A Model for the Optimization of the Maintenance Support Organization for Offshore Wind Farms

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***Abstract*—Maintenance of offshore wind power plants is known to be extensive and costly. This paper presents a model for optimizing the maintenance support organization of an offshore wind farm: the location of maintenance accommodation, the number of technicians, the choice of transfer vessels, and the use of a helicopter. The model includes an analysis of a transportation strategy using alternative transportation means, a queuing model of maintenance activities, and an economic model of the maintenance support organization. An example based on a generic 100 wind turbine 5-MW wind farm is used to demonstrate the application of the model. The results show the benefit of the production losses of the different options, which enables the identification of an optimal maintenance support organization based on the reliability, logistic costs, and electricity price. The most cost-efficient maintenance support organization in the case study consists of an offshore accommodation with technicians on service 24 hours a day, 7 days a week. The solution suggests transportation by use of a crew transfer vessel equipped with a motion compensated access system.**

***Index Terms*—Maintenance, offshore wind energy, optimization, support organization.**

I. INTRODUCTION

THE maintenance cost is known to be an important part of the cost of energy generated by offshore wind parks. The transportation of maintenance technicians to the wind turbines must be performed by workboats, which are constrained by wave height and may lead to poor accessibility resulting in long downtimes, or by a helicopter, alternatives which are both costly. The reliability of onshore wind turbines has been reported in such sources as [1]–[4]. The availability of onshore wind turbines is typically in the range of 95%–99%, while for early offshore projects, an availability as low as 60%–70% has been observed at some wind farms [5], [6]. Despite high capital cost and the cost of operation and maintenance, the installed capacity of offshore wind power has increased exponentially in Europe from 800 MW installed at the end of 2006 to 3.8 GW at the end of 2011 and many offshore wind farms are expected to be built in the near future, especially in the U.K., Germany, Denmark, and the Netherlands. The reasons for this trend are high wind resources, the availability of space, low visual and noise impact, better understanding of the economic risks, and high financial incentives [17]. The target of the European Wind Energy Association is to reach 230 GW of installed wind power in Europe by the end of 2020, of which 40 GW shall be generated by offshore wind power plants [7].

Operation and maintenance is expected to contribute between 15%–30% of the cost of energy generated by offshore wind farms [9]. The optimization of maintenance can be separated into interconnected areas, including 1) maintenance strategies (see, for example, [10]–[12]), and 2) maintenance scheduling (see such sources as [13] and [14]), in addition to maintenance support organization. Commercial models have been developed for the analysis of maintenance support organization; see, for example, [18] for an analytical model, and [19] and [20] for simulation models. To the knowledge of the authors, no model has been published that evaluates the possibility of using alternative transportation means, for example, the use of a helicopter in cases when the transportation by workboat is impeded by harsh weather. Moreover, no analytical model has been published that considers the effect of the work shift and the queuing of maintenance work in case of a lack of technicians.

This paper proposes an analytical model which enables fast computation of the performance of a maintenance support for offshore wind farms with alternative transportation means. The following aspects have been identified as critical to the maintenance support organization of offshore wind farms:

1) location of maintenance accommodation;
2) number and type of crew transfer vessels;
3) use of helicopter;
4) work shift organization;
5) spare part stock management;
6) technical support;
7) purchase or contracting of a crane ship.

The proposed model focuses on factors 1–4 and distinguishes between major and minor failures with respect to repair time and required means of transportation. However, it does not consider the replacement of major components, e.g., blades, main bearing, gearbox, or generator. These components are continuously monitored, which enables proactive planning of resources, and their replacement is afflicted with different logistic needs than those taken into account in the present study, e.g., a crane ship.

II. MODEL DESCRIPTION

An offshore wind farm consists of N_{WT} wind turbines with an installed capacity of P [MW] each and a season-dependent capacity factor of C_f^s.

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A. *Time, Season and Environmental Conditions*

Historical data regarding environmental conditions at offshore wind farms are generally collected in time series of 1- or 3-h steps. In the proposed model, it is assumed that the time series are indexed by $t \in T = \{0, 1, \ldots, N_T - 1\}$, where T is a time set with a number of N_T steps Δt. The time series for the wind speed and significant wave height are denoted w_t and h_t, respectively.

The year is divided into the four seasons of winter, spring, summer, and autumn indexed by $s \in S = \{\mathrm{win}, \mathrm{spr}, \mathrm{sum}, \mathrm{aut}\}$. $T^s \subset T$ denotes the subset of the time set belonging to each season indicated by N_T^s time steps.

