Advanced Wind Farm Operation and Maintenance Strategies Considering Turbine Interaction

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Abstract

The rise of new technologies also creates new challenges that must be faced: among them, maintenance is a critical aspect, as operations and maintenance account for 23 % of the overall costs of the project. As currently existing software and tools are mostly not open-source, it is of paramount importance to develop an algorithm that is able to reduce the costs associated with maintenance and increase the annual energy production. This work aims to plan preventive maintenance to meet these needs. The case study analyzed is at the WindFloat Atlantic site in Viana do Castelo, as WavEC has extensive weather data and expertise in said location. The present work investigates the advantages given by optimizing the maintenance strategy considering wake effect, as opposed to a sequential scheduling. To select the turbines to maintain on a certain day, a representative value of wind direction and speed is chosen, to consider the variation of condition throughout the day. Several cases were simulated, changing four variables: vessel type (regular and novel), scheduling logic (optimized, sequential, and worst-case), criterium (binary and non-binary) and size of set of turbines simultaneously maintained (five and six). The results obtained are very promising, as it was possible to decrease downtime losses by 48.2 % by implementing a non-binary criterium for preventive maintenance scheduling.

Keywords: Offshore wind energy, preventive maintenance, wake effect.

1. Introduction

1.1 Motivation

As of 2022, the global Offshore Wind installed capacity sums up to 57.6 GW, and according to forecasts it will reach 519 GW installed by 2035 [1]. Nevertheless, currently offshore wind only makes up for 7% of the overall wind power installed, the remaining 93% being onshore. Even though the sector has grown significantly lately, decreasing the Levelized Cost of Energy (LCOE) of offshore wind energy down to 0.75 USD/kWh as of 2021 [2], the availability of offshore wind farms (OWFs) is only between 60 % and 70 %, whereas this number increases up to 95-99 % for onshore wind farms [3]. Among other reasons, OWFs require specialized operation and maintenance (O&M) activities, which are costly and complicated because of the harsh marine environment [2]. Operation and maintenance account for 23 % of the LCOE for an OWF, whereas this percentage is only 5 % for onshore wind farms. The main reason for this is the maintenance costs, namely the cost to replace the equipment and revenue losses due to downtime of the turbines [4].

Therefore, the interventions must be planned meticulously to reduce the LCOE. This can be done in two ways: reducing the costs or improving the energy production. A well-planned O&M schedule can achieve both, hence further decrease the LCOE.

1.2 Objective

The objective of the present work is to assess the impact of considering aerodynamic interactions between turbines to schedule preventive maintenance, such that downtime energy losses are minimized, as opposed to performing maintenance in a sequential order. Namely, wake effects are analyzed, to discover if it is a key factor to consider to decide which turbines to maintain under certain wind conditions.

To do so, the open-source software Flow Redirection and Induction in Steady state (FLORIS) is used. FLORIS is a Python package that can be used to calculate the energy production of a given wind farm, considering wake losses, hence it is a suitable tool for the scope of the present work.

2. Methodology

2.1 Wind Farm Characteristics

The wind farm analyzed in this case study consists of 25 turbines, disposed in a squared layout with a distance equal to eight diameters between one another, as shown in Figure 1. As current developments in turbines size are going towards bigger machines, the IEA 15 MW Reference Wind Turbine is chosen and its characteristics are summarized in Table 1.

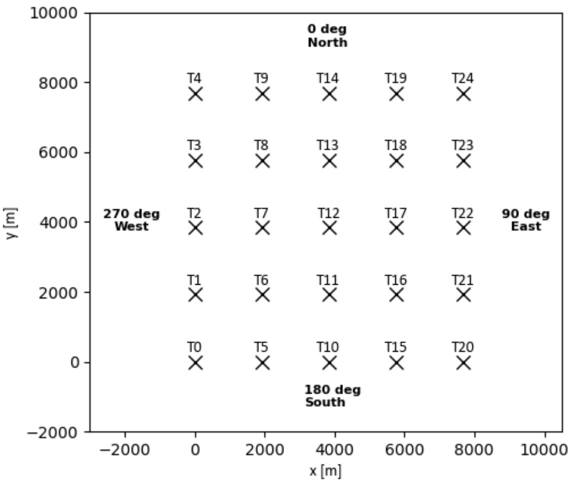


Figure 1 - Wind Farm Layout

Table 1 - IEA 15 MW Reference Turbine parameters. Adapted from [64]

