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Impact of vessel logistics on floating wind farm availability

Virginia Trueba^a, Álvaro Rodríguez-Luis^{b*}, Sergio Fernández-Ruano^b and Raul Guanche^b;

^a Technical University of Madrid (UPM), 28040, Madrid, Spain

^b Environmental Hydraulics Institute of Cantabria (IH Cantabria), University of Cantabria (UC), 39001, Santander, Spain

* E-mail: alvaro.rodriguezluis@unican.es (A Rodríguez-Luis)

Abstract. This paper presents a study of the impact of the Operations and Maintenance (O&M) vessel logistics over the power availability of an Offshore Wind Farm. In particular, the vessel size and availability are considered. The study is performed with a life-span simulator, based on historical metocean data, walk-to-walk characterization based on a frequency domain hydrodynamic modelling of multibody systems, wind farm fault simulator (based on a catalogue of more than 1800 faults) and an algorithm to reproduce the O&M intelligence (i.e. sea transportation, workability, among others). The frequency domain model is applied on an hourly basis considering the specific significant wave height, peak period, peak enhancement factor, mean heading, directional spreading, and a wave-by-wave strategy is used to find if personnel transfer and workability criteria are met. The WindFloat Atlantic wind farm, located off the coast of Viana do Castelo (Portugal), was chosen together with the TRL+ project semi-submersible platform and the 10MW turbine as a reference case. Different vessel logistics options are compared, including full vessel availability and several options of waiting times. The power availability changes among the different cases of study could be compared with the cost changes, optimizing the LCOE (Levelized Cost of Energy) of the wind farm. The presented study is a valuable example of the potential of the proposed O&M simulation model as an optimization tool.

1. Introduction

1.1. Floating offshore wind

Onshore wind power is one of the cheapest forms of new power generation and offshore wind is approaching. Its costs have been reduced by more than fifty percent in recent years. Once built, wind farms provide almost zero marginal costs. At the end of 2019, wind energy covers on average 15% of the energy demand in the EU, [1] with 205 GW of energy capacity (22 GW offshore, covering 2.3% of European demand) [2]. Currently, there are 110 offshore wind farms in 12 European countries. According to the International Energy Agency (IEA), offshore wind energy will become the most important source of generation in Europe by 2042. The European Commission says that Europe needs between 230 and 450 GW of offshore wind energy by 2050, becoming an important pillar of the energy mix, along with onshore wind energy [3].

Compared to onshore wind energy, offshore wind energy has advantages such as more space to install the farms, more high-quality wind resource and less visual pollution. However, the economic costs of offshore projects are currently at least three times higher than onshore projects [4].



The European floating wind fleet is the largest in the world with 45 MW installed, increasing the size of its turbines and reaching fixed-bottom parks capacities. The main European markets are France, Spain, Portugal, Ireland and the UK, as they have large and deep territorial waters and important wind resources. Floating offshore wind (FOW) has some costs advantages compared to bottom fixed offshore wind (BFOW): it requires less operations taking place at sea and the installation process is less dependent on weather, soil and sea conditions [5].

1.2. Operation and maintenance

Currently, there is a lack of information about the operation and maintenance costs of offshore wind farms, either because it is difficult to predict when maintenance work should be performed due to unpredictable weather; or because companies keep this information to themselves for the sake of competitiveness.

O&M costs comprise 25-30% of the total costs of an offshore wind farm, which also include development and planning costs, the cost of the turbine itself and construction and installation. O&M costs include insurance, regular maintenance, repair, spare parts and administration. O&M costs are typically estimated at 1.2-1.5 cents per kWh of power produced over the total life of the turbine (based on studies in Germany, Spain, UK and Denmark). They represent 53% of the OPEX (15% operation + 38% maintenance). The remaining costs come from port activities and license fees. In order to save costs during the operational life of the farm, the factors that influence operational expenses must be identified [6]. With the help of these factors, managers can make the right decisions regarding maintenance strategy. Some examples of previous work on O&M simulation models of offshore wind farms are [7], [8]

1.3. Impact of logistic times

Logistics and maintenance supply chain management are very important issues in offshore wind industry. A failure in any of these aspects may have a negative impact on the availability, and therefore a reduction in the power provided by the wind farm and the economic profits [9].

