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Automated wind turbine maintenance scheduling

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ABSTRACT

While many operation and maintenance (O&M) decision support systems (DSS) have been already proposed, a serious research need still exists for wind farm O&M scheduling. O&M planning is a challenging task, as maintenance teams must follow specific procedures when performing their service, which requires working at height in adverse weather conditions. Here, an automated maintenance programming framework is proposed based on real case studies considering available wind speed and wind gust data. The methodology proposed consists on finding the optimal intervention time and the most effective execution order for maintenance tasks and was built on information from regular maintenance visit tasks and a corrective maintenance visit. The objective is to find possible schedules where all work orders can be performed without breaks, and to find out when to start in order to minimise revenue losses (i.e. doing maintenance when there is least wind). For the DSS, routine maintenance tasks are grouped using the findings of an agglomerative nesting analysis. Then, the task execution windows are searched within pre-planned maintenance day.

1. Introduction

The cost of maintenance is a major contributor to the total levelized cost of energy (LCOE) from wind farms accounting for a share of around 20%–25% [1]. Minimisation of the maintenance costs requires as precise as possible maintenance scheduling. Extended downtime, which can occur when maintenance interventions are delayed during poor weather, incurs financial costs for wind farm owners.

Wind farm operational scheduling has been found in the literature to be a function of a range of factors such as the energy demand [2], electricity market price and wind speed [3]. When the constraints are investigated, wind farm accessibility normally comes in first place in terms of importance. Farm accessibility depends on the variability of the wind speed and the associated health-safety and environment regulations (HSE) [4–9]. In other words, finding an appropriate weather window is a major criterion for any type of intervention for wind turbines and there is a research need closing the gap between academic models and application in practice [10]. According to the literature, maintenance weather windows are dependent on the wind speed for an onshore wind farm, while the wave height is also a decisive factor for offshore wind farms where accessibility depends on the type of maintenance vessel utilized [11–14]. For offshore wind farm operations, the location (distance to shore and water depth), meteorological and oceanographic variables influence the site accessibility, it is highlighted in the literature that there is a trend of moving from near-shore to deep water for offshore wind farm installations, which results in lower site accessibility and higher costs for the executions of corrective maintenance actions [15].

In addition to the measured mean wind speed, industry practice highlights wind gust as an important parameter when considering access to a wind turbine [16].[1] However, thus far, this has not been referred to in the literature concerning scheduling studies as a constraint which affects either operational scheduling or downtime. Previous academic work in this field has considered only wind speed and output power as the decisive parameters when generating a feasible maintenance plan in onshore [18,19] and significant wave height, wave peak period and wind speed in offshore [7,15]. It is already noted in both onshore and offshore crane manuals and safe working guides that working height and wind gust speed influence executions of crane operations [20,21]. When a crane operation cannot be performed, the corresponding wind turbine maintenance action can also not be performed as well and results in delay for O&M actions. This delay

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[1] In this study, two major wind turbine manufacturers' O&M guidelines are used. These two companies are also leading original equipment manufacturers in the wind sector. According to 2017 statistics, the original equipment manufacturers of wind turbine have the highest market share among the wind farm O&M service providers [17].

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contributes to weather related downtime, which is resulting from coarse maintenance planning and insufficient accessibility of both wind farm site and wind turbine component.

In the present study, the authors consider both mean wind speed and wind gust as limiting factors for accessibility to an onshore wind turbine and demonstrate the applications of wind speed measurements in determining task execution sequence whilst minimising downtime due to adverse weather conditions during periods of intended maintenance. The goal is automated scheduling of tasks to be performed within a workday, such that tasks with strict requirements are scheduled when conditions are most benign. The normal practice depends on two weeks ahead maintenance service team booking with a single call entailing which alarm is activated for which turbine. These work orders are lacking detailed planning of the maintenance day and the tasks to be performed. Therefore, there are coarse planning and weather related waiting periods in the wind farm site.

The structure of this paper is as follows: in the following section, an overview of a typical wind farm maintenance policy is described. General characteristics of mean wind speed, wind gust, maintenance log books and task completion duration data are presented in Section 3. The next section describes the methodology, and the proposed framework. Case-studies are then presented to show the value of a proposed maintenance planning methodology, which demonstrates how an optimal sequence for maintenance interventions can be devised. Then, in Section 6, practical explanation of the findings, the limitations and the assumptions are presented. The final section summarises the main outcomes of this study.

2. Maintenance plans & problem statement

Wind turbine maintenance can consist of both corrective and preventive actions. Long term maintenance policies must cover both of these. Corrective maintenance is normally carried out once a fault has been detected, whereas, preventive maintenance is generally performed according to calendar-based pre-determined intervals such as biannual, annual, biennial and quinquennial periods [4,5,22–24]. The number of tasks and the duration of a scheduled maintenance action are different from one case to another and depend on specific sub-assembly, components, manufacturer, model and capacity of the wind turbine. Scientific literature and manufacturers' maintenance guides give figures for the required duration of a range of maintenance tasks that vary from lubrication which typically takes few hours to other more lengthy which last up to 18 hours [23,24] during a biannual maintenance visit. In addition, working practices may differ from one operator to another. These factors must be taken into account in terms of defining a comprehensive maintenance strategy and provide a challenge when developing a model for maintenance optimisation.

Preventative maintenance is usually planned a year in advance on an annual basis for onshore wind farms [25]. A typical flow diagram of this type of advanced planning is shown in Fig. 1a where account needs to be taken of the weather and electricity market prices as well as the availability of a maintenance team [16]. Requirements of preventative maintenance can also be seen even when planning corrective actions as shown in Fig. 1b. Both, regular and corrective maintenance involve uncertainties, particularly concerning the weather related limitations. The typical limiting factor for executing maintenance actions is the wind speed. Regulations and manufacturers' good practices set the maximum values of the wind speed which allow work at different locations on the turbine. This information has been used in previous research works to develop maintenance frameworks. For example, one study fixed the wind speed limit as 10 m/s for accessing the whole turbine [5], while another based the safe working limit on cut in wind speed, i.e., the turbine was only considered maintainable when the wind speed was lower than cut-in [6]. Furthermore, current regulations and maintenance guides include dynamic safety limits taking into account not only the mean 10-minute wind speed value but also the gust value, when a crane usage is required for such a case like major component replacement. The definition of gust is a short-duration (seconds) maximum of the fluctuating wind speed [26].

The maximum permissible wind gust speed for crane usage depends on various factors such as mean wind speed, intervention height and weight of the load [20]. Therefore, corresponding wind gust restriction for any intervention requires timely and case based controls. Moreover, high gust values cause more restrictive wind turbine component specific accessibility rules reducing the highest allowed mean wind speed.

Taking into account only wind speed limits, the safe working rules are also different depending on turbine model and size. For example, in the case of MADE AE 46 turbines, preventative maintenance requires wind speeds below 20 m/s at the nacelle, however changing the whole nacelle requires the wind speed to be not more than 5 m/s. If we check the requirements for NEG Micon NM 52 turbines, working in the hub requires wind speeds below 15 m/s while working in the nacelle roof is allowable until 12 m/s and generator alignment should not be performed for wind speeds above 10 m/s. Finally, for the Vestas V 90 3.0 MW model, generator alignment intervention can't be done for wind speeds above 8 m/s, changing pitch angle requires wind speed values smaller than 6 m/s and working in the drive train is allowed up to 7 m/s [16].

Within a work shift, various tasks must be completed on a wind turbine according to the prevailing time and labour force restrictions. As stated in [11], it is almost impossible to generate a flawless maintenance plan in terms of avoiding production loss, since it is difficult to find a period where the turbine is not producing due to low wind speeds. What can be done in this sense is to schedule the maintenance with an acceptable uncertainty [27,28].

3. Data source, wind farm maintenance procedure and data

Maintenance logs, service work orders and SCADA data were obtained from a Spanish wind farm. In this analysis, O&M service reports, which cover a 3 years window, are used to define the list of actions and the needed duration for each type of intervention and activity in the studied wind farm. Regarding the meteorological data, 10-minute wind speed and wind gust data are collected for year 2019. In the final analysis, accessibility investigations for 24 hours windows are provided for the example cases. According to the information gathered, the average duration of the biannual, annual, biennial and quinquennial visits are approximately 21, 26, 15 and 18 hours respectively. The total number of different tasks to be performed in maintenance visits is 169. Most of them, 117, are included in the biannual visit actions while the others are distributed over the other visits. However, not all maintenance actions are carried out during each planned visit as some of them have priority based on the findings of previous service visits and the needs of the wind turbine.

Fig. 2 shows the considered turbine working zones, while the task numbers associated to these zones are listed in Table 1. In this work, for the sake of simplicity, only the tasks numbers listed in Table 1 are used to define a case study considering a regular service visit. A second case study is based on a major intervention, which requires a crane usage. More specifically, a generator replacement is studied and more information will be provided regarding the corresponding task. To explain the working environment of the service personal for performing either a regular service or a major intervention, the seasonal and general characteristics of the subject wind farm are shown in Figs. 3 and 4.

In Fig. 3, the wind speed seasonal histograms from the case Spanish wind farm are presented. The annual histogram is included in each graphic to highlight the seasonal contribution. It can be seen that the majority of wind speed observations lie between 0 and 10 m/s in summer months. Then, summer looks the best season for maintenance actions, but there are still a significant number of wind speed observations with values higher than 15 m/s.