Parameter	Unit	Value
Cut-in wind speed	m/s	3
Rated wind speed	m/s	10.59
Cut-out wind speed	m/s	25
Hub height	m	150
Rotor diameter	m	240

2.2 Weather Data Analysis

The wind direction variation throughout the day is analyzed to find a trend. To do so, the data are separated into months, only including months between April and October as it is the workable period. Moreover, within each month, days are furtherly divided into sixteen groups, depending on the wind speed and direction at 6 a.m..

Table 2 - Wind direction and wind speed groups

Wind speed groups (V) [m/s]	0 – 3	3 – 6.5	6.5 – 10	10 – 15
Wind direction groups (D) [°]	315 – 45 (North)	45 – 135 (East)	135 – 225 (South)	225 – 315 (West)

These graphs highlight a strong variability of wind direction throughout the day, since several days have a variation between 90 ° and 180 °. Therefore, to decide on which turbines to operate, it is important to select the set to maintain based on a proper representation of the wind directions that occur during the day. To do so, a representative wind direction is calculated, as well as a representative wind speed. The wind directions are separated into the sectors mentioned in Table *2*. Moreover, only values that belong to the domain H are taken (from 6 am to 19 pm). Within this domain, the median of modal class is taken as representative wind direction. The representative wind speed is proportional to the cube of the wind speed itself, the representative value chosen is the value of velocity that averages the cube of wind speed. Due to the strong variability of the wind condition within a day, it is crucial to obtain values that properly represent the day, to choose on which set of turbines to operate.

2.3 Conditions for Maintenance

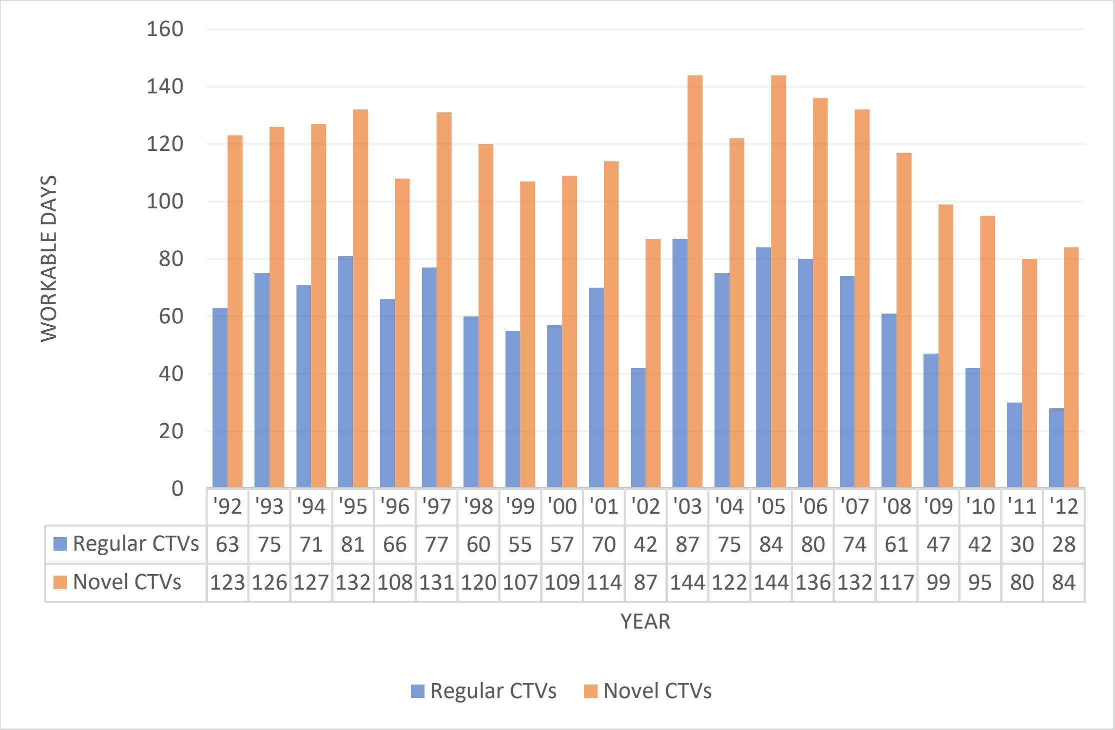
Information provided by WavEC suggests that each turbine requires 80 hours of preventive maintenance per year and that maintenance should be performed in shifts of 10 hours during daylight (between 8 a.m. and 8 p.m.), from April to October. Moreover, the Crew Transfer Vessel (CTVs) that are used have some limitations in terms of maximum wind speed and significant wave height at which they can operate:

