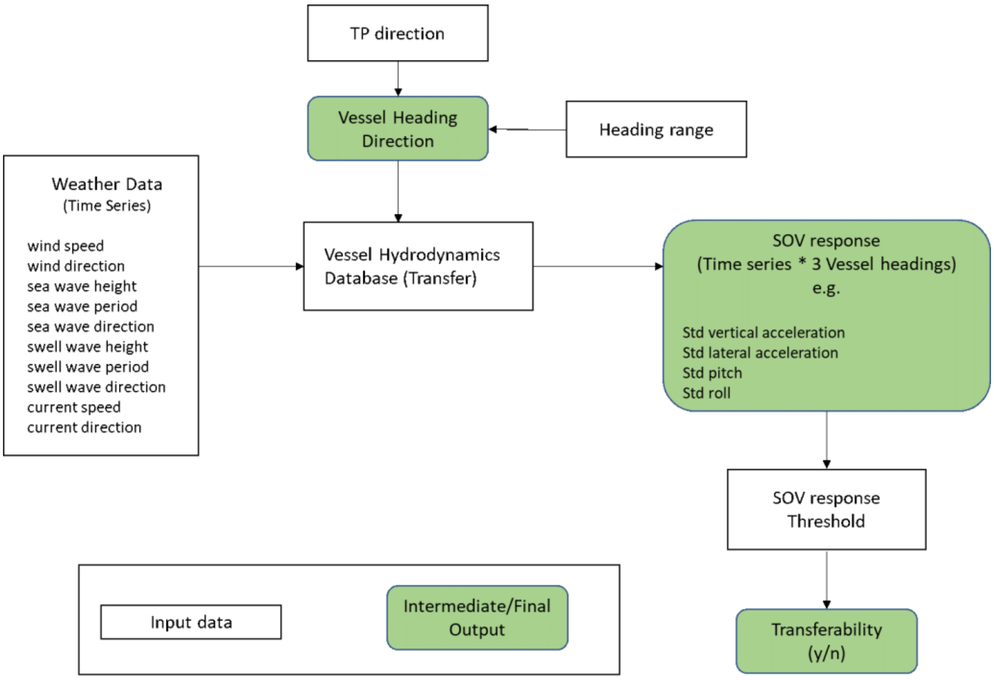

Figure 6 SOV transferability scheme

2.4 Change in v2.0: Weather Simulator

In version 1.0 of ECN O&M Access, the weather time series (wave height and wind speed) for each simulation is created by random sampling of years in the historical input time series.

In this project, however, ECN O&M Access is enhanced by incorporating a weather simulator [4] which provides independent simulations of the future weather based on the statistical properties of the historical data.

2.5 Change in v2.0: Port and Wind Farm Location & Boat Landing/TP Direction

In the weather data input, the directional weather parameters (e.g. wind direction, sea wave direction, swell wave direction and current direction) are conventionally presented relative to North. However, in the hydrodynamics database the directional weather parameters are defined relative to the vessel heading. Therefore, the vessel heading needs to be calculated and the directional weather parameters transformed relative to the vessel heading. The heading of the vessel is determined as follows:

1. For the transit phase, it is calculated based on the location of the port and wind farm, assuming the vessel lies in the straight line from the port to the wind farm (or vice versa).
2. For the transfer phase, it is assumed that a CTV is heading into the boat landing. For SOVs, the default vessel heading is perpendicular to the TP direction, with the port (left) side facing the TP. In addition, the flexibility in heading range is considered when determining the transferability (see Section 2.3.3).

The boat landing direction, TP access direction, and the locations of the wind farm and ports are added in the new version of the tool. The location of the wind farm and ports are also used to calculate the distance between the wind farm and port for the transit phase.

2.6 Change in v2.0: Condition Based Maintenance

In *ECN O&M Access* a set of "repair classes" are pre-defined and hard-coded. The repair classes describe how different maintenance tasks are carried out in the simulations, i.e. type of the maintenance (remote reset/inspection/ repair/ replacement), different phases, required vessels and equipment, required number of technicians, required duration of work. In version 1.0 of *ECN O&M Access*, the repair classes are defined for corrective maintenance and calendar based (preventive) maintenance. This is enhanced in version 2.0 by adding repair classes for condition based (preventive) maintenance. The concept of repair classes and the modelling of condition based maintenance are similar to those in *ECN O&M Calculator.*

2.7 Change in v2.0: Time Resolution

In version 1.0 of *ECN O&M Access,* the time resolution for the simulation is fixed to be 1 hour. Version 2.0, however, allows the use of finer time resolutions: 1, 5, 10, 15, 20, 30 or 60 minutes. It should be noted that this change is only made in the back-end of the tool and not in the graphical user interface. By default, a simulation time resolution of 15 minutes is used. The weather data time series input should still be given in a one-hour or three-hour resolution. The tool will interpolate the weather data to the simulation time resolution.

2.8 Change in v2.0: Graphical User Interface (GUI)

Due to the changes mentioned above, the GUI of O&M Access is adapted to allow access to the relevant inputs of settings for the new features.

3 Case Studies

3.1 Introduction

This study investigates the effect on accessibility and O&M cost of using the vessel hydrodynamics databases for five offshore wind farms. The O&M strategies for these farms were optimized in an earlier ECN study [1] (hereafter referred to as the “reference study”). The same O&M strategies for each wind farm are used in this study.

The remainder of this chapter describes the simulation setup and compares Key Performance Indicators for O&M for the five wind farms in two scenarios:

- **Reference limits**: The default vessel operability limits mentioned in the reference study are used;
- **New limits**: The new method with operability limits in vessel hydrodynamics and motion induced human fatigue is used.

3.2 Simulation Setup

3.2.1 Wind farm and Port characteristics

The characteristics of all five wind farms and ports are the same as in the reference study. They are reiterated in Table 1. At each wind farm location, weather data files with hourly resolution of ten parameters[4] spanning ten years are used.