Fig. 3 shows the seasonal characteristics of the nacelle wind speed

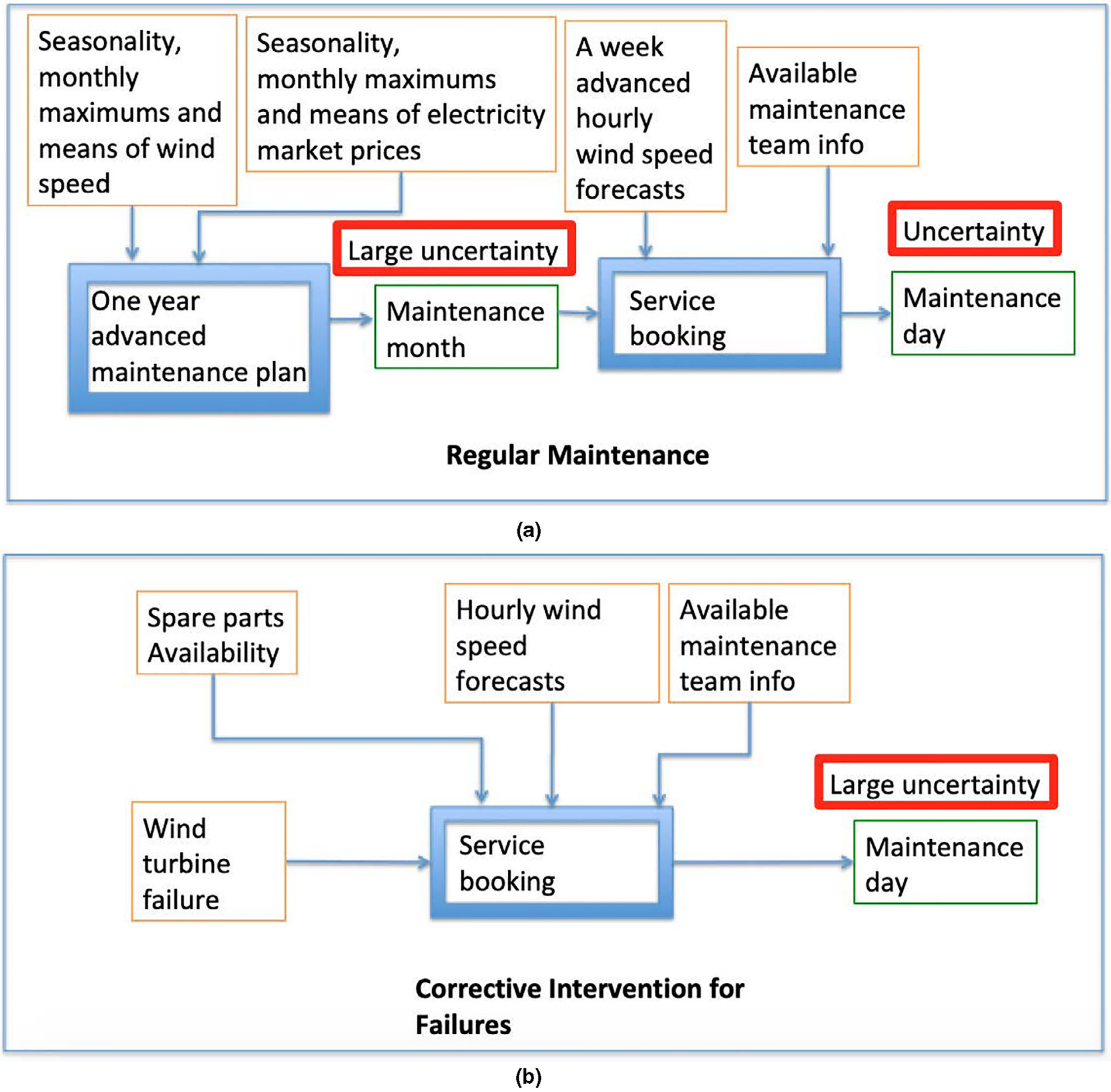


Fig. 1. Maintenance scheduling procedure (a) preventative policy and (b) corrective intervention.

obtained from the analysed wind farm. It is known that the seasonal wind speed behaviour is dependent on the location of the wind farm. The annual maintenance plan must be prepared considering the seasonal wind behaviour and the electricity market prices of the country where the analysed wind farm is located. Then, the seasonal wind behaviour is an important factor for long term scheduling, which is not the aim of this study. The resulting program from the annual maintenance plan is an input to decision making support tool. Therefore, this input must be modified, when the analysed wind farm is changed.

Fig. 4 illustrates the diurnal behaviour of the wind speed for each season during 2019 comparing the maximums recorded in hourly data per seasons. It can be seen that the day shift (08:00 to 18:00) in summer, with wind speed maximums lower than 20 m/s, indicates relatively reasonable wind farm accessibility to perform a maintenance visit.

The majority of scheduled maintenance interventions are planned in summer and autumn months in the case study maintenance log. For this reason, the cases are modelled considering summer and autumn conditions, and input wind speed and wind gust measurements from the case Spanish wind farm for this study are shown in Fig. 5.

Within available data period, two challenging days (the summer day is 27th June 2019 and the autumn day, 08th November 2019), which do not display extreme wind speed values but neither the calm day characteristics, are selected in order to test the capabilities of the proposed DSS. Wind speed data are available in 10-minute resolution as averaged values. Whereas, wind gust data are measured by the turbine nacelle anemometer as 1 second values during an hour.

4. Methodology

In this section, employed mathematical tools, data mining algorithms and search concepts are given. Firstly the mathematical formulation of the scheduling problem and the search algorithm for the generation of feasible solutions are presented. Then, the agglomerative nesting for the problem simplification phase is given. Finally, the proposed framework is introduced.

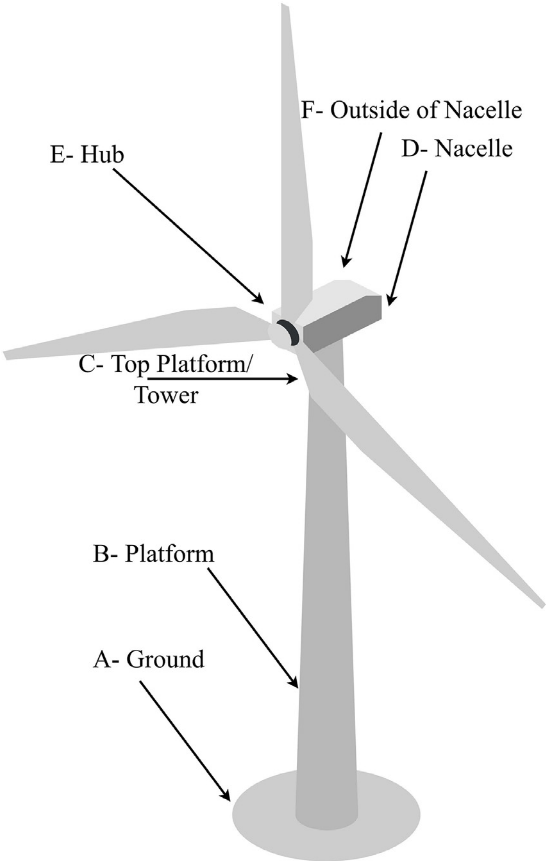


Fig. 2. Example of turbine working zones.

Table 1
Executed tasks for the scheduled visit.

Turb. Work Zone	Sub System	Task Numbers
A-Ground	Tower	1 to 2
A-Ground	Electrical Parts	3
A-Ground	Rotor-Blades	4
B-Platform	Electrical Parts	5 to 7
C-Tower	Yaw System	8 to 14
D-Nacelle	Main Shaft and Bearing	15 to 17
D-Nacelle	Gearbox	18 to 27
D-Nacelle	Generator	28
D-Nacelle	Base Structure and Cover	29 to 31
D-Nacelle	Electrical Parts	32
E-Hub	Rotor	33 to 34
F-Outside of Nacelle	Sensors	35 to 36

4.1. Scheduling problem

In a single visit, there can be various tasks to be performed by a maintenance team, and each task requires a completion time and the fulfilment of the HSE rules regarding accessibility to the working zone. For n number of tasks to be completed in a single visit, each task's (and later on each cluster's) required time window for completion is C_k, where k is in $\{1, 2, \ldots, n\} \in \mathbb{Z}$. For a working interval W, $W = [t_1\colon t_w]$ in 10-minute resolution, $t_1 = 1$ indicates the starting time step, t_w is the final time step. The assigned time slot for execution of the cluster of tasks is symbolised with A_k, Fig. 7b shows graphically A_k and C_k.

When a maintenance team visits a wind turbine and stops it, the corresponding duration without power production is called maintenance downtime. If a maintenance team's work is interrupted due to unfavourable weather conditions, the team must wait until the safe working rules and weather conditions are met, and meanwhile the turbine remains in an idle state for corrective interventions (e.g. generator replacement). In the case of preventative interventions, this waiting time is a loss in labouring resource considering maintenance team working hours. It must be noted that due to practical reasons, it is not feasible for the maintenance team to leave one wind farm site, go to another one and then return to the initial site, since onshore wind farms are located in remote locations. Instead of doing this, waiting in the site is a more preferable option. The resulting waiting time is called weather downtime and will be denoted as Z in this study.