- The wind speed at 10 meters height must be below 15 m/s;
- The significant wave height must be lower than 1.5 m (for Regular CTVs).

A day is considered workable if the wind speed and the significant wave height are below the limits defined during the whole workable window, from 8 a.m. to 8 p.m., to ensure safe weather conditions while the CTV goes from the port to the wind farm and back, and when it is moving between turbines.

As CTVs typically have a capacity between 12 and 16 technicians [5] and internal information from WavEC suggests 2 to 3 technicians are required to perform preventive maintenance on a single turbine, with a single CTV it is possible to maintain 5 turbines at a time. Moreover, this number of turbines guarantees a high probability that all the turbines receive the hours of maintenance they require throughout the year [6]. This means that, for all the 25 turbines to receive 80 hours of maintenance, at least 40 workable days per year are required, if it is assumed to perform maintenance whenever it is possible. Despite the high probability of having enough workable days, not all years have 40 workable days. Therefore, to implement a non-binary criterium that allows to reduce the energy losses due to downtime, novel CTVs are contemplated. In particular, three CTVs that can operate with significant wave heights up to 2 meters are already available in the market, hence this threshold can be used for the scope of the present work.

Figure 2 display the number of workable days that are obtained with the two types of CTVs, highlighting the great advantage given by novel CTVs.



	'92	'93	'94	'95	'96	'97	'98	'99	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12
🟦 Regular CTVs	63	75	71	81	66	77	60	55	57	70	42	87	75	84	80	74	61	47	42	30	28
🟧 Novel CTVs	123	126	127	132	108	131	120	107	109	114	87	144	122	144	136	132	117	99	95	80	84

Figure 2 - Workable days with Regular and Novel CTVs

2.4 Wind Farm Aerodynamics and Servicing

In the present work, FLORIS is mainly used for two scopes: ranking all the possible sets of turbines based on their associated energy losses due to downtime, and calculating the AEP and yearly energy losses caused by maintenance when preventive maintenance is scheduled with different logics and algorithms. The following steps are completed under the assumption that, if a turbine is switched off, it behaves as if it did not exist, hence it is removed from the layout.

The function to compute the rankings is written in Python and tested to evaluate if wind speed and direction both influence the ranking. These tests highlighted that the ranking depends mainly on the wind direction, and it is not remarkably influenced by wind speed, confirming what had been observed in the work that the present thesis builds up on [6].

The ranking is calculated from 0 to 360 degrees, with a step of 5 degrees. Thanks to the squared layout of the farm, it is possible to only compute the ranking between 0 ° and 45 °, and apply symmetries to obtain the rankings for the remaining directions.

The second scope FLORIS is used for is to schedule maintenance; thus calculate its associated downtime energy losses, and the AEP. In fact, while it is important to evaluate the impact that scheduling maintenance considering wake effect has on energy losses, it is also crucial to assess its impact on the annual energy production, which is clearly closely related to the energy loss.