Table 1 Overview of all wind farms used in the case studies

Case Study	Wind farm Name	Port Name	Vessel	Capacity of Wind Farm (MW)	Number of turbines	Water Depth (m)
A	Horns Rev 3	Esbjerg	Catamaran 20	400	100	20
B	Borssele 1 and 2	Zeebrugge	Catamaran 20	400	50	20
C	Dogger bank – Creyke Beck A	Sunderland	Catamaran 20	800	200	30
D	Nord-Ost Passat I	Wilhelmshaven	SOV 84m + Catamaran 20	800	100	50
E	Hywind - Demo	Haugesund	SOV 60m	400	50	200

The coordinates of wind farms and ports are adjusted to match the distances specified in the reference study, while maintaining the appropriate direction. For some wind farms, offshore based maintenance strategies are used, either by having an offshore station for CTVs (wind farm C), or by employing offshore based SOVs (wind farm D, E). In these cases, it is assumed that access vessels only need a short transit distance to access the wind farm. For other wind farms, the distance from the port to wind farm is used to evaluate the vessel transit time.

[4] These ten weather parameters are the ones used in the hydrodynamics database, as shown in Figure 2

Table 2 Location characteristics of wind farms and ports

Case Study	Wind farm Name	Port Name	Distance from port to wind farm (km)	Presence of offshore base	Actual transit distance (km
A	Horns Rev 3	Esbjerg	33	No	33
B	Borssele 1 and 2	Zeebrugge	32	No	33
C	Dogger bank – Creyke Beck A	Sunderland	155	Yes (Substation)	4
D	Nord-Ost Passat I	Wilhelmshaven	148	Yes (SOV)	4
E	Hywind - Demo	Haugesund	20	Yes (SOV)	4

The locations of all five wind farms and ports are shown in Figure 7.

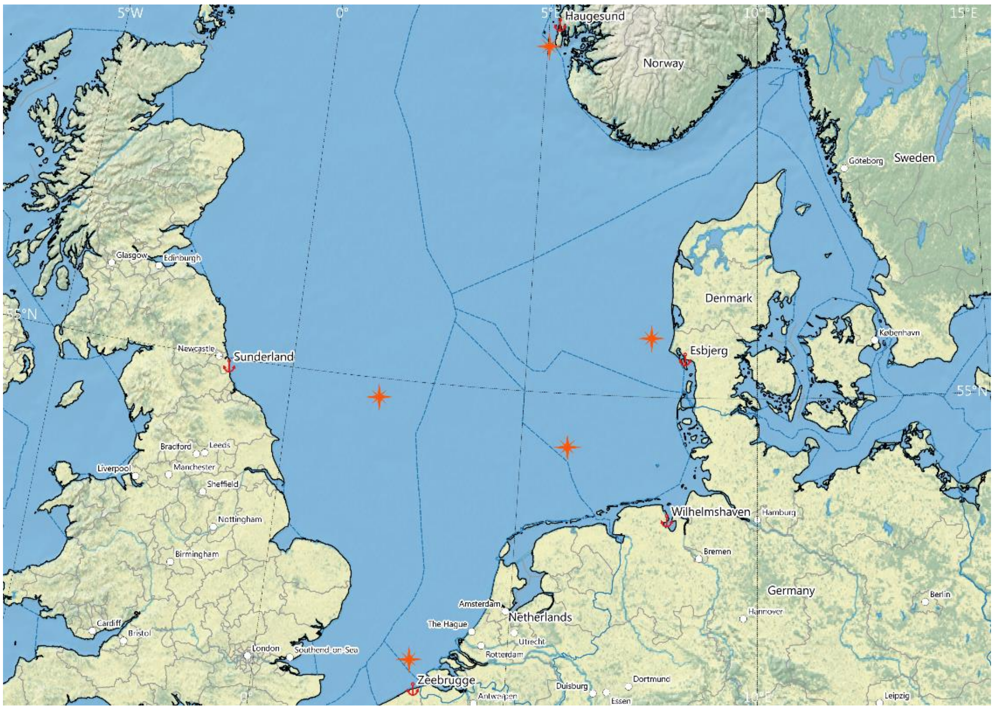

Figure 7 Location of selected wind farms and ports

3.2.2 *Operability Limits*

In the *reference limits* scenario, vessel operability limits during transit and transfer stages are taken from wind speed and wave height limits mentioned in the reference study; and the wind farm accessibility is evaluated using the “old approach” as described in Section 2.3.

The *new limits* scenario uses the limits defined in the following paragraphs with the “new approach” of modelling accessibility.

Transfer Limits of CTV

For transfer limits of CTV, the vessel stickability (defined in Section 2.3.3) is used. This limit is a threshold probability, below which the transfer of technicians is not allowed.

To arrive at a suitable value for the transfer limit of CTVs, an attempt was made to match the wave height (Hs) threshold used in the reference study. By fixing this Hs value in the vessel hydrodynamics database and varying the other nine weather parameters, all possible stickability values are obtained. The average of these values is found to be 11% and was therefore chosen as the transfer operability limit for wind farms that involve technician transfer by CTVs.

Transfer Limits of SOV
For SOVs, a choice has to be made which parameter is governing in transferability. In [3], typical limits are given as the root mean square of roll of 4°, pitch of 1.5°, vertical acceleration of 0.2g, and lateral acceleration of 0.1g. All of these vessel response parameters are given at the access gangway position on the vessel. In order to determine which of these parameters is governing, the standard deviation of all roll, pitch, vertical and lateral acceleration in the database are plotted in Figure 8, normalized to the limit (of 4°, 1.5°, 0.2g and 0.1g respectively).