For the first assigned task k during interval W, the corresponding weather downtime Z_k, equals the difference Δt_k, between t_1 and the starting time step of the first assigned task. The second weather downtime occurs between the completion time of task k and the starting time of the next assigned task and so on. Then, using the given notation, the total duration of a single visit, L, will include the function of each task k and its corresponding weather downtime:

$$Z_1 + A_1 + Z_2 + A_2 + \ldots + Z_n + A_n = L \tag{1}$$

With these assumptions, $W \geq \sum_{k=1}^{n} C_k$ and $W \geq L$ guaranteeing the execution of the tasks with duration L, during interval W in multiple ways. It is assumed that once C_k is assigned to a window, its execution requires continuous work without any break or interruption.

In a compact form, L can be written as:

$$L_r = \sum_{k=1}^{n} [Z_k + A_k]_r \tag{2}$$

where r stands for the task completion sequence, $r = \{1, 2, \ldots, n!\}$. As an example, for a task pool containing four candidates, $r = 1$ represents sequential assignment of (C_1, C_2, C_3, C_4) as (A_1, A_2, A_3, A_4) into W, whereas $r = 2$ stands for the assignment of (C_1, C_3, C_2, C_4) as (A_1, A_2, A_3, A_4) into W.

Placement of C_k into A_k is done using the decision vector p_k of the same length (in order to fit the tasks in W) containing the value of b_k. b_k is constructed for each task and each time step as:

$$b_k = \begin{cases} 1, & v_t < V_k \& g_t < G_k \\ 1, & v_t < V'_k \& g_t \geq G_k \\ 0, & v_t \geq V_k \& g_t < G_k \\ 0, & v_t \geq V'_k \& g_t \geq G_k \end{cases} \tag{3}$$

where v is wind speed, V_k is the HSE wind speed limit of task k, g is wind gust, G_k the wind gust limit of task k, and V'_k is the HSE wind speed limit of a task k when the wind gust is higher than its limit ($V'_k = V_k$-2 m/s).

In this problem our variable is the total duration of the scheduled tasks, L, and the objective function for this maintenance scheduling problem is:

$$\min\{L_r\} \quad \forall\, r; \quad r \in S_n \tag{4}$$

where S_n represents all permutations of the elements of task completion sequence, r.

This objective function is subject to the following constraints:

$$\begin{gathered} \sum_{k=1}^{n} A_k = \sum_{k=1}^{n} C_k \\ \forall\, C_k,\ \exists\ (p_k = 1)\ \text{for}\ W = [t_1\colon t_w] \\ W \geq \sum_{k=1}^{n} C_k \\ W \geq L \end{gathered}$$

By finding the optimal configuration for elements of r, it is possible to perform a maintenance visit with minimum total duration.

4.2. Solution: search algorithm for the optimal time window

After defining the scheduling problem in detail, and generating all possible combinations, a search algorithm must be used to find the

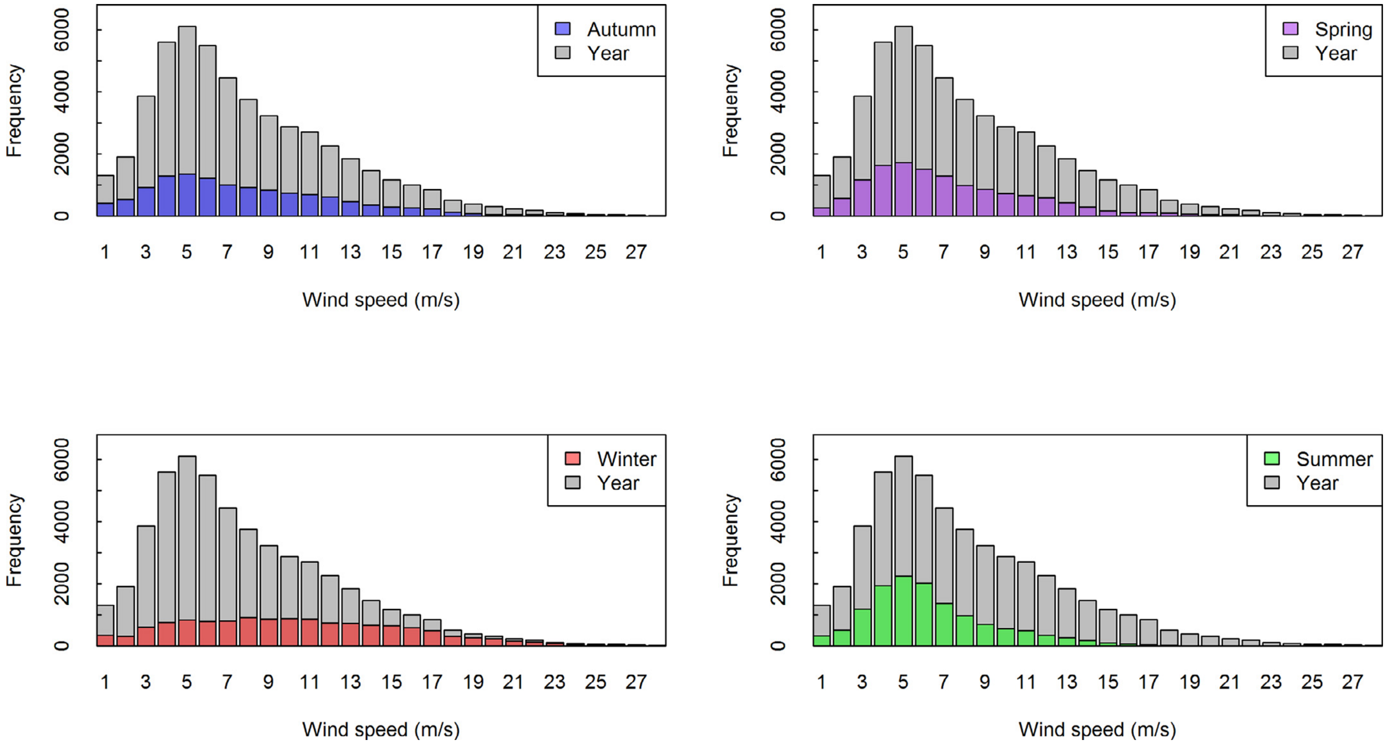


Fig. 3. Annual versus seasonal wind speed histograms using 10-minute averaged mean wind speeds .

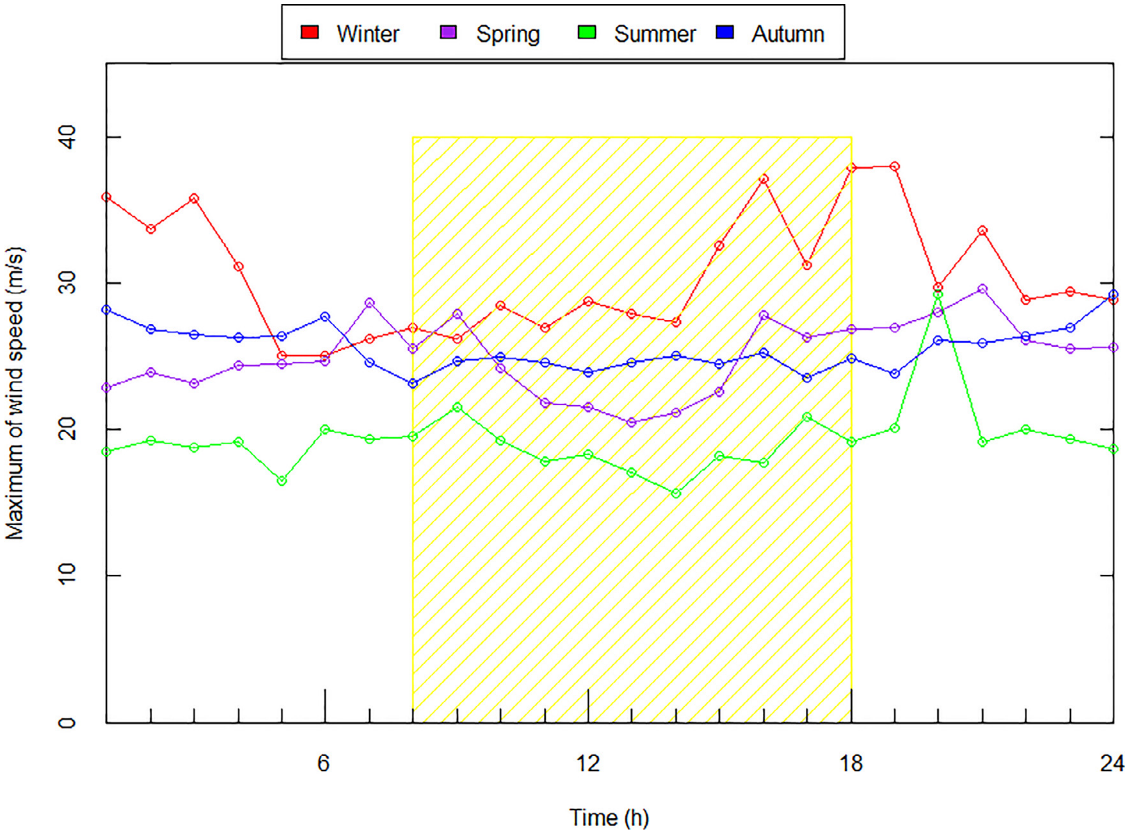
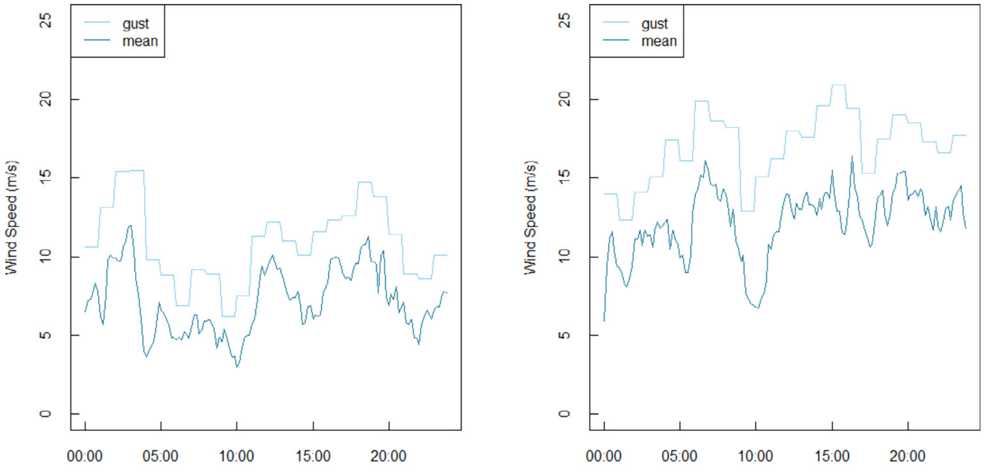