Existing statistics show that maintenance expenditures (including costs of maintenance work, hiring of the vessels and purchasing the spare parts) constitute the largest part of O&M costs. Considering the location of harbour facilities and economic issues, spare parts inventories should be established to ensure continuous supply of components. Between production and offshore installation, there is onshore transport and offshore transport. Disruptions can range from capacity problems to problems with traffic or weather conditions. Therefore, we must deal with delays in the supply chain [10]. Another example of a study on offshore wind farm maintenance logistics simulations is [11]

1.4. Objective and motivation

The aim of this paper is to evaluate the impact of vessel logistic times of operation and maintenance on the energy production of a floating offshore wind farm with a recently developed tool to simulate the marine operations associated to O&M from a long-term perspective. The novelty of the O&M analysis model is: (1) combine several submodels found in literature and described in Section 2, (2) improve the crew transfer sub-model introducing the effect of directional spreading and a wave-by-wave analysis approach, and (3) integrate all the submodels with a new fault repair protocol algorithm to consider vessel logistics. Motivation for this study comes from the uncertainty of the LCOE of floating offshore wind, the need of optimizing availability, facilitate the decision-making during personnel transfer operations, the improvement of personnel safety access and the optimization of transport vessel selection.

The present paper is organized as follows: Section 2 describes the methodology proposed. Section 3 contains the data for the considered case study, in which a floating offshore wind farm in the coast of Portugal is studied. Section 4 illustrates results for this study. Lastly, in Section 5 we draw some conclusions and present the future work.

2. Methodology

A methodology is proposed to analyse how to increase wind farm's availability regarding the logistics of vessels used to transport the staff to the turbines and its rental contract, the existence of spare parts storages and the minimum working time. With this objective, a model that simulates the life-span of a floating offshore wind farm is used. The model provides long-term information to perform a statistical analysis of weather downtime, time and power availability, energy production, reparation time and number of vessel trips.

2.1. Metocean data

The metocean database used for our simulations comes from IHDATA. It consists in 20 years of hourly calibrated data of the coast of Portugal and it gives information about both wind (intensity and direction) and waves (peak period T_p , significant wave height H_s , peak enhancement factor γ , wave direction θ , and wave directional spreading s).

In a local scale, any wind farm distribution and any wind turbine can be considered, introducing its power and thrust curves. In order to consider interaction among turbines, wake model [12] and wake overlapping [13] are used. Floating wind turbines operational limits are set based on [14] and [15].

2.2. Accessibility characterization

The main objective of the accessibility characterization is to find all the windows in which is possible to work for the different types of failure. The interaction between platform has to be analysed numerically.

Two Walk-to-Work (W2W) strategies can be considered: one in which there is no gangway and the access to the platform is performed with a ladder from the Crew Transfer Vessel (CTV) (see Figure 1); and another one in which there is a Service Operation Vessel (SOV) with a gangway. In the first one, the condition of no-slip motion between the vessel and the platform is considered. In the second strategy, thresholds are set on the relative movements at the gangway with the information given by the provider. For this article, the first option is considered.



Figure 1. Service vessel with fender, courtesy of Northern Offshore Services.

On the first step, the coupled hydrodynamic system composed by CTV and platform is analysed by means of a potential frequency domain hydrodynamic model, when both are in crew transfer position. The procedure followed to obtain the Response Amplitude Operators (RAOs) is improved with respect to the literature and the details of the modifications are described below.

Firstly, the inertia matrices (M), hull geometries, mooring system description and fender-boatlanding positions from the vessel and platform designers are obtained. Next, a Boundary Elements Method (BEM) frequency domain model is used to calculate the added mass, radiation damping, hydrostatic stiffness matrices and the waves excitation forces. In this case, the commercial code SESAM is used, but an opensource software such as NEMOH could also be used. Next, the mooring system is linearized,

using a Finite Element Method (FEM) model by means of off-set numerical tests, obtaining a mooring stiffness matrix (G_M) for the platform (the vessel has no moorings). Again, SESAM software is used [19].

Then, the RAOs are computed following the methodology described in [14] and [15]. The procedure for the linearization of the mooring forces and hydrodynamic viscous forces is also taken from the same reference. Examples of these RAOs for the case studied in this paper are shown in Figure 2 and Figure 3. The frames used to describe the system behaviour are shown in Figure 4.