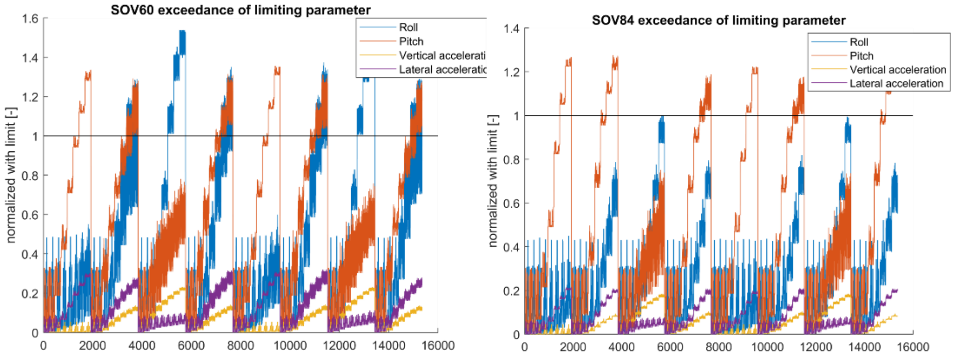

Figure 8 Exceedance of limit for all entries in the hydrodynamic database (limit given in root mean square, response parameter as standard deviation)

From Figure 8 above, we find that the standard deviation of vertical and lateral acceleration never surpasses the limit. For the larger SOV84, the limit for roll motion is never exceeded. For this reason, pitch standard deviation (with a limit of 1.5°) is chosen for the case studies.

The user-specified heading range (introduced in Section 2.3.3) also has a large impact on non-accessibility (i.e. percentage of time a successful transfer is not possible because the threshold is violated). In order to determine the sensitivity of the non-accessibility to this heading range, three different heading ranges were tested for both SOVs and compared to a typical reference limit based on significant wave height threshold of 3m, shown in Figure 9.

It can be seen, as expected, that not allowing any heading range (i.e. the SOV is always positioned perpendicular to the TP) results in the highest percentage of non-accessibility. However, when introducing a large heading range like 30°, the non-accessibility is significantly improved. The 60m SOV shows a higher non-accessibility for all cases, compared to the reference limit. It is clear that caution should be taken in the selection of a realistic heading range, as it has a large effect on the accessibility. For the remainder of this study, a heading range of 10° is chosen.

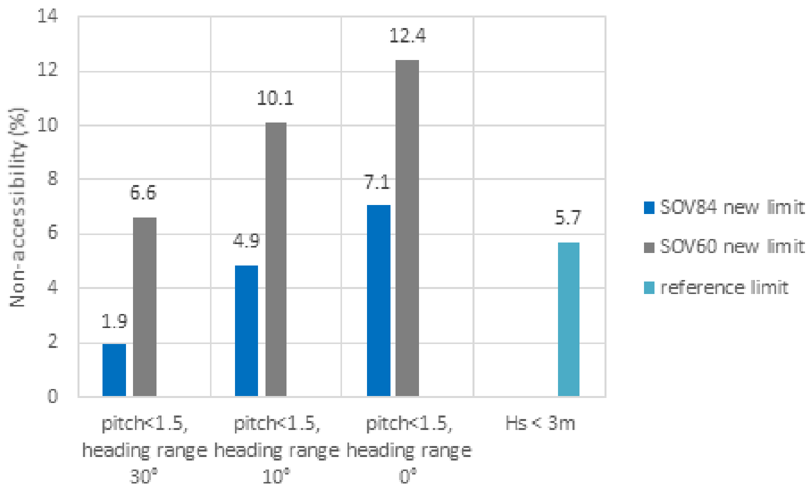

Figure 9 Sensitivity of non-accessibility for different heading ranges, compared to typical limit in reference study (Hs<3m)

Transit Limits

For transit limits, the 'MSI' or motion sickness incidence parameter is used. MSI is defined as the percentage of passengers who vomit after 2 hours of exposure to a certain motion [5]. This transit parameter is used for both CTVs and SOVs for the five wind farms. To calculate this limit, the wave height thresholds used in the reference study are initially considered.

Plots of MSI values from the database for each vessel at various significant wave heights are created. The plot in Figure 10is for a 20-metre Catamaran (CTV). The transit limit of the CTVs in the reference study has a threshold of significant wave height of 2 metres. For this vessel, the average MSI value corresponding to the 2-metre significant wave height is approximately 25%. In addition, research suggests that an MSI threshold of 20% is commonly used for four-hour transit operations [6]. Bearing in mind the lower transit times involved, it seems reasonable to select the MSI threshold for vessel transit to be 25%. With this threshold, it can be seen from Figure 11 and Figure 12 that the larger vessels are in general more capable of transiting in higher wave heights.