To define the cases, which are summarized in Table 3, four variables are considered: CTV type, criterium, scheduling logic, and turbines serviced simultaneously.

Table 3 - Cases

Case	CTV Type	Criterium	n	Scheduling logic
Base Case – 0	Regular	Binary	5	Sequential
1	Regular	Binary	5	Optimized
2	Regular	Binary	5	Worst-case
3	Novel	Binary	5	Sequential
4	Novel	Binary	5	Optimized
5	Novel	Non-Binary	5	Sequential
6	Novel	Non-Binary	5	Optimized
7	Novel	Non-Binary	6	Optimized

Regarding the scheduling logics, they can be defined as follows:

- *Optimized Scheduling*: the maintenance plan is scheduled considering wake effect, in order to minimize the energy losses associated to it. When the best set of turbines to maintain is chosen based on the representative wind direction, it is necessary to check if any of the turbines has already received 80 hours of maintenance. If this is the case, the second-best set is tried and so on, until a set of turbines who have not received the annual required maintenance is found.
- *Sequential Scheduling*: the maintenance plan is scheduled ignoring wake effect, starting from the five southern-most turbines (T0, T5, T10, T15, T20), and moving up once a set of turbines has completed 80 hours of maintenance.
- *Worst Case Scheduling*: the maintenance plan is scheduled to maximize the downtime energy losses, to assess the difference between this and Optimized Scheduling.

The binary criterium implies that maintenance activities are scheduled whenever the weather conditions allow it, namely when the maximum significant wave height and wind speed during the day are lower than the thresholds imposed by the vessels, the significant wave height being the limiting factor. In fact, novel CTVs open more workable windows; hence it is possible to schedule maintenance with these vessels with a non-binary criterium. Namely, it is possible to impose stricter limitations on wind speed and operate when it is low; thus, reducing the energy loss due to downtime. Obviously, the decision on whether to work or not on a workable day can be more conservative or less depending on the turbines that are maintained at the same time. Hence, different criteria were implemented in the two cases analyzed: five turbines and six turbines.

For the first two months, the threshold is manually defined, and it is equal to 3 m/s. In the following months, the limit wind speed depends on what percentage of maintenance has already been carried out: in June and July, the threshold is one third of the annually maintenance; in August it is two thirds of the total. The limit wind speed in these months depends on the size of the sets of turbines: if 5 turbines are maintained simultaneously, the limits are 4.5 m/s and 5.5

m/s, respectively; if each set consists of 6 turbines, the limit is 4 m/s in June and July and 5 m/s in August. Finally, in September and October, when maintenance is completed the process is ended; otherwise, the limit wind speed increases to 7 m/s and 6.5 m/s respectively for sets of five and six turbines.

Once it is decided if maintenance is carried out on the day and the set of turbines to be maintained is selected, the energy loss for the day is computed as the difference between the nominal energy production and the energy produced when the chosen set of turbines is switched off.

3. Results

3.1 Regular CTVs

It can be expected that the optimized scheduling would lead to lower losses than sequential scheduling with the worst-case scheduling being, as the name suggests, the one that entails the highest energy loss. While the worst-case scheduling is always the logic that entails the highest losses, there are some years in which sequential scheduling seems to be the best solution. This is because the set of turbines to maintain with optimized scheduling is chosen based on the representative wind direction, and thus there can be days in which this value does not represent the variation of wind direction properly. Nevertheless, along the 21 years examined, the optimized scheduling logic considering wake effects allows to reduce downtime losses on average by 2.27 % with respect to sequential scheduling and by 5.91 % with respect to worst-case scheduling, as shown in Table 4.

Table 4 - Average percentual improvement obtained by Optimized Scheduling with respect to Sequential and Worst-case Scheduling

	Percentual reduction of downtime energy losses
Sequential Scheduling	2.74 %
Worst-case Scheduling	6.26 %

3.2 Novel CTVs

In this section the results obtained with novel CTVs are presented. At first, results obtained with a binary criterium are shown, then moving on to a non-binary criterium to furtherly reduce downtime energy losses.