B. *Corrective and Preventive Maintenance*

Wind turbines are subject to corrective maintenance (CM) and preventive maintenance (PM) activities. CM is carried out after failure should occur and is intended to restore an item to a state in which it can perform its required functions [7]. If a failure occurs, a wind turbine would stop operating until the required repair has been performed. Because of this possibility and the limited accessibility of offshore wind turbines, the occurrence of unexpected failures can have a severe impact on turbine availability and, therefore, on the revenue from production. Failures may be classified into minor and major failures according to the logistic needs for repair. To repair a minor failure, the wind turbine can be accessed by both workboat or helicopter, while a major failure always requires a workboat. This classification is necessary due to the significant differences in dimension and weight of spare parts as well as the equipment required to perform the maintenance. The failure rate for minor and major failures per season are denoted by λ_m^s and λ_M^s, respectively, and the durations of the related corrective maintenance activities in the wind turbine are denoted by r_m and r_M. Each repair action is assumed to require one maintenance team.

PM is carried out at predetermined intervals or corresponding to prescribed criteria, and is intended to reduce the probability of failures or the degradation of a system [7]. In the case of offshore wind turbines, PM covers the annual service maintenance and condition-based maintenance. The PM activities require r_{PM}^s hours and N_{PM}^s maintenance teams per wind turbine. It is assumed that the PM activities consist of short duration activities that may be performed on several discontinuous work shifts. In case of PM, the wind turbine is stopped for the duration of the maintenance work only.

C. *Maintenance Technicians and Work Shift*

The maintenance technicians at the wind farm are organized into teams of N_{team} technicians working in shifts of d_{shift}^s[h] duration. A maintenance team works for d_{team}^s [h] per season. It is distinguished between permanently employed and supplementary maintenance technicians. Permanently employed maintenance technicians can perform both CM and PM activities, while CM activities are always prioritized due to their crucial impact on turbine availability and production as explained above. The minimum duration of a maintenance activity in the wind turbine is $r_{\min}$[h]. If the number of permanent maintenance technicians would not be sufficient to perform all PM activities scheduled for a season, supplementary maintenance technicians working mainly on PM would be hired for the season in agreement with common practice at existing offshore wind farms.

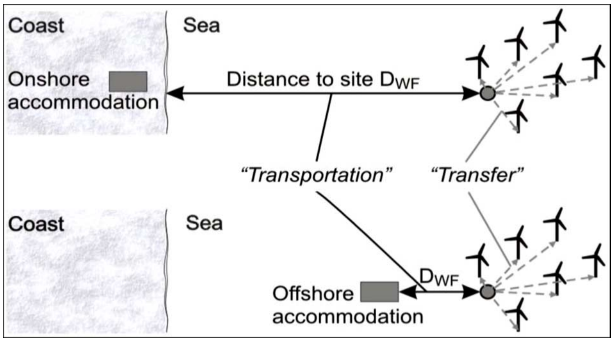

Fig. 1. Locations of the accommodation of maintenance technicians, and transportation related terminology.

A variety of work shift arrangements are possible, e.g., working 7 days a week for 12 hours a day or 7 days a week for 24 hours a day. A subset $T_m \subset T$ represents the working hours when maintenance technicians are available to perform maintenance. For a given work shift arrangement, the total number of maintenance teams to cover the work through the year equals the number of maintenance teams per shift multiplied by a work shift multiplier denoted by M_{shift}.

D. *Accommodation and Transportation*

The accommodation for the maintenance technicians is located at a distance of D_{WF} [km] from the wind farm either onshore or offshore (see Fig. 1).

The main transportation mean to the wind turbine is a workboat referred to as crew transfer vessel (CTV). The access to the wind turbine using the CTV is constrained by a maximum significant wave height H_b [m] and maximum wind speed W_b [m/s]. The speed of the vessel during transport to the site is v_b [km/h], and the average time needed for the transfer of a maintenance team to a wind turbine once it has been transported to the site is denoted τ_b [h] (see also Fig. 1). A CTV can carry a maximum of $N_b^{\max}$ technicians.

An alternative to the transfer of technicians using CTVs is the hoisting of the technicians by means of a helicopter. A helicopter is not constrained by the significant wave height. The maximum wind speed for access by helicopter is W_h [m/s]. It is assumed that only one maintenance team can be transported by helicopter at a time. The speed of the helicopter is v_h [m/s] and the hoisting time per team of technicians is denoted by τ_h [h].