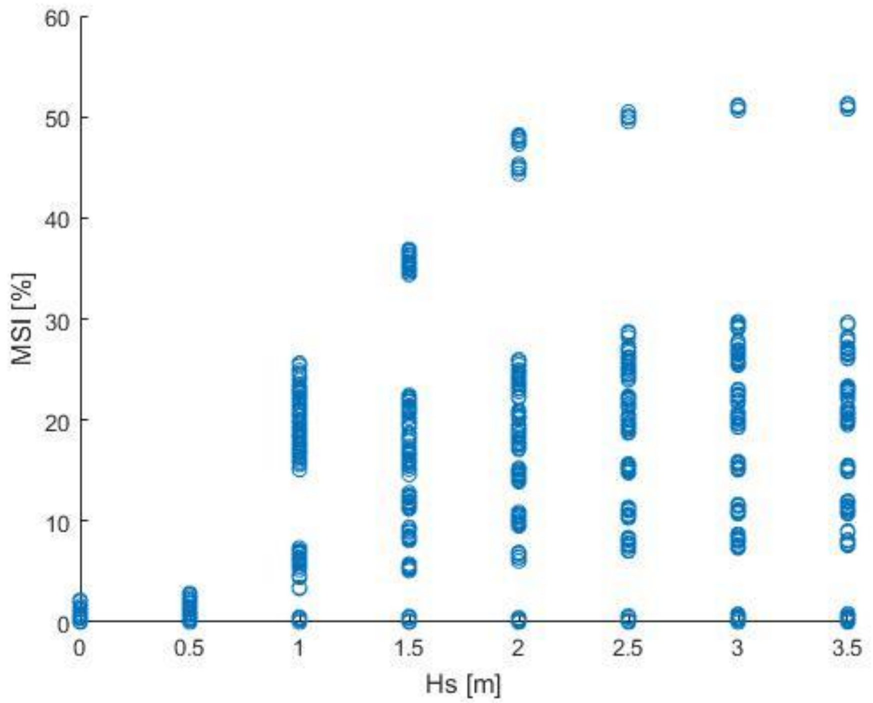

Figure 10 Motion sickness incidence versus significant wave height for 20-metre Catamaran (CTV)

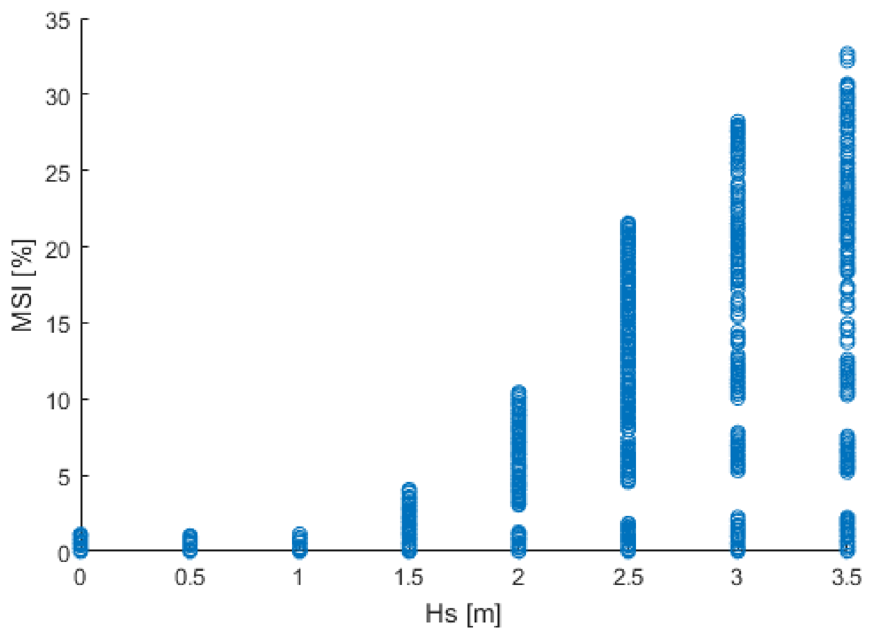

Figure 11 Motion sickness incidence versus significant wave height for 60-metre SOV

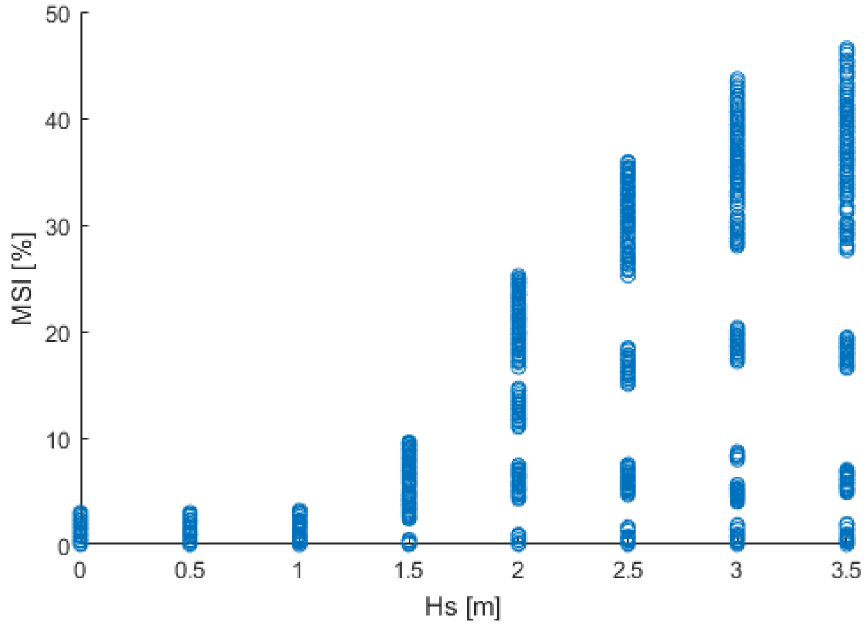

Figure 12 Motion sickness incidence versus significant wave height for 84-metre SOV

3.2.3 *Vessel Characteristics*

The access vessels used in the five case studies are explained in considerable detail in the reference study. A summary comparison of the vessels chosen is shown in Table 3.

Table 3 Characteristics of CTVs and SOVs accessing the wind farms

Case Study	Vessel name (reference study)	Vessel used for the hydrodynamics database (present study)	Transit operability limit (reference study) (Hs max Vw max)	Transfer operability limit (reference study) (Hs max Vw max)	Transit operability limit (new approach) (MSI)	Transfer operability limit (new approach)
A	CTV-S (small)	Catamaran 20m	2.0 m, 12 m/s	2.0 m, 12 m/s	25%	Stickability: 11%
B	CTV-XL (large)	Catamaran 20m	2.0 m, 15 m/s	2.0 m, 15 m/s	25%	Stickability: 11%
C	Workboat S	Catamaran 20m	2.0 m, 15 m/s	2.0 m, 15 m/s	25%	Stickability: 11%
D	Mother Vessel + CTV-S	SOV 84m + Catamaran 20m	SOV: 3.0 m, 17 m/s CTV: 2.0 m, 14 m/s	SOV: 3.0 m, 17 m/s CTV: 2.0 m, 12 m/s	25%	SOV: Pitch standard deviation: 1.5° CTV: stickability 11%
E	Mini Mother Vessel	SOV 60m	2.0 m, 15 m/s	1.0 m, 10 m/s	25%	Pitch standard deviation: 1.5°

While using *new limits*, the operability limits for CTVs and SOVs are modified compared to the reference study. The operability limits for all other vessels and helicopters in the reference study have not been modified in this study.