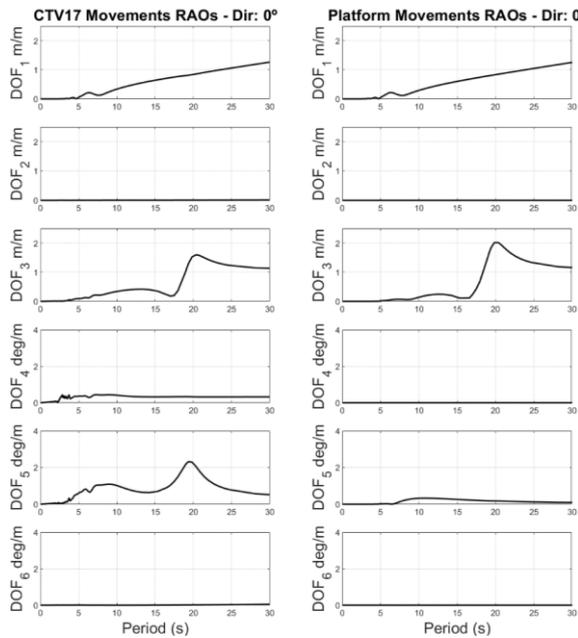


Figure 2. Six DOF movements RAOs for the system with the CTV17 (left) and the platform(right). Heading 0°.

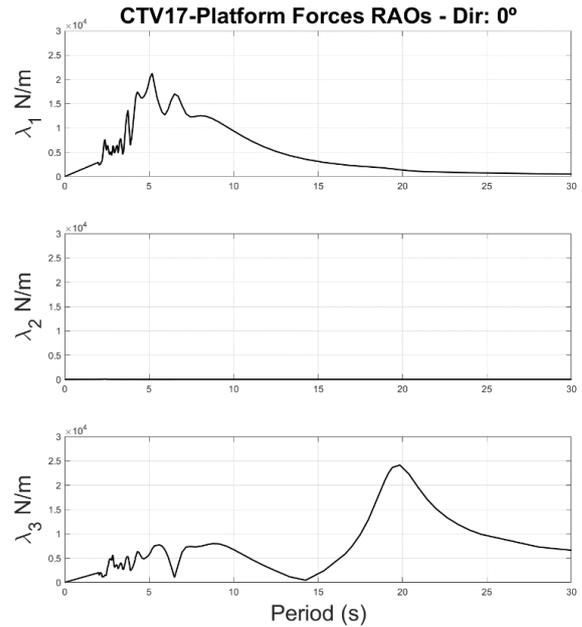


Figure 3. Contact point forces RAOs for the system with the CTV17 and the platform. Heading 0°.



Figure 4. Contact between platform and CTV

Once the system response is obtained, accessibility is studied mixing the RAOs with the metocean data mentioned in Section 2.1. A wave-by-wave approach is used to reconstruct the movements and the forces that take place in that system and that allows to obtain a conclusion in whether it is possible or not to perform the crew transfer and work on the platform for the current sea state. For each sea state, the metocean database is used to build a wave spectrum which will be the base for a random time series reconstruction. Then, for each sea state, first the free surface time series is checked in order to see if it

meets realistic statistical requirements. Then, the time series for the 15 degrees of freedom (6 movements for the vessel, 6 movements for the platform and 3 forces at contact point) are reconstructed [16].

When each sea state has its corresponding 15 degrees of freedom time series, they will be checked in order to validate if they meet the operational limits for transferability and workability. For transferability, relative rotations between vessel and platform must be below the limit, represented by the horizontal red lines in Figure 5, and static friction force at contact point must be enough to stand the computed forces during minimum consecutive time intervals (jumping window), as shown in Figure 5, and for a minimum percentage of the total time. In this work, based on [14][15] and on the authors previous experience in O&M projects, the following parameters are considered for transferability characterization:

- Maximum relative Roll: 2.5°
- Maximum relative Pitch: 10°
- Maximum relative Yaw: 2.5°
- Minimum jumping window: 10s
- Proportion of time for which transfer must be possible: 34%

For workability, vertical and horizontal Root Mean Square (RMS) accelerations at the hub must be under limits based on International Maritime Organization (IMO) rules. It is assumed that transferability must be possible all the working time for security reasons. This analysis is not necessary for a sea state if the wind speed, the current or the wave height are above the maximum limit.