E. *Economical Parameters*

The electricity price C_{el} [€/MWh] includes both incomes from potential incentives and the electricity-market price. The yearly cost for each permanent technician is C_{tech} [€/yr]. The cost for supplementary technicians is assumed to be the same as for permanent technicians, yet proportional to the duration of their employment.

The seasonal chartering cost and daily operating costs for one CTV are denoted by C_b^{yr} [€/yr] and C_b^{day}, respectively. The

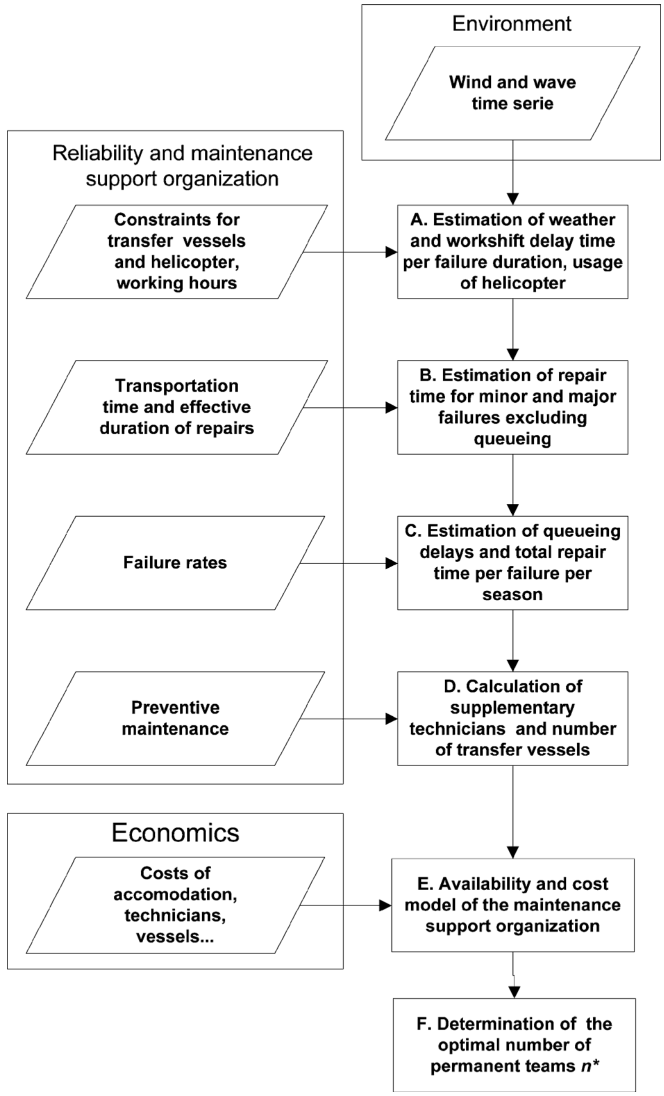

Fig. 2. Workflow of the different steps of the model.

yearly cost and cost per failure for the helicopter are C_h^{yr} and C_h^f. The fixed overhead costs for the accommodation, maintenance coordination, and support are denoted by C_{over}.

III. MATHEMATICAL MODEL

Fig. 2 summarizes the steps in the model for the evaluation of a maintenance support organization including a helicopter. Steps A–C focus on determining the total downtime per failure as a function of the number of maintenance teams n. The number of supplementary technicians $n_{\mathrm{PM}}^s(n)$ for performing the PM and the number of CTVs $b^s(n)$ are calculated in Step D. The wind farm availability, the cost of production losses, and the cost of the support organization are assessed in Step E. The final step is to determine the optimal number of maintenance teams n^*.

Each step in the model is discussed separately below for the case of a support organization including a helicopter. The model can be simplified if only CTVs are used.