3.3 Simulation Results

The key performance indicators considered are time-based availability (%), energy yield availability (%), total O&M cost per kWh (c€), repair costs (M€/year), revenue losses due to lost yield (M€/year), and total O&M effort (M€/year).

Table 4 summarizes the O&M performance and effort for *reference limits* scenario.

Table 4 KPI's of wind farms for reference limits scenario

Case Study	Availability (time) (%)	Availability (yield) (%)	Costs per kWh (**c€**)	Repair Costs (M**€/year**)	Revenue Losses (M**€/year**)	Total O&M Effort (M**€/year**)
A	94	93.5	2.06	29.75	13.11	42.85
B	94.8	94.6	1.84	22.1	8.29	31.02
C	93.8	93.2	1.58	51.74	31.29	83.02
D	94.7	94.4	1.41	46.71	25.85	72.55
E	91.9	91.1	1.88	32.76	22.24	54.99

Table 5 summarizes the O&M performance and effort for *new limits* scenario.

Table 5 KPI's of wind farms for new limits scenario

Case Study	Availability (time) (%)	Availability (yield) (%)	Costs per kWh (**c€**)	Repair Costs (M**€/year**)	Revenue Losses (M**€/year**)	Total O&M Effort (M**€/year**)
A	94.7	94.6	1.99	29.09	10.87	39.96
B	94.7	94.7	1.89	22.76	8.83	31.59
C	95.0	94.9	1.59	53.20	23.66	76.86
D	94.9	94.7	1.43	47.64	24.12	71.76
E	93.7	93.4	1.81	32.24	16.54	48.78

The results obtained are in general similar to those in the reference study. However, there are some interesting differences in wind farms A, C and E.

3.3.1 Availability

Figure 13 and Figure 14 compare time based and yield based availabilities between the *reference limits* and *new limits* scenarios.

For wind farms B and D, the values of time and yield based availability are almost exactly the same as in the *reference limits* study. The difference in availability results obtained for the other four wind farms are marginal and can be attributed to more accurate weather data, wind farm and port locations used in this scenario.

However, wind farm A, C and E display larger difference in availability, ranging from 0.7 % to 2.3%. Results from the two scenarios are compared in the sections below.

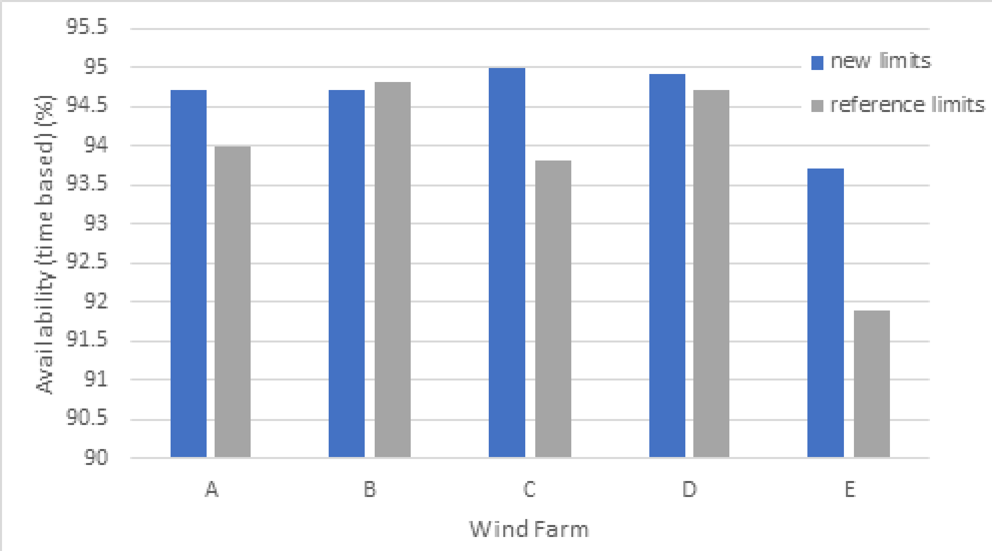

Figure 13 Comparison of time based availability for all wind farms in reference and new limits scenario