Fig. 4. Seasonal wind speed trends as hourly maximums. This figure is obtained calculating the maximums per hour of each day over a season in 2019. The window, which is shaded in yellow represents the day shift from 08:00 to 18:00. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



(a) (b)

Fig. 5. 10-minute mean wind speed and hourly gust during 24 hours. Gust value is repeated for six time steps, since it is only available as one maximum value per hour.(a) Summer day, (b) Autumn day.

optimal one. Therefore an extensive decision pool, containing a prioritised list of all possible scheduling combinations, can be provided to the decision maker. For such a decision pool, all scheduling combinations must be generated considering problem-specific heuristics. This straight forward way is known as brute force search by its definition in literature [29]. Brute-force search is simple to implement and it always finds a solution, if it exists.

As an example, a maintenance visit can include the execution of 36 tasks grouped in 4 clusters, whereas another one could be defined just with 4 tasks. Tasks and clusters have two common features: the execution duration and the corresponding wind and/or gust related safety restrictions. Specifically, a task is the fundamental element and a cluster consists of many tasks. A task has its own safety restrictions and execution duration, whereas the cluster execution duration is the summation of its member tasks' execution durations. The safety restriction for a cluster corresponds to the most restrictive wind speed limit found for its member tasks. The optimal schedule is then chosen from the whole set of execution combinations. Furthermore, the selection criteria for the optimal solution depend on the minimum execution time, the starting time and the work shift. It is worth highlighting that the minimum execution time implies the execution of all tasks avoiding downtime due to weather restrictions as much as possible. The process of generating the combinations for the clusters is as follows.

The algorithm uses the wind speed, the wind speed working restrictions and the clustered tasks. Initially, the algorithm starts matching the wind speed limit of each cluster with the wind speed for the whole period (typically one day) obtaining the allowed wind speed windows for each cluster, as can be seen in Fig. 6a.

Hereinafter, the execution of n number of clusters for a single visit will be examined. In Fig. 6, the squares stand for 10-minute accessibility periods. Each red square represents non-executable period for a corresponding cluster. As an example, let's assume that the execution of the Cluster 1 (C_1) requires 20 minutes accessibility (i.e., two 10-minute time steps) to the corresponding wind turbine location, whereas the needed time for the Cluster 2 (C_2) is 40 minutes and for the final cluster (C_n) is 10 minutes. In Fig. 6a, it can be observed that the execution of the Cluster 1 can be performed from the first step (*Start*) until the 3rd as it can be placed in two different manners in that interval or from the 5th to the 10th (in this interval five different options are available). Regarding the Cluster 2, although there exist time steps confirming the HSE requirement (time steps 1 and 3), their length is not enough to perform all the tasks of the Cluster. Therefore, these tasks can be executed from the 5th to the 8th time steps.

In the second part of the process, the clusters are allocated together into the allowed forecast windows based on their duration, see Fig. 6b. A symbolises the assigned task in Fig. 6b, A_1 starts from the first time step in 1st and nth combinations but in the second combination, A_1 starts at fifth time step. This illustrates why the scheduling differences occur among combinations. Via cluster permutation, the assignment is done as many times as possible whilst changing the allocation order and obtaining all possible execution windows.

The whole process is then repeated increasing the starting time in order to shift the wind speed assignments by one time-step. The process finishes when there is no room to allocate the minimum execution duration. In this way, a solution plan pool, which consists of many maintenance plans (combinations), is generated. The best combination minimises the downtime occurrence (red blocks), and it must reflect the most appropriate start and finish time according to the decision maker's preferences.

4.3. Agglomerative nesting

For a maintenance visit, requiring the planning of many tasks, it is wise to combine the tasks in the same working zone or to group the tasks that require the fulfilment of the same HSE rules regarding the accessibility. This procedure is known as clustering and here it refers to problem simplification for a brute-force search.

Agglomerative nesting is a data-mining tool and a sub-category of hierarchical clustering. This approach is known as a bottom-up process, since the algorithm is based on a separate cluster (maintenance tasks in this study) assignation for each observation and then a merging of these clusters. In this way, hierarchy is defined from bottom to up.

To apply this approach, firstly the distance between clusters and their merging rule must be defined in advance [30]. Various distance definitions can be found in the literature such as Euclidean, Manhattan, Mahalanobis, etc. The rule governing the merging of clusters is related to the minimisation of the distances, which is known as the Ward algorithm [30].

A dendrogram illustration is the common way to show the arrangement of clusters that are generated by agglomerative nesting [31–33]. One of the drawbacks of the process is the difficulty for the identification of the number of clusters just from the dendrogram only. As it is recommended in the literature, the selection of the relevant number of clusters is made by considering the agreement between various indexes taking into account the majority rule, a decision rule which states the greatest number of votes exercises the greatest

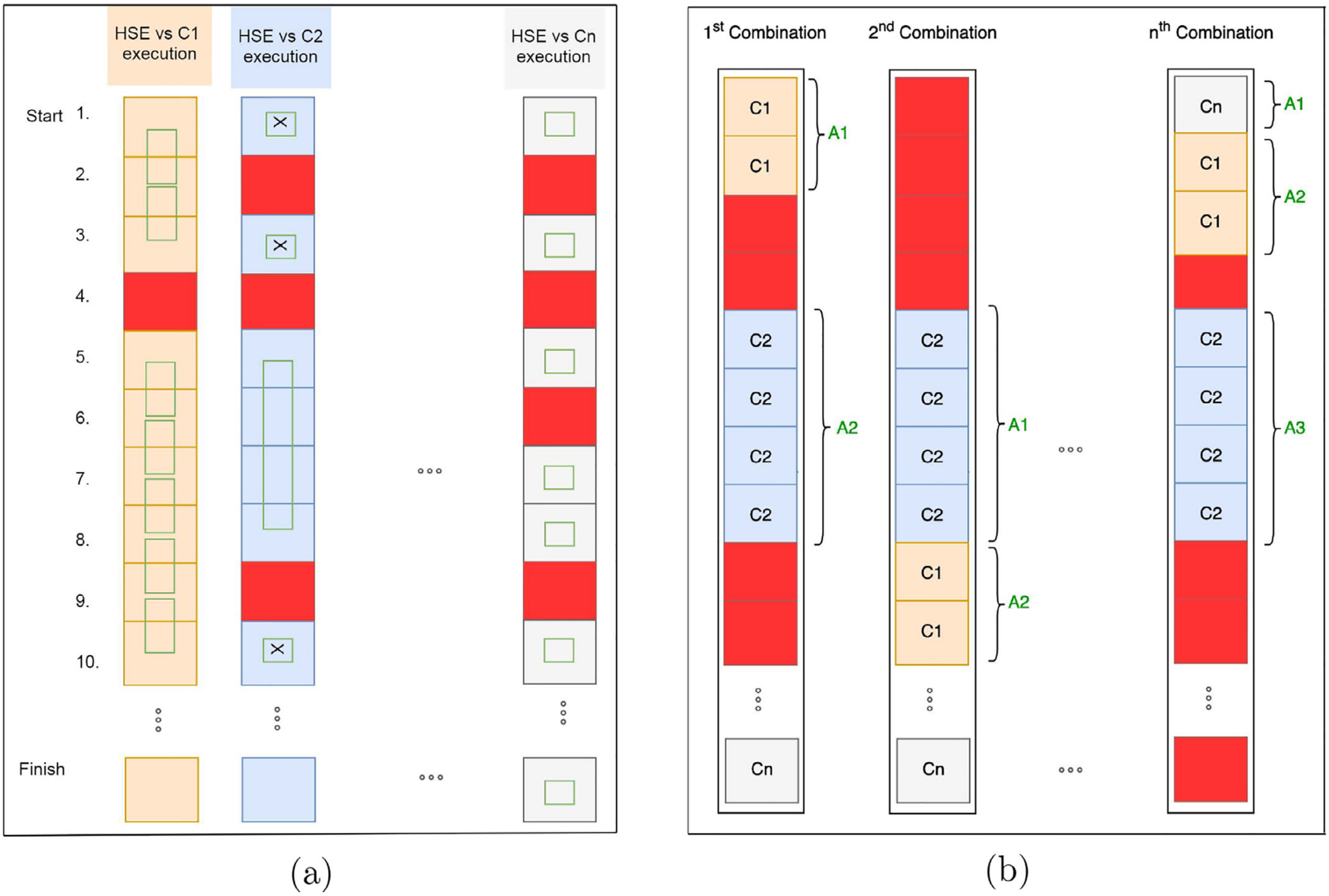


Fig. 6. Search algorithm working principles: (a) Wind speed-Safety rule matching (b) Clusters allocation.

influence for the selection of alternatives [34].