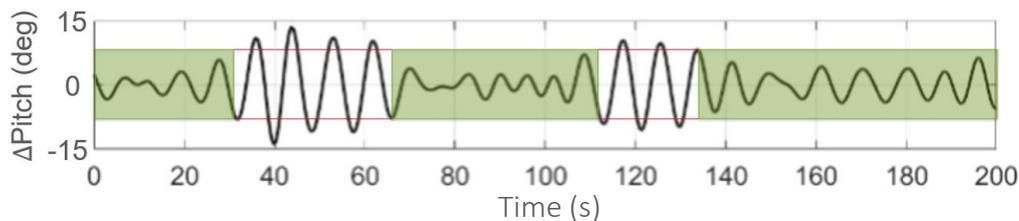


Figure 5. Windows for crew transfer.

To analyse the transport, a Dijkstra algorithm is used to find the shortest path between harbour and the wind farm and the transport distance and time is computed. Then, several nodes along the transport routes are taken from IH Cantabria climate database. Transportability limits for all the hours in the lifespan are set by constant wind speed and wave heights limitations on the maximum values along the route.

Accessibility is finally computed mixing transportability, transferability and workability. Minimum and maximum window size are also considered and with all these inputs, all weather windows in which transport, work and crew transfer are possible are computed. These windows are increased by adding the possibility of starting the travel before workability and crew transfer are possible

2.3. Simulation of the fault repair algorithm

A database with failure rates, repair time and repair cost per component of a wind turbine is considered. Using this data, vessel availability and the reparation time of the failed component, an algorithm is performed in order to obtain the total time from the moment the fault occurs to the moment in which the turbine starts working again. This algorithm is performed several times under different failure rates, providing long-term information to perform a statistical analysis of weather downtime, time and power availability, energy production, reparation time and number of vessel trips. In this work in particular, the algorithm was performed for 20 metocean years (1980-2000) and for 40 different random distributions of failure events. The algorithm used is detailed in Figure 6.

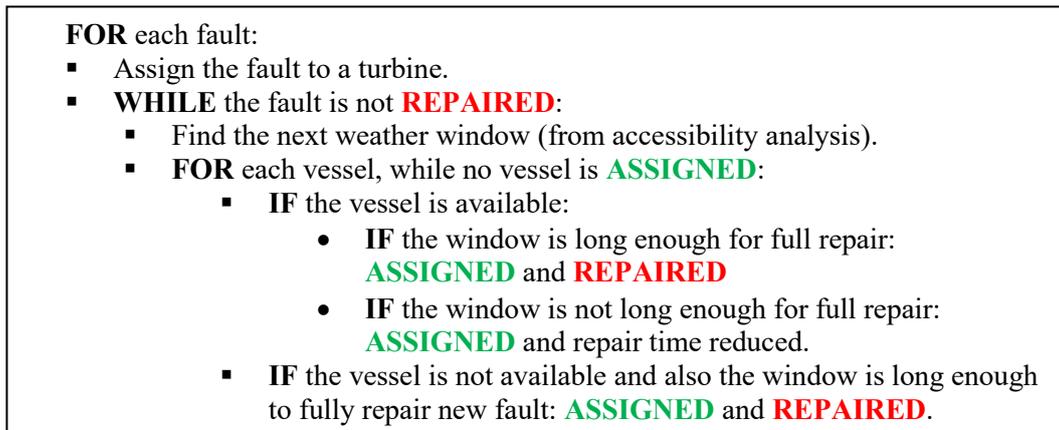


Figure 6: Algorithm used in the simulation

2.4. Methodology for vessel logistics

The model described in 2.1-2.3 is then used to study vessel logistics. The methodology proposed consists of varying several parameters that affect the logistic time spent for turbine repair, with the objective of studying how the availability of the farm varies.

First, the minimum working time will be varied, increasing it from 1 to 2 hours. With this variation, the smallest weather windows will be excluded from the analysis, so the availability will be reduced.

Then, the variable to be changed is the existence of storage of small and medium spare parts. In the first case, it is assumed that there is no storage of medium spare parts, so medium repair logistic time will be increased. In the second case, there is no storage of any kind, so both light and medium repair logistic times will be increased.