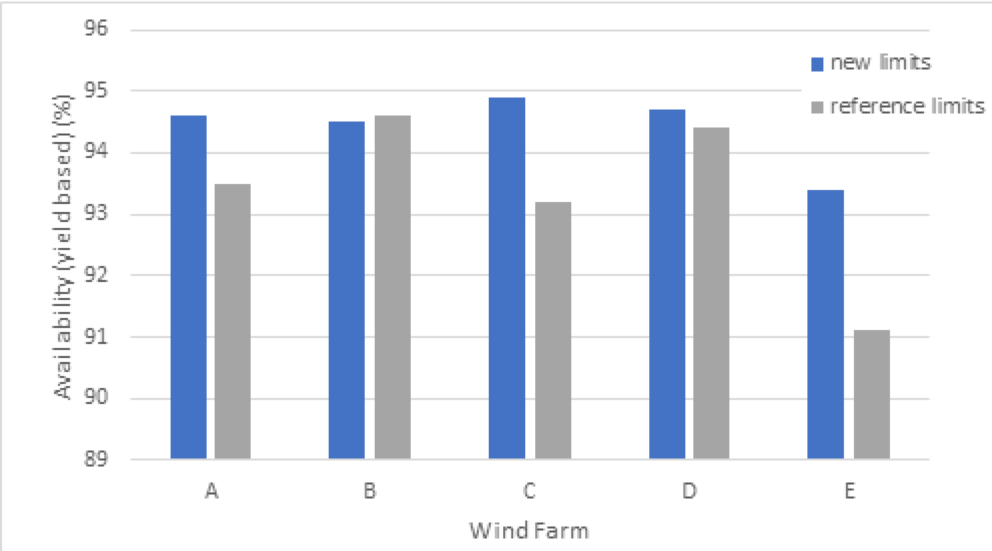

Figure 14 Comparison of yield based availability for all wind farms in reference and new limits scenario

It can be seen that, using *new limits* generally results in an increase in time and yield based availability, except for wind farm B.

3.3.2 Cost

Repair costs are the sum of costs owing to corrective, preventive and condition based maintenance activities, including the costs of vessels, technicians and spare parts, but excluding revenue losses. According to Figure 15 and Figure 16, for all wind farms, both the repair costs and costs per kWh are very close between the two scenarios. This suggests that the number of repair activities performed during the simulation period are similar.

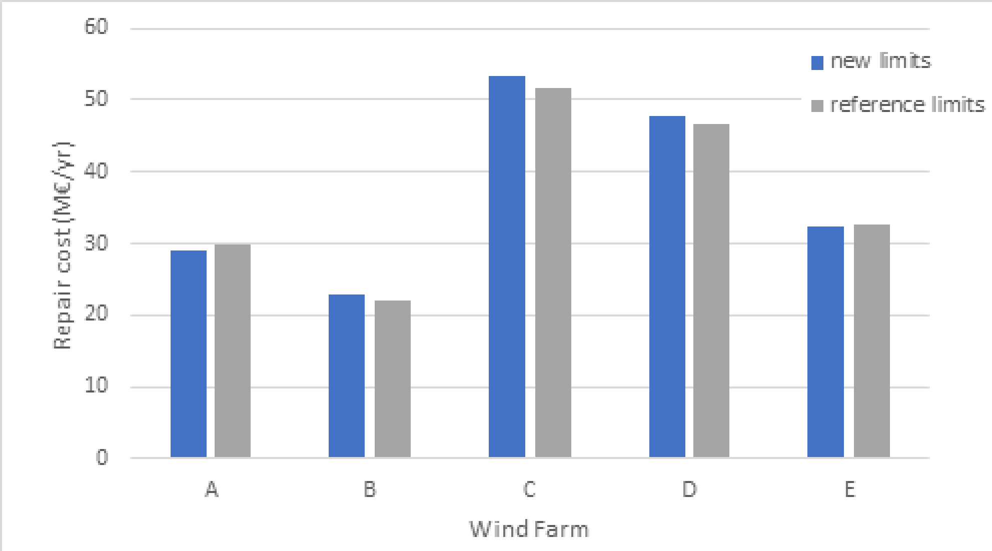

Figure 15 Comparison of repair cost for all wind farms in reference and new limits scenario

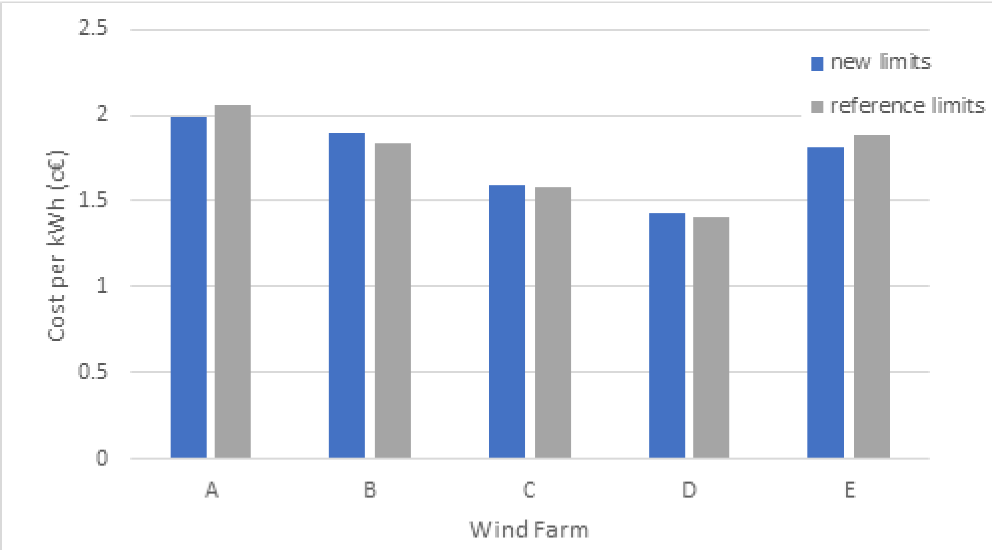

Figure 16 Comparison of cost per kWh for all wind farms in reference and new limits scenario

Figure 17 shows that the revenue losses in *new limits* scenario are generally lower than that in *reference limits* scenario, especially for wind farm C and E. However, for wind farm B, the revenue losses in *new limits* scenario is slightly higher. This agrees with the pattern shown in the yield availability (Figure 14).