In dendrogram visualisation, height represents the value of the Euclidean distance between clusters. To estimate this distance, input data must be scaled. As an example, for an input consisting of 100 rows and 2 columns, the first column indicates the working zone and the second one stands for the corresponding wind speed restriction. After scaling the input data each observation is firstly assigned to a temporary cluster. Following this procedure, in the first step there exist 100 clusters (100 tasks) and, for instance, the Euclidean distance between Cluster 1 and Cluster 2 can be obtained as;

$$Euc_{dist} = \sqrt{\left(HSE_{v_{C_1}} - HSE_{v_{C_2}}\right)^2 + (WZ_{C_1} - WZ_{C_2})^2} \tag{5}$$

where HSE_v represents the wind speed restriction and WZ represents the working zone. The same calculation is repeated for all 100 clusters. Afterwards, the Ward algorithm groups these clusters according to the minimisation principle of Euclidean distances.

4.4. Proposed framework

The proposed methodology is graphically explained in Fig. 7. The initial step is to provide information on the type of the intervention, initial safe working rules and wind forecasts. Then, it is required to decide if wind gust measurements and estimations are needed as decision variables. The corresponding answer depends on the specific requirements of the planned intervention, such that intervention may require a crane usage.

In the proposed methodology i is the user defined limit for initiating the agglomerative nesting process, as shown in Fig. 7. Here, we assumed that a maintenance task can be done within a minimum of four stages such as: access to working area, access to failed component, remove failed component and placement of the new component. Then, for a case that each stage requires a unique safe working rule, the minimum total number of safe working rules is 4. Therefore, predetermined comparison value, i, is set to 4.

For an intervention consisting of more than four tasks or requiring the fulfilment of more than four safety rules related to wind speed, forecasts must be used along with the outcomes of the agglomerative nesting as input in the search process. The gust forecasts are necessary if the intervention is performed using a crane, which requires reduction of the wind speed limits due to the high gust values. Lastly, the search process scans the available time windows during the intended maintenance day to find the optimal time window for the work to take place. If the maintenance intervention can be executed during the pre-planned day, optimal execution time and order of the tasks are determined. If not, a change in the pre-planned day is suggested.

This methodology can also be used for offshore applications, but it is very important to update HSE requirements considering wave height and offshore operations specific rules. Moreover, intervention type, required duration, outputs of annual maintenance, etc. must be updated considering the technology type and the working environment.

5. Results

The trials with the proposed approach for two distinct maintenance visits are reported in this section. Case 1 is an application test for a routine maintenance visit, whereas Case 2 focuses on a major component replacement.

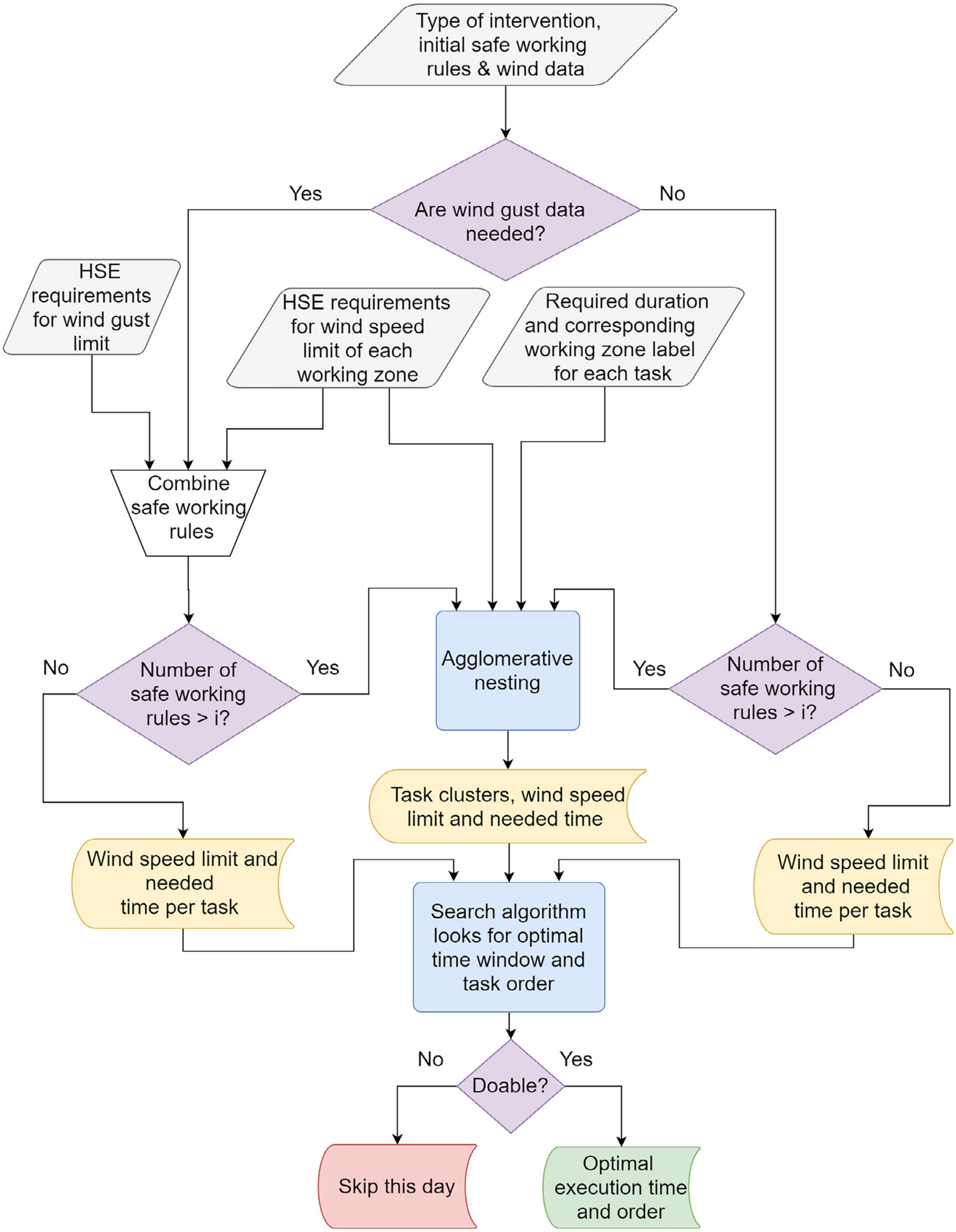


Fig. 7. Flowchart of proposed solution, HSE: Health-Safety and Environment regulations.

5.1. Case 1: Routine maintenance

5.1.1. Clustering

The problem of planning a high number of tasks is simplified by applying the agglomerative nesting methodology to the pool of 36 tasks. Clustering was performed using the Euclidean distance as similarity criterion. It was calculated using the wind speed limit and the corresponding turbine working zone of each operation. Fig. 8 shows how the tasks are grouped forming a total number of 4 clusters (represented with different colors) as a function of the restrictions, wind turbine working zone and wind speed.

A summary of the clustering results is given in Table 2 where the cluster duration and its wind speed limit are shown. As maintenance tasks are usually accomplished by two technicians, which will require half the time, and the required resolution for the planning schedule is based on 10-minute steps, the rounded duration per person on a 10-minute scale is also provided.

5.1.2. 24 hours evaluation for executable/not executable windows

Now by applying the procedure, explained in Section 4.2, with measured wind speed data of test days (the summer day was 27th June 2019 and the autumn day, 8th November 2019) executable and not

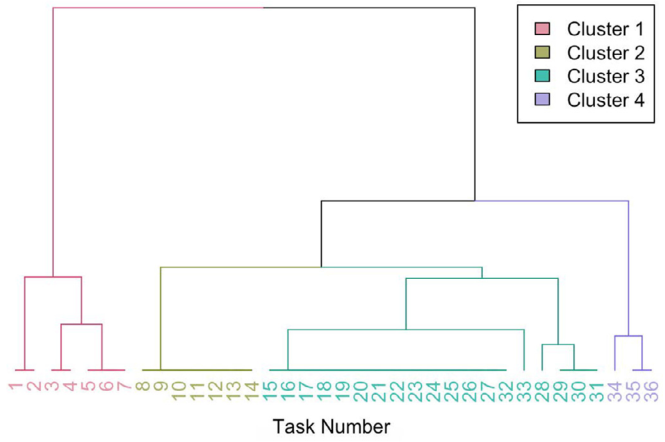


Fig. 8. Graphical representation of the clustering process. Different colours represent the different clusters of tasks. (The dendrogram needs to be re-generated for different technologies considering maintenance intervention lists.).

Table 2
Clustering results.

Cluster	Duration (min)	Per person (10 min)	v_{lim} (m/s)	Required time window
1	66	4	20	7 × 10
2	106	6	15	11 × 10
3	491	25	12	50 × 10
4	50	3	10	5 × 10

executable periods for the maintenance clusters are determined. Figs. 9 and 10 show the allowed intervention starting times for each of the clusters found in the previous section.