As it happened with Regular CTVs, optimized scheduling ensures an improvement with respect to sequential scheduling throughout the whole period considered, with an average of 1.99 % decrease in yearly downtime energy loss. For both optimized and sequential scheduling, downtime losses are significantly higher than the ones occurring with Regular CTVs. This is because increasing the limit significant wave height increases the workable days that are available. Therefore, with a binary criterium that imposes to perform maintenance whenever a workable day occurs, most of the activities are carried out during spring. Spring is characterized by higher wind speeds than summer, thus maintaining the turbines during this season entails higher downtime losses. To take advantage of the higher number of workable days available with novel CTVs, a non-binary criterium was implemented, for optimized and sequential scheduling. For the former, only the possibility of maintaining 5 turbines simultaneously is considered, whereas for the latter simulations are run for sets of 5 and 6 turbines maintained at the same time. The results obtained over the 21 years are summarized in Table 5, highlighting the overall great advantages given by imposing stricter wind speed thresholds to perform maintenance. Sequential scheduling applied with a non-binary criterium, thanks to novel CTVs, already reduces downtime losses significantly throughout the 21 years, with respect to the Base Case. Nevertheless, if the non-binary criterium is applied to minimize downtime losses caused by wake effect (optimized scheduling), it is possible to reduce the energy losses by up to 48.2 % with respect to the Base Case if 6 turbines are maintained simultaneously, or by 36.5 % if operating on sets of 5 turbines. Figure 3 shows how the non-binary criterium allows to exploit the favorable wind conditions in Summer, by reducing the working days in Spring, unlike for the binary criterium.

Table 5 – Downtime energy losses. Non-Binary Criterium with sets of 5 turbines (5T) and 6 turbines (6T) compared with Base Case (Sequential Scheduling with Binary Criterium)

	Base Case	Sequential 5T, Non-Binary	Optimized 5T, Non-Binary	Optimized 6T, Non-Binary
Total Energy Loss [MWh]	70311.0	45770.4	44625.6	36438.6
Percentual Improvement	-	34.9 %	36.5 %	48.2 %