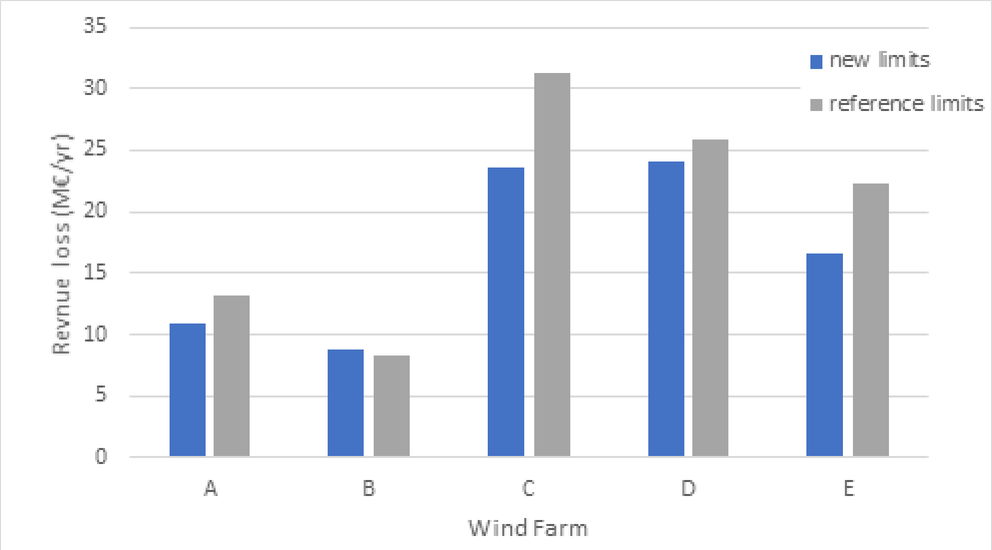

Figure 17 Comparison of revenue losses for all wind farms in reference and new limits scenario

The total O&M effort, which is the sum of repair costs and costs due to revenue losses, is shown in Figure 18. It can be seen that the total O&M effort in the *new limits* scenario is much lower for wind farm C and E, slightly lower in wind farm A and D, and slightly higher in wind farm B.

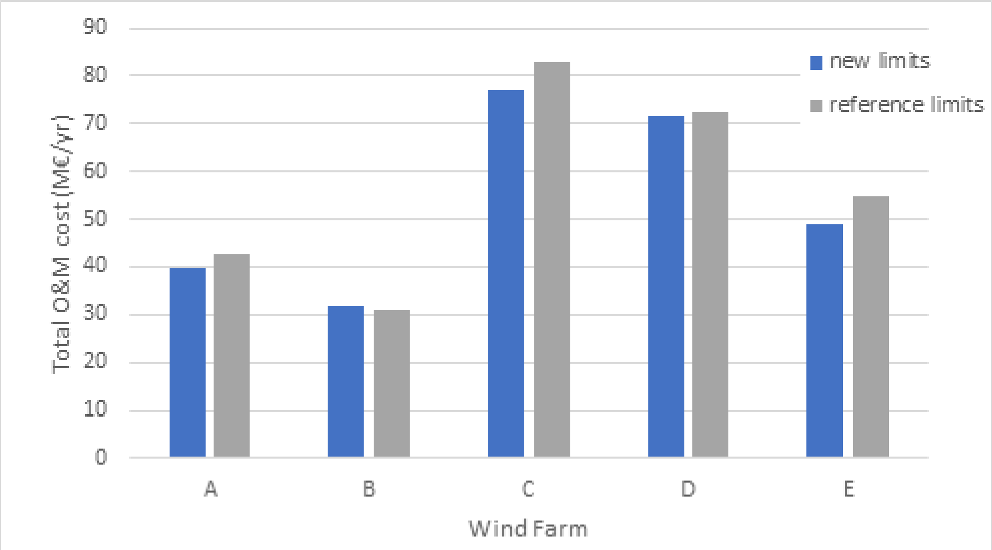

Figure 18 Comparison of total O&M cost for all wind farms in reference and new limits scenario

3.3.3 *Investigation*

To further investigate the results, the percentage of time available for transit, transfer and the percentage of time in an working window are shown in Table 6 and Table 7 for all the five wind farms.

It should be noted that a single working shift from 07:00 to 19:00 is applied to all the five wind farms in the case studies, outside which no work can take place.

The trend of percentage of time in an working window in these wind farms correlates with availability values and can be considered as the main cause for the differences between the scenarios.

Table 6 Analysis of weather windows during the simulation period for wind farm A, B and C

	Wind Farm A: CTV-S		Wind Farm B: CTV XL		Wind Farm C: Workboat S	
Parameter	Reference limits	New limits	Reference limits	New limits	Reference limits	New limits
Average Transit Time (hours)	0.75	1.2135	0.75	1.109	0.25	0.2536
% of time available for Transit (to Farm)	40.2%	45.9%	45.7%	46.2%	39.9%	48.8%
% of time available for Transit (to Port)	40.2%	46.0%	45.7%	46.6%	39.9%	45.5%
% of time available for Transfer	42.2%	49.4%	47.8%	48.0%	39.9%	47.4%
% of time in an Working Window	28.0%	29.9%	32.4%	29.5%	29.8%	33.1%

Table 7 Analysis of weather windows during the simulation period for wind farm D and E

	Wind Farm D: Mother Vessel		Wind Farm D: CTV-S		Wind Farm E: Mini Mother Vessel	
Parameter	Reference limits	New limits	Reference limits	New limits	Reference limits	New limits
Average Transit Time (hours)	0.25	0.25	0.25	0.25	0.25	0.25
% of time available for Transit (to Farm)	47.1%	48.8%	42.9%	50.0%	40.2%	41.8%
% of time available for Transit (to Port)	47.1%	45.5%	42.9%	50.0%	40.2%	43.8%
% of time available for Transfer	47.1%	47.4%	42.4%	49.0%	29.9%	44.7%
% of time in an Working Window	35.9%	33.1%	31.9%	37.5%	21.8%	29.8%

Wind Farm A and C
CTVs are used as access vessel for wind farm A and C. Comparing the two scenarios, the percentages of time available for both transit and transfer are much increased in the *new limits* scenario for these two wind farms. This is the main reason for the increase in the number of available weather windows for wind farm A and C in the *new limits* scenario.