Execution of the maintenance service is only possible, if the starting time of the intervention is within the green dots. Here green dots represent valid periods for both wind speed safe working limit and the availability of a window to accomplish the task within its minimum required completion duration. In these figures, v_{lim} represents wind speed limit and *Dur* stands for the required duration for the execution of the corresponding cluster.

Figs. 9 and 10 are given in order to display the complexity of programming with dynamic weather restrictions. The decision maker must consider all the intervention specific accessibility windows and generate a maintenance program combining them.

The results for each of the clusters were:

Cluster 1: Tasks are executable during both analysed days, since the corresponding wind speed restriction is very flexible and its duration is relatively low, see Figs. 9a and 10 a.

Cluster 2: Tasks are mostly executable for both days, see Figs. 9b and 10 b. Although, there are short non-executable windows in the autumn day, see Fig. 9b.

Cluster 3: Tasks are executable for the calmer summer day and tasks are non-executable for the windier autumn day, see Figs. 9c and 10 c. Cluster 3 tasks are the most challenging group, because they require a longer time with major wind speed restrictions.

Cluster 4: The execution of Cluster 4 tasks depends mostly on the most restrictive wind speed limit. Nevertheless, it can be seen that there exist some executable windows, since the execution of this cluster requires the lowest duration, see Figs. 9d and 10 d.

These preliminary analysis shows that in the summer day all tasks can be performed, whereas in the autumn day there is no suitable time window to perform Cluster 3 tasks. Therefore, in the next analysis only the results obtained from the summer day are presented.

Considering the hourly electricity market price, it is possible to combine it with the energy losses for each plan, estimated from measured wind speed values and manufacturer's power curve, to obtain the revenue prioritised decision pools. Fig. 11 shows the day-ahead

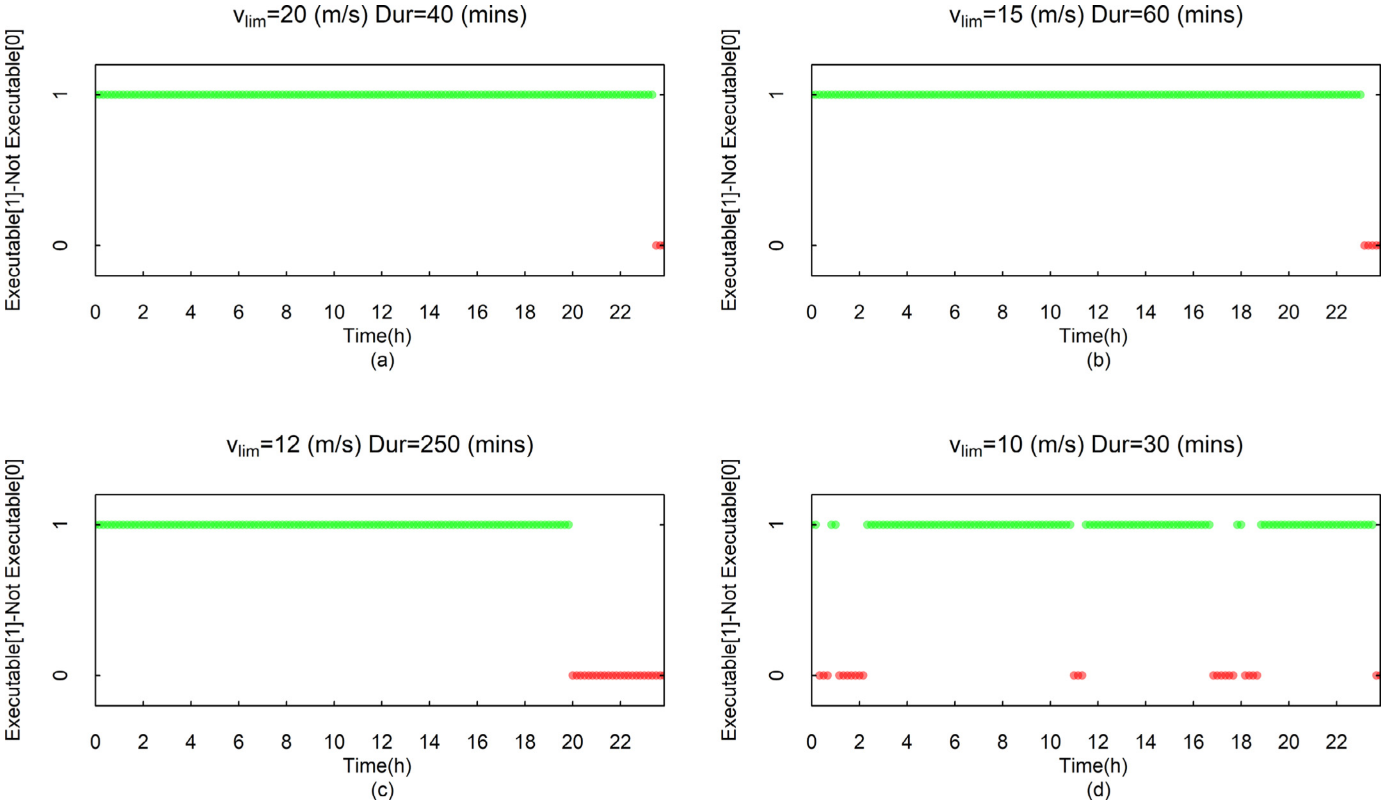


Fig. 9. Routine maintenance evaluation with actual input data for the summer day (a) cluster 1, (b) cluster 2 (c) cluster 3 (d) cluster 4.

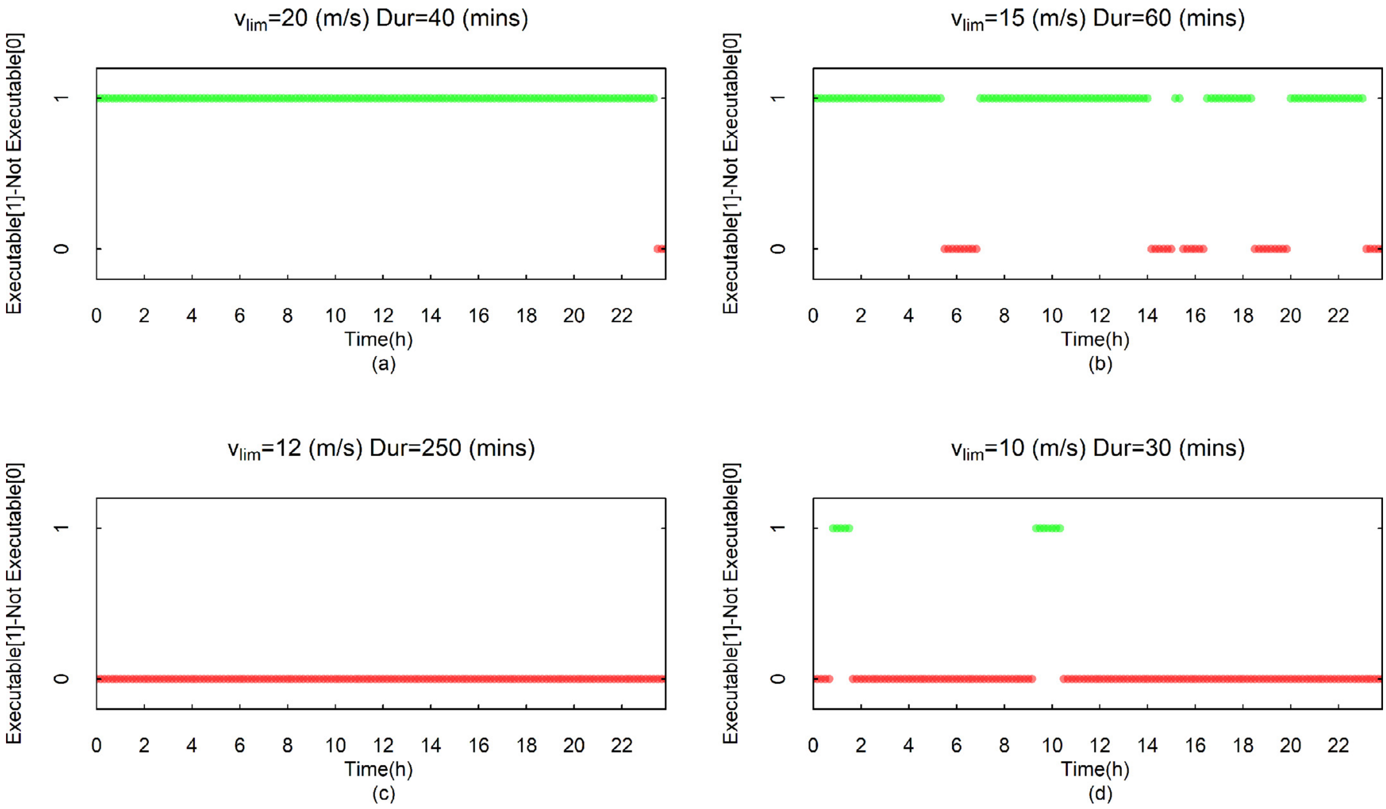


Fig. 10. Routine maintenance evaluation with actual input data for the autumn day (a) cluster 1, (b) cluster 2 (c) cluster 3 (d) cluster 4.