Finally, how the availability of the farm varies depending on the type of vessel rental contract will be studied. The type of contract will affect the logistic time, both for light and medium faults, since it is not the same to have the vessel in property than to have contracts in which the vessel is not available until 8, 12, 24 or 48 hours after the fault is detected.

3. Case of study

3.1. WindFloat Atlantic

WindFloat Atlantic is an offshore floating wind farm located 20km off the coast of Viana do Castelo, Portugal. This project includes three V164-8.4MW wind turbines installed on floating foundations.

The WindFloat Atlantic project uses the WindFloat technology developed by Principle Power, a US-based technology developer that focuses on the deep-water offshore wind energy market. With a total installed capacity of 25MW, the wind farm supplies electricity to approximately 60,000 households a year.

For context, O&M work centre is in Viana do Castelo. It's equipped with a storehouse and a CTV (Vortex- Tinita). Large component replacements are conducted in the port using standard onshore cranes. Port of Vigo (100km approx.) has confirmed its availability for these activities. Transportation time from the port of Vigo to the farm is 1 to 2 days. WindFloat already has quotes for suitable onshore cranes [17]. The detail of the assumptions taken for the case of study are detailed in Section 3.1.1.

In terms of logistic times, effects of delays such as waiting for a service technician and that some spare parts are not in stock are considered. When the wind turbine shuts down because of a failure, the fact that the technician needs a spare part to repair the system is assumed. The fact that the service station is staffed 24 h, reduces the mean logistic delay time (MLDT) to 4 hours. Most of the time, the spare parts are in stock and the waiting time then is 4 h. Although, there is a chance that the service team have to wait 24 h for the specific spare part to be delivered from another stock. MLDT also depends on the

weather condition, since it is an offshore wind farm where boats can't go when winds and waves are too strong. The return sail is not exposed to any delays.

3.1.1. Base case

A base case is considered with the following assumptions: a CTV of 17 m is owned by the operators, there is a storage of both small and medium spare parts in Viana do Castelo and the minimum working time is set in 1 hour. These assumptions make the logistic time for light and medium repair 4 hours.

The floating platform chosen in this study is the OC4 semi-submersible, designed by the National Renewable Energy Laboratory (NREL), and used in the TRL+ project. This system is conceived to support a 5MW wind turbine and is composed of a main column and three off set columns (equipped with heave plates). It is moored to the seabed by means of three catenary lines [18]. Figure 7 displays the submerged geometry of the vessel and platform, used for the hydrodynamic analysis, and Figure 8 shows the full OC4 platform with its wind turbine.

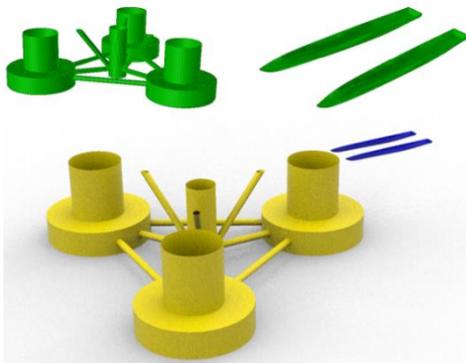


Figure 7. Hydrodynamic interaction model, SESAM meshes and setup.



Figure 8. OC4 semi-submersible platform

With the objective of studying the impact of logistic times in the availability, three variables are analysed: the minimum working time, the existence of spare parts storage and the type of rental contract of the CTV. Results of this study may not correspond to those of the Windfloat project, as different platform and CTV are considered.

4. Results

Starting from an optimistic base case assuming the use of a 17m CTV, the existence of both small and medium spare parts storage in the port of Viana do Castelo and a minimum working time of 1 hour, these logistic times are sequentially increased. The inter-annual and intra-annual variation analysis of the energy-based availability is shown in Figure 10 and Figure 11. Energy-based availability is defined as the percentage of the ideal production that is obtained when failures are considered. The ideal production is obtained considering that the turbines are always available, but not always producing, the wind hindcast is applied. The average availability over 20 years for this base case is 96.0%.

The accessibility rose shown in Figure 9 represents the limiting wave height for which accessibility is possible for each period-direction pair. This rose remains constant for every case studied below.