It is also noted that the average transit time for wind farm A is longer in the *new limits* scenario. This is because in the new approach of modelling CTV transit, where the vessel hydrodynamics and human fatigue factor are used, the vessel has the flexibility to adjust and lower its thrust levels (hence less speed) in order to maintain the appropriate MSI levels (hence higher transitability). In case with an offshore base as for wind farm C, the travelling distance is too small for a significant change in transit time with the use of vessel hydrodynamics database.

Wind Farm B

Wind farm B also uses CTV as access vessel. In the *new limits* scenario, the percentage of time available for transit and transfer are slightly higher (< 1%), but the percentage of time in an working window is lower. This is most likely caused by the longer average transit time in the *new limits* scenario. Even if with the same or slightly higher amount of access windows, the longer transit time will reduce the length of the working window within the access window, making the percentage of time in working windows lower.

Wind Farm D
Wind farm D uses both a mother vessel (SOV) and daughter craft (CTV) as access vessels. For the SOV, the average transit time and the percentage of time available for transfer are almost identical between scenarios. The *new limits* scenario has a higher percentage of time available for transit to wind farm, and lower percentage of time available for transit to port. However, the percentage of time in an working window is slightly lower in the *new limits* scenario. This is likely caused by the fact that transit and transfer windows do not occur as often simultaneously. The availability of an access window requires the combined occurrence of two transit and two transfer windows at the appropriate times.

For the CTV, the percentage of time available for transit, transfer and in an working window are all much higher in the *new limits* scenario. Combining the two opposite effect on the SOV and CTV, the availability of wind farm D is slightly higher in the *new limits* scenario.

Wind Farm E
A mini mother vessel (SOV) is used as access vessel for wind farm E. With the small traveling distance, the average transit time in the two scenarios are almost identical. As for the percentage of time available for transit, it is slightly higher in the new limits scenario. It is noted that the percentage of time available for transfer for this mini SOV is much larger with the new operational limits, because the operational limits in the reference study for this vessel is very restrictive. Due to the large increase in the transferability, the percentage of time in an working window is much higher in the *new limits* scenario, leading to much higher availability for wind farm E compared to the *reference limits* scenario and therefore much lower revenue losses.

4 Conclusions

During the Offshore Maintenance Joint Industry Project (OM JIP), the simulation tool *ECN O&M Access* has been upgraded from version 1.0 to 2.0, by implementing a new approach to modelling wind farm accessibility. This new approach utilises vessel hydrodynamics databases to determine vessel transitability and transferability, taking into account: up to 10 weather parameters; variable vessel speed and multiple thrust levels; the transit heading; and the boat landing direction for CTV transfer and Transition Piece access platform direction for SOV transfer.

For transits of the vessel between the port and offshore wind farm, the new approach uses either vessel acceleration or motion induced fatigue measures for the technicians as the operability limit. For transfers of technicians between the vessel and wind turbine using CTVs, the new approach uses vessel stickability (the proportion of time for which the vessel is stationary against the boat landing for a period greater than 5 seconds during a transfer operation). For SOVs, the root mean square (RMS) of the pitch motion, roll motion, horizontal acceleration and vertical acceleration at the access gangway location can be used as a threshold for transfer. Non-accessibility (i.e. percentage of time a successful transfer is not possible) for SOVs is heavily dependent on the flexibility in heading range that the vessel is allowed for positioning.

Five wind farms, for which O&M strategy optimization was performed in a previous study, are re-visited in this report, to analyse the differences in Key Performance Indicators, once the more sophisticated modelling of vessel hydrodynamics and human factors are included in the simulations. Thresholds for motion induced human fatigue (MSI) during transit and for stickability during transfer are chosen based on a reverse analysis of the vessel databases.

The results, in terms of O&M costs and wind farm energy output, are largely similar, however, interesting differences in downtimes are seen between the wind farms. The impacts on expected O&M performance are generally positive, except for wind farm B (a 400MW nearshore wind farm in Dutch waters).

In cases where the vessel travels between the wind farm and an onshore port, the new approach increases transit time while resulting in a higher percentage of time available for the transit. This is because the vessel has the flexibility to adjust and lower its thrust levels in order to maintain the appropriate MSI levels, thereby increasing transit time.

In cases with an offshore base (e.g. an SOV), the distance travelled by daughter craft is too small for a significant change in transit time with the use of the vessel hydrodynamics database.

The investigation of the SOV used at wind farm D (a 800MW far offshore wind farm in German waters) shows that the wind farm accessibility depends not only on the percentage of time when an access vessel can transit to/from the wind farm and transfer technicians, but also on the alignment between the transit windows and transfer windows in the timeline. This underlines the importance of running a full simulation compared with simple statistical analysis of the historical weather data.

5 Bibliography

[1] A. Dewan and M. Asgarpour, “Reference O&M Concepts for Near and Far Offshore Wind Farms,” report ECN-E--16-055, ECN, Petten, December 2016.

[2] “The European offshore wind industry (Key trends and statistics 2016),” Wind Europe, 2016.

[3] J. Ross, Human factors for naval marine vehicle design and operation, Ashgate Publishing Ltd., 2009.

[4] C. Stock-Williams, “Development of a Stochastic Weather Simulation Capability,” report ECN-E--16-064, ECN, Petten, December 2016.

[5] V. Piscopo and A. Scamardella, “The overall motion sickness incidence applied to catamarans,” International Journal of Naval Architecture and Ocean Engineering, Naples, April 2015.

[6] S. C. Stevens and M. G. Parsons, “Effects of Motion at Sea on Crew Performance: A Survey,” Marine Technology, Vol. 39, No. 1, January 2002.