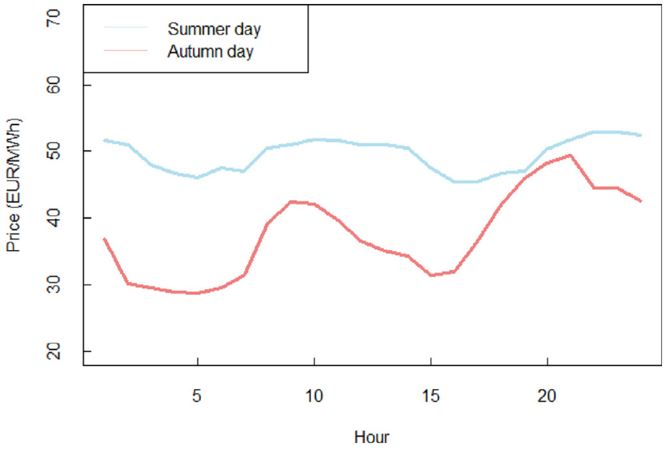


Fig. 11. Day-ahead hourly electricity market price .

electricity market prices for 27th June 2019 and 8th November 2019 [35]. It can be clearly seen that in Summer, 27th June 2019, the electricity market prices higher than 50 EUR/MWh, while in Autum, 08th November 2019, most of the prices are between 30 and 40 EUR/MWh, following the common trend observed in the spanish market [35].

Fig. 12 shows the corresponding revenue losses of the prioritised maintenance plans, labelled as “low” when they are below the mean of the revenue losses estimated for the day under consideration. When they are lesser than the third quartile and greater than the mean, the label is “medium”. Lastly, for the plans with the revenue losses greater than the third quartile, the label is “high”.

This DSS is prepared as a computational tool and the visualisation of the reporting module is given in the Appendix 1, where the alternative plans and the revenue evaluation procedure are exemplified.

In Fig. 12, only selected alternative maintenance plans are plotted when a cost-wise clear separation can be observed among the 1093 alternatives (14 of 1093) for the analysed summer day. Each alternative represents a program, which confirms that weather related downtime is minimised. According to Fig. 12, the early hours of the day are more preferable in order to perform preventative intervention considering the revenue losses. Although electricity market prices are high during these hours, the limited wind resource availability, reduces power production losses and corresponding revenue losses.

5.2. Case 2: Generator replacement

5.2.1. 24 hours evaluation for executable/not executable windows

In this case study, the generator replacement is investigated for the proposed scheduling process. To replace the generator, a crane must be used. Firstly, the nacelle cover must be removed and then the failed generator must be taken out. These removals are followed by installation of the new generator and re-installation of the original nacelle cover. In other words, this intervention requires two types of lifting /unloading tasks. Safety requirements with regards to wind speed vary due to the gust values. The mean wind speed limit for safe working has to be decreased by 2 m/s when the wind speed gust is above 5 m/s for operation requiring a crane usage [16], from 10 m/s, for a gust lower than 5 m/s, to 8 m/s for a gust higher than 5 m/s in the case of nacelle cover and from 8 m/s to 6 m/s, for the same gust values, in the case of the generator. It is worth mentioning here that the gust limit, to the authors knowledge, has never been considered in previous scientific studies. Another difference, regarding routine maintenance plan, is the requirement to follow a fixed task order, as obviously, it would not be possible to perform removal of old generator before removing the nacelle cover. Therefore, the maintenance execution order is fixed for this problem.

The obtained results for a corrective maintenance visit in the previously selected Summer day are shown in Fig. 13. Executable (green) and not executable (red) time windows are shown for the four main tasks of a corrective intervention. Here, a 120 minutes window is

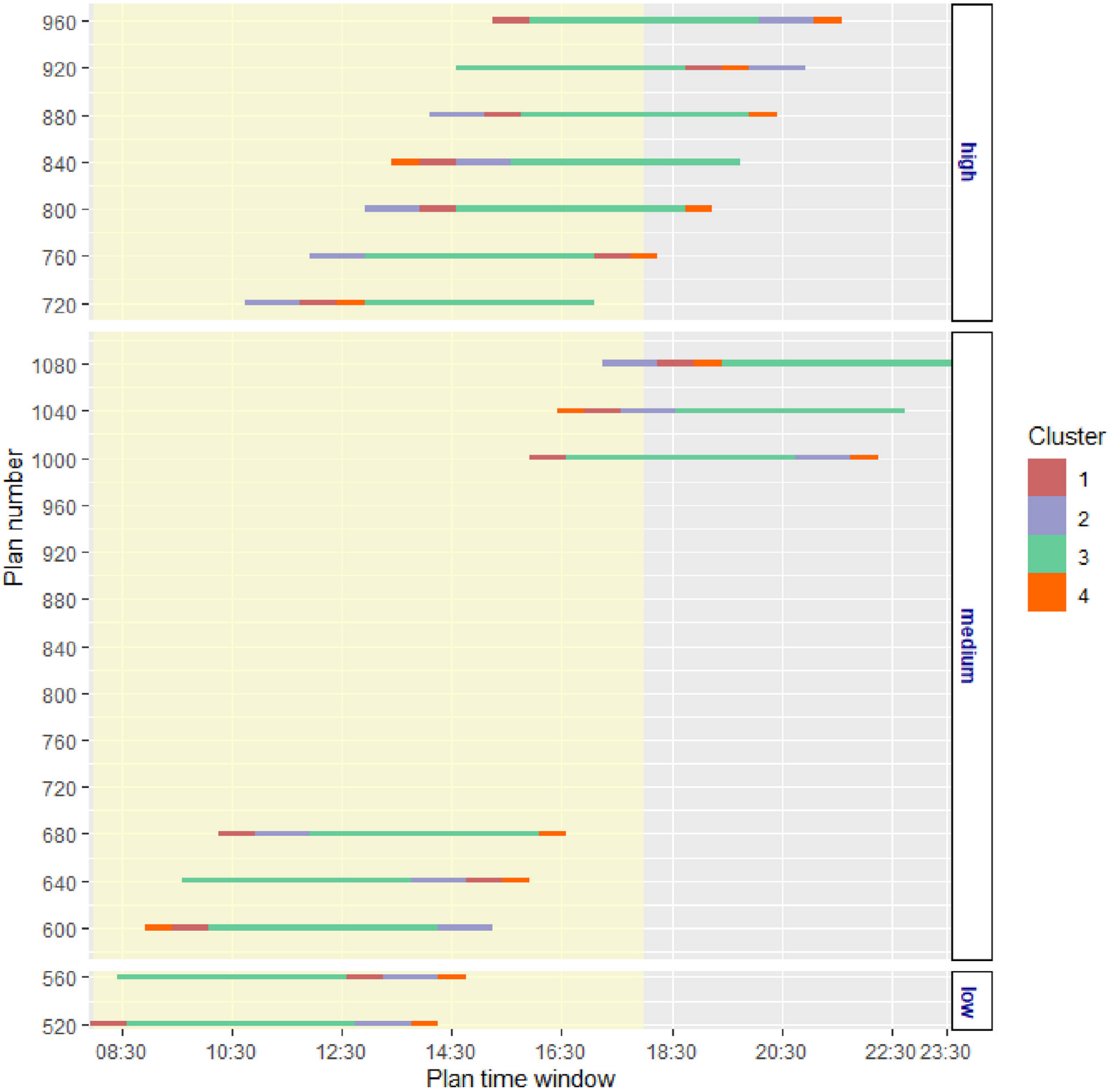


Fig. 12. Decision pool for routine maintenance visit scheduling for the summer day, the second y axis stands for the grouping according to the revenue losses, yellow shaded window shows the day shift. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

searched for the removal of the old generator and another 120 minutes window for placement of the new one. In these searches, the permissible wind speed reduces from 8 m/s to 6 m/s, when the wind gust value exceeds 5 m/s. The remaining tasks require a 90 minutes window search for the removal of the nacelle cover and another 90 minutes for the placement. In these searches, the permissible wind speed reduces from 10 m/s to 8 m/s, when the wind gust value exceeds 5 m/s.

It is rather easy to highlight the impact of the gust variable with a simple comparison between Figs. 13 and 10. Due to the gust related restrictions, a corrective intervention cannot be performed in this case, although it was possible to perform a preventative maintenance intervention.

6. Discussion and limitations

When a decision maker uses only the mean wind speed characteristics, any day from the summer season is a good candidate in order to prepare the maintenance plans. This study presented that each candidate day must be analysed profoundly. Because, while the power losses resulting from the maintenance interventions could be limited, the revenue losses could be severe due to the electricity market prices and vice versa. As it is shown in this study, not only the mean wind speeds, but also the wind gusts are the limiting factors for performing some major maintenance activities. The implementation of other environmental limiting factors (fog, rain, etc.) was not possible due to data unavailability.

The practicality of such a DSS highly depends on the input data. Uncertainties in regards to duration of tasks and in relation to weather forecasts are not considered in the present study. It must be noted that in order to use the proposed DSS in the field, one must use as input: wind speed, wind gust and electricity market price forecasts to be able to asses, which day is preferable to schedule maintenance activities in near future.