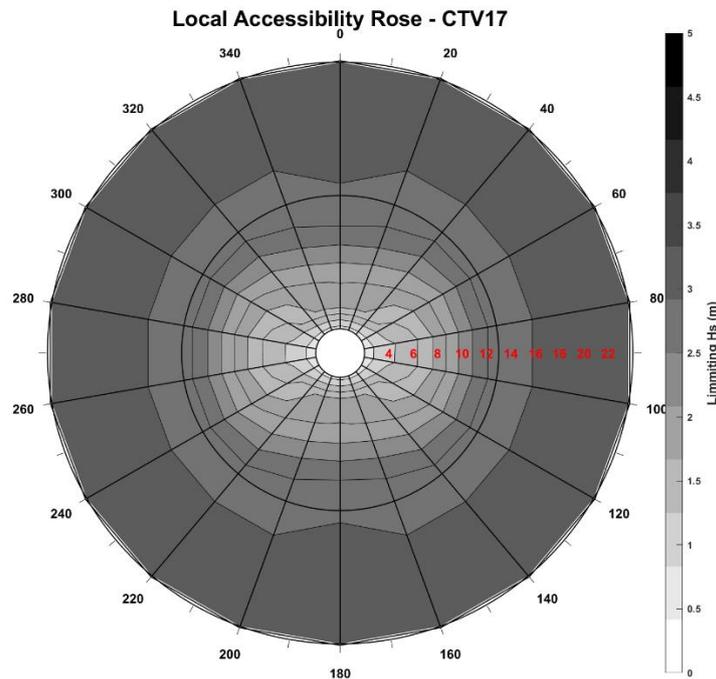


Figure 9. Accessibility rose.

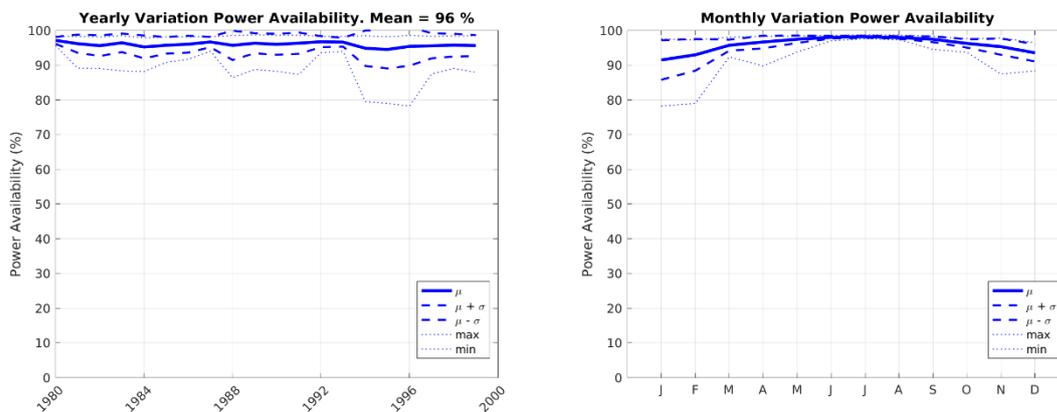


Figure 10. Availability and monthly variation of power availability of the base case.

4.1. Minimum working time

In order to analyse the impact of the minimum working time in the availability of the park, a new scenario in which this variable is increased from 1 hour to 2 hours is considered. It can be appreciated that the availability has been reduced by only a 0.1% (from 96.0% to 95.9%). On the other hand, the number of trips also decreased from a yearly average of 68 vessel trips per year to 65. Knowing the energy price and the vessel trip cost would allow to choose the optimal minimum working time on site.