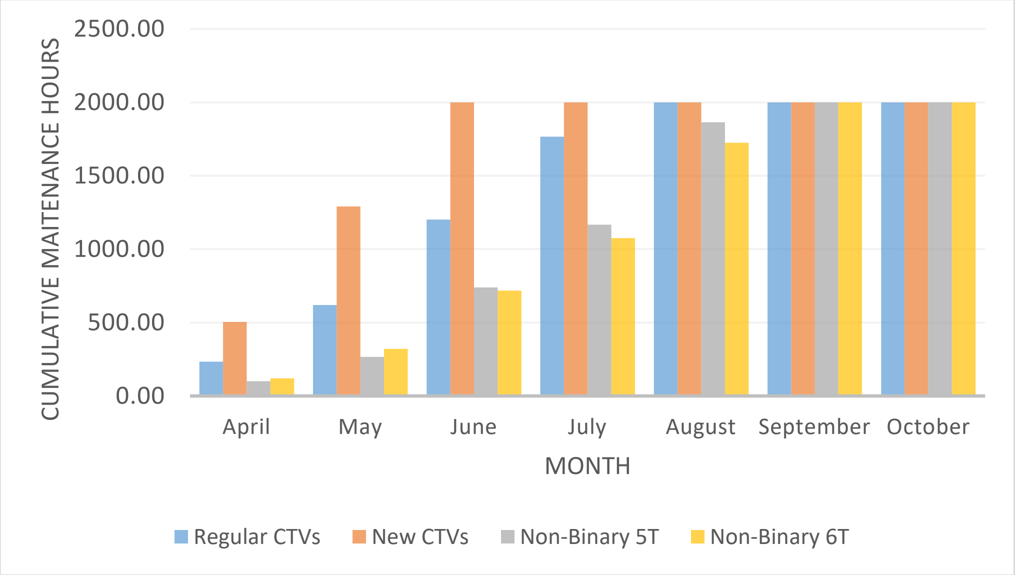


Figure 3 – Average cumulative hours of maintenance for the cases studied

3.3 Annual Energy Production

Finally, the AEP is calculated over the whole period, with hourly data for wind speed and direction, to assess the impact of the maintenance strategies that were implemented on the energy produced. Table 6 summarizes the results obtained, showing that implementing a maintenance strategy following a non-binary criterium can increase the AEP by 0.14 % if operating on sets of five turbines and by 0.18 % if six turbines are maintained at the same time. These numbers might seem small, but they translate in, respectively, 117 and 161 households supplied per year, as one household consumes around 10 MWh of electricity per year [7].

Table 6 - Comparison with Sequential Maintenance (Binary Criterium) with Regular CTVs

	Optimized, Regular CTVs	**Optimized Binary New CTVs**	**Optimized 5T, Non-Binary**	**Sequential 5T, Non-Binary**	**Optimized 6T, Non-Binary**
Energy Loss [%]	-2.74 %	34.09 %	-36.53 %	-34.90 %	-48.18 %
AEP [%]	0.01 %	-0.13 %	0.14 %	0.13 %	0.18 %
Households	9	-114	122	117	**161**

Therefore, this approach is proved to reduce significantly the downtime energy losses that are associated with preventive maintenance, by operating on three aspects: considering wake effects to schedule activities, the type of CTV, and the possibility to operate only below a certain wind speed. All these variables have an impact on the outcome, although the most significant improvement is obtained by using a non-binary criterium, as opposed to the binary one. Nevertheless, the possibility to implement such a criterium solely depends on the choice of CTVs, in this location. In fact, without the use of novel CTVs, it would have not been possible to have enough workable days available to apply a non-binary criterium based on wind speed. Finally, wake effects have an impact, as optimized scheduling entails less downtime losses than sequential scheduling, but the reduction is not as significant as the one obtained thanks to the non-binary criterium. Combining all these factors allowed to schedule a preventive maintenance plan that significantly reduces the downtime losses compared to the base case of planning sequential scheduling, with regular CTVs and binary criterium.

4. Conclusion

The development of the present thesis, as mentioned, builds up on previous work and is expected to be followed by future steps, to further improve the results obtained and add ulterior considerations. It was possible to improve the results, compared to the previous work, mostly thanks to the fact that the method to calculate the representative wind direction was changed and that Novel CTVs were contemplated. This increased the number of workable days, hence allowing a more conservative strategy to only carry out maintenance at low wind speed. This strategy was demonstrated to be able to significantly reduce downtime energy losses with respect to a binary criterium, according to which maintenance is carried out whenever the significant wave height allows it, hence operating at high wind speeds causing significant losses.

4.1 Main Findings

(1) The representative wind direction describes how the wind conditions change throughout the day in a more realistic way than the mean value, which was used in previous studies.

(2) The fact that in some years the Sequential Scheduling seems to be the best solution, entailing less downtime losses than the Optimized Scheduling, suggests that the calculation of the representative wind direction could be further improved.
(3) A non-binary approach that allows to exploit low wind days to perform maintenance can guarantee a significant improvement with respect to a binary criterium.
(4) In locations with severe weather conditions like the Atlantic Ocean, a significant wave height of 1.5 meters is too strict of a limitation to be able to implement such strategy.

4.2 Future Development

Future work could deepen the topic of the advantages given by maintaining even more turbines at the same time. Moreover, different layouts and bigger wind farms could be investigated, as well as other locations. Also, the use of forecasting weather conditions could be compared to hindcasting, as in the present thesis it was assumed that the hindcast is completely reliable, while in reality there is a margin of error in forecasting.

Finally, an economic evaluation on these novel CTVs should be conducted, to assess whether the reduction obtained in terms of downtime energy losses is enough to compensate the price of such CTVs, which are expected to be more expensive than regular ones. Sticking to the economic point of view, it would be of great importance to further develop the present work, by calculating the LCOE, to evaluate if it is competitive with other energy sources, traditional and renewable.

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