Various stakeholders must participate in wind farm O&M

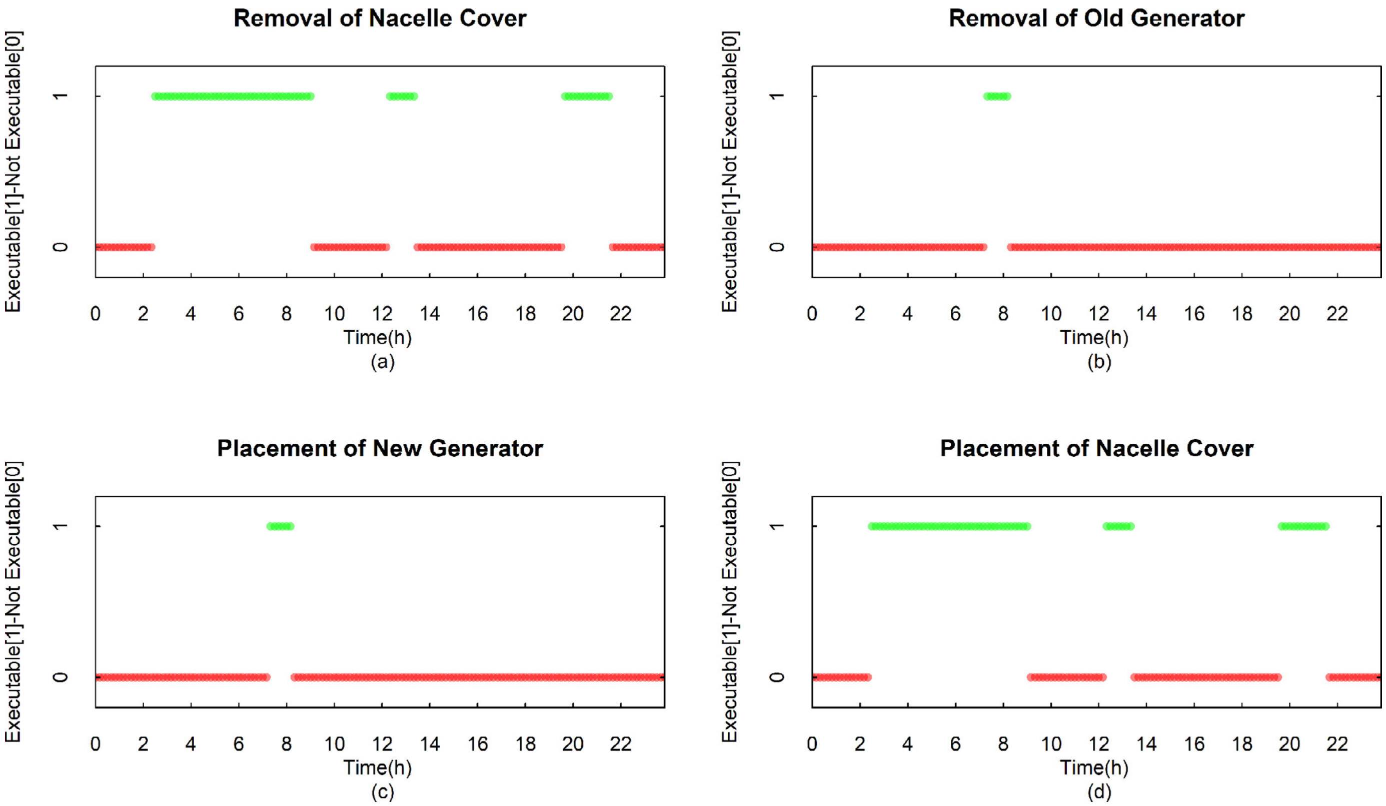


Fig. 13. Evaluation of generator replacement when considering dynamic safe working limits due to gust (Summer day).

interventions. In this study, only the revenue losses aspect, which is important for the wind farm owner, is studied. However, O&M service provider might be interested in the efficient usage of its own labour force and man-hour salary analysis, which are not examined here.

The proposed DSS generated successful decision pools for the examined days, however, further trials are needed to be performed in order to verify the applicability of the generated plans. Further, refinement can be adapted in the clustering process for non-executable cases by splitting the clusters again, if it is not possible to execute all tasks within a period with low winds.

7. Conclusions

This study presents maintenance intervention scheduling challenges and possible solutions for two different maintenance cases, routine and corrective. Safety restrictions for wind farm maintenance visits are studied in detail. It is found that in addition to wind speed, wind gust is also a limiting parameter for wind turbine accessibility and maintainability. The proposed method is capable of determining if it is more optimal to start the work later, to avoid being at the site and not being able to perform any tasks due to high winds, and it can estimate the loss of revenue for each plan.

A possible extension of this study would be to schedule a maintenance plan for multiple wind turbines in a single visit by taking into account short term forecasts. Moreover, gust variable might be used as a more serious contributor in the decision support tool by including crane usage permissible wind speed limits. Then, the combination of dynamic safe access pre-requisites for wind turbine and crane could be simulated together for a maintenance day by using both wind speed and wind gust forecasts.

CRediT authorship contribution statement

Nurseda Y. Yürüşen: Conceptualization, Methodology, Software, Data curation, Writing - original draft, Visualization, Investigation, Formal analysis. **Paul N. Rowley:** Conceptualization, Writing - review & editing. **Simon J. Watson:** Conceptualization, Visualization, Writing - review & editing. **Julio J. Melero:** Conceptualization, Data curation, Visualization, Supervision, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue. The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript

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Appendix A

The reporting module of the developed DSS is given in Fig. A.1. This module consists of four zones.

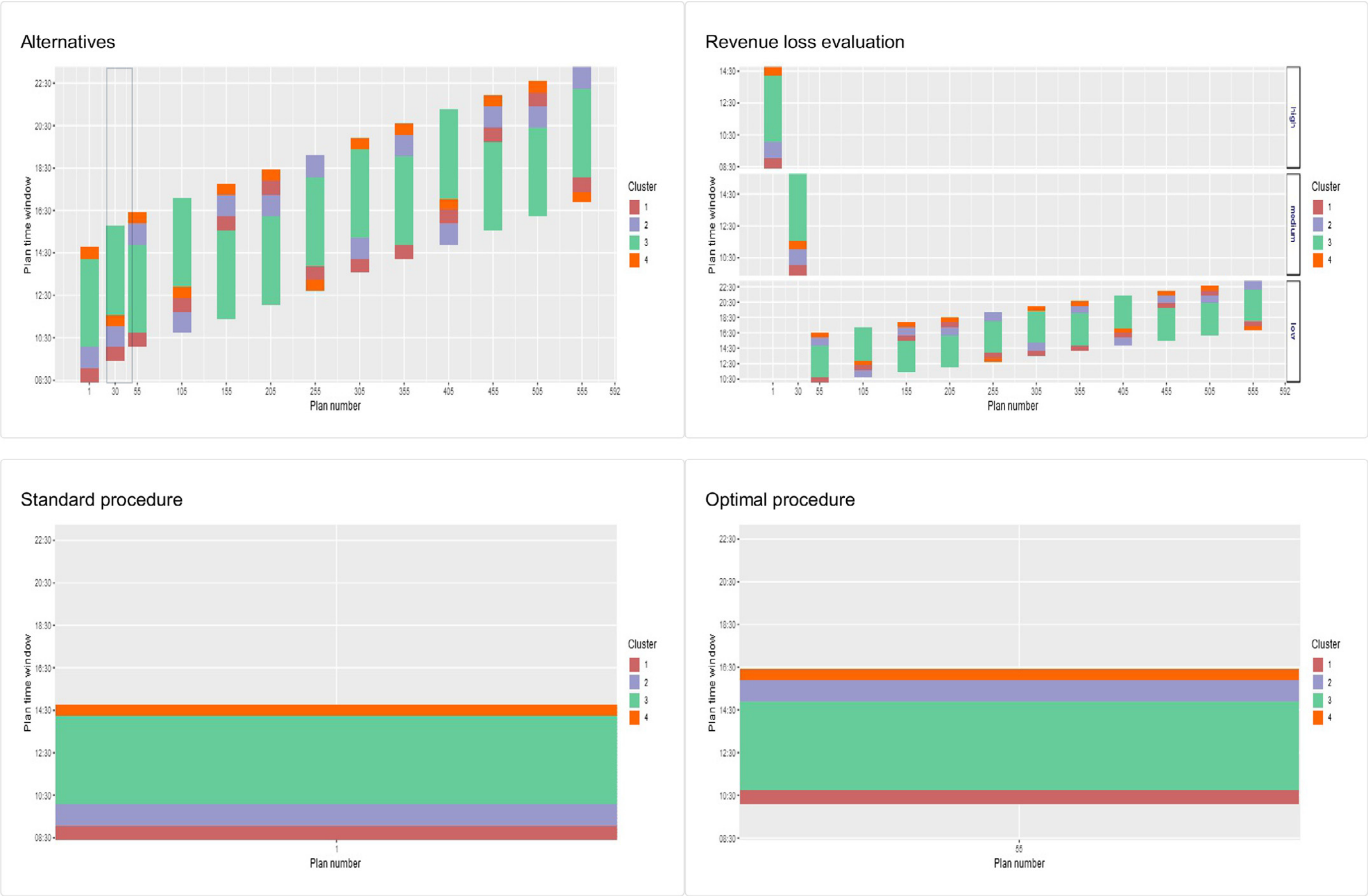

Fig. A1. Maintenance plan evaluation tool. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- Alternatives: it is possible to see all the alternatives, which confirm the safe working rules. Among them, it is possible to request only a sample, in this example only 13 of them are shown.
- Revenue loss evaluation: In this window, for the plans that are given in the ‘Alternatives’, the revenue losses are estimated and the plans are grouped as high, medium and low.
- Standard procedure: This window refers to the default procedure, regarding the day shift which starts at 08:30 and the execution of the clusters performed in an order of 1,2,3 and 4.
- Optimal procedure: This is the optimal plan obtained with the proposed methodology, which results in the minimum revenue loss.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.ress.2020.106965

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