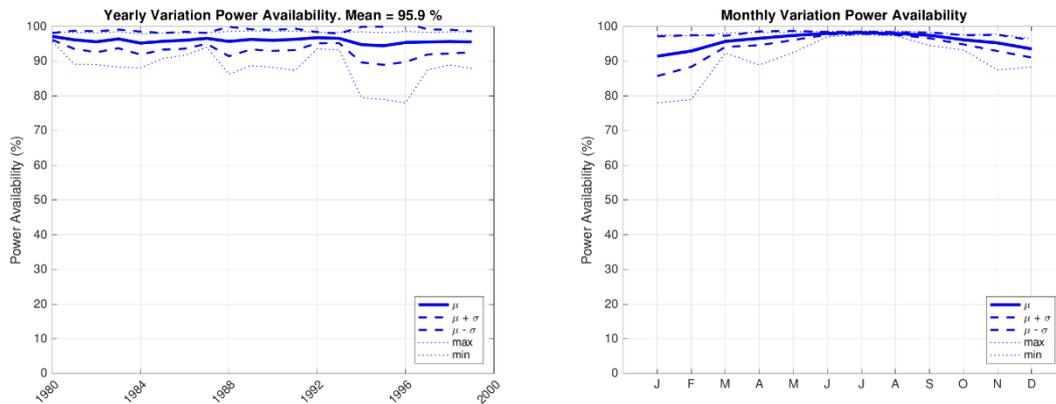


Figure 11. Availability and monthly variation of availability increasing the minimum working time.

4.2. Spare parts storage

Next, with the aim of analyzing the impact of the existence of spare parts storages, two new scenarios are considered. In the first one, it is assumed that there is only storage for small spare parts. This change doesn't affect the logistic time for light repair but increases the logistic time for medium repair from 4 to 24 hours. In the second one, it is assumed that there isn't any spare part in stock. That affects both light and medium repair logistic times, increasing them to 24 hours.

Table 1. Case assumptions and results

Type of rental contract	Existence of small spare parts storage	Existence of medium spare parts storage	Light repair logistic time	Medium repair logistic time	Availability
In property	Yes	No	4h	24h	95.7%
In property	No	No	24h	24h	94.5%

The availability for these two scenarios is reduced by 0.3% to 1.5%, respectively.

4.3. Type of rental contract of the CTV

Finally, four new scenarios are considered, varying the type of rental contract of the CTV. In the base case, the fact that the CTV was operators' property was considered. In these new cases, not having the CTV in property is considered and time necessary to dispose of it will be 8, 12, 24 and 48 hours, respectively.

Table 2. Case assumptions and results

Type of rental contract	Existence of small spare parts storage	Existence of medium spare parts storage	Light repair logistic time	Medium repair logistic time	Availability
8 hours	Yes	Yes	8h	8h	95.7%
12 hours	Yes	Yes	12h	12h	95.3%
24 hours	Yes	Yes	24h	24h	94.5%
48 hours	Yes	Yes	48h	48h	92.8%

For the case in which the waiting time is 8 hours, the availability is reduced 0.3%. In the second scenario, in which we have to wait 12 hours for the vessel to come, the availability decreases 0.7%. When the waiting time increases to 24 hours, the availability loss is 1.5% and lastly, when we have to wait 48 hours, it is 3.2%. These results can help the operator to choose the ideal option for optimizing the CTV contract. The impact on the monthly variability of the power availability should be also considered.

5. Conclusions and future work

A new O&M analysis model has been developed. First of all, this model allows to select the type of wind farm to work with (location, number and type of turbines, type of platform, layout...), as well as the type of vessel available. This tool allows to introduce the metocean data of the wind farm, considering both wind and wave data.

The model then performs an analysis of the time windows in which it is possible to carry out turbine repair work. The crew transfer model includes the fluid-structure-vessel interaction problem, in which wave height, period and direction are considered. An improvement implemented in this study is that a wave-by-wave analysis is performed, instead of an extreme response analysis. Also, the wave directional spreading is considered.

Next, a transport model evaluates the feasibility of boatlanding as a function of wave conditions along the route. Finally, a failure model is fully parametrizable per component and type of fault. All of these aspects make the model highly modular in its implementation that allows to easily adapt to a changing O&M scenario.

The O&M tool can be used for operation and maintenance strategies design, including boatlanding number and orientation, support harbour selection and vessel type and contract selection.

For the case studied, we can conclude that the minimum working time considered for the park has a low impact on the power availability, decreasing the availability by only 0.1%. Meanwhile, spare parts storage may have an impact of 0.3-1.5% in power availability. For the vessel rental contract types studied, the variation in power availability reached up to 3.2%.

Future work is orientated to include a hydrodynamic module for a better representation of the dynamics of the vessel during the sea transport (not only wave height transportation limits but also wave period and direction). Another possible path of study is the analysis of the heavy faults repair and the tow-in of the turbines to repair them at harbor. The authors also aim to include randomly generated climate data for the following 25 years, considering climate change impact over O&M.

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