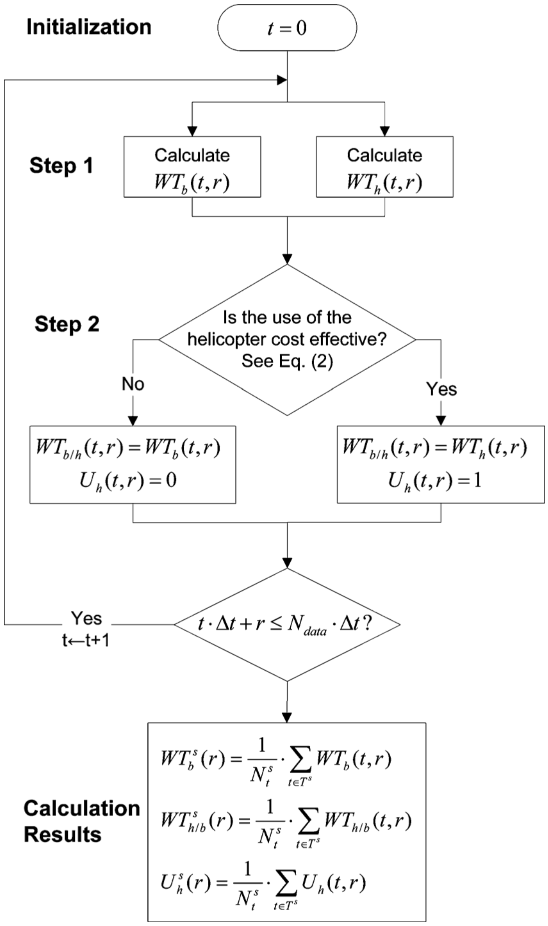

Fig. 3. Flowchart of the algorithm for estimating the weather and work shift delay and usage of helicopter for a maintenance activity of r [h].

A. Weather and Work Shift Delays, and Use of the Helicopter

The expected maintenance delay due to the weather and work shift constraints can be statistically determined for a given duration of maintenance activity based on environmental time series for the site. The approach used is described in the flowchart in Fig. 3. While being similar to the approach presented in [18], the novelty of this algorithm is its capability to include an alternative transportation means, i.e., the use of a helicopter in the present work, to improve accessibility during harsh weather. The algorithm presented in Fig. 2 is described in more detail below.

Step 1: For each time step in the time series, the algorithm evaluates the maintenance delay, due to weather and work shift restriction, to perform a repair activity of duration r [h]. This results in $WT_b(t,r)$ [h] in the case of the CTV and $WT_h(t,r)$ [h] in the case of the helicopter.

It is assumed that r [h] is a multiple of the time step Δt, i.e., $r = r_{\Delta t} \cdot \Delta t, r_{\Delta t} \in Z^+$, where $r_{\Delta t}$ represents the number of time steps. If r is not a multiple of Δt, a linear interpolation of the results is used.

If a failure occurs at time $t \in T$, the earliest time for performing the maintenance is $t + k \in T$ when the weather and working hour constraints are fulfilled each instance l for the

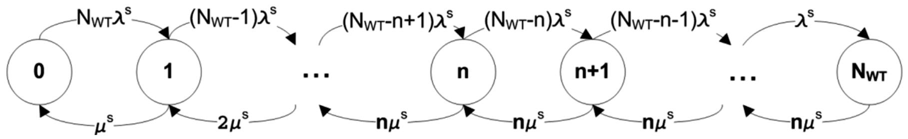

Fig. 4. Markov diagram for the queuing model of maintenance activities. The state numbers represent the number of wind turbines in the wind farm that are in a failed state.

duration of the maintenance activity $r_{\Delta t}$. Therefore, using the CTV, the maintenance delay time is

$$\begin{aligned} &\mathrm{WT}_b(t,r) = \min\{k\cdot\Delta t\}\ \text{s.t.}\\ &k\in Z^+,\ \forall l\in\{t+k;\ldots;t+k+r_{\Delta t}-1\},\\ &w_l\le W_b,\ h_l\le H_b,\ l\in T_m. \end{aligned}\tag{1}$$

The same equation may be used in the case of the helicopter, with weather constraints modified accordingly.

Step 2: The second part of the algorithm is an evaluation of the usage of the helicopter. The helicopter is used if the cost benefit for the reduction of production losses is higher than the helicopter cost per event

$$(\mathrm{WT}_b(t,r)-\mathrm{WT}_h(t,r))\cdot P\cdot C_f^s\cdot C_{\mathrm{el}} > C_{\mathrm{heli}}^f,\ t\in T^s. \tag{2}$$

Calculation results: The calculation results based on the algorithm are season-specific estimates of delays due to weather and work shift restrictions as a function of the duration of the repair activity, $WT_b^s(r)$ [h] and $WT_{b/h}^s(r)$ [h], for a support organization with and without the use of the helicopter, respectively. Moreover, the probability of usage of the helicopter per minor failure and season, $U_h^s(r)$ [%] is determined.

The accessibility using the CTV, AC_b^j, is defined as the percentage of working hours when wind turbines can be accessed using the CTV without weather delay for the minimum duration of maintenance activity $r_{\min}$ hours.

B. Repair Times Excluding Queuing of Maintenance Activities

The repair time for the minor and major failures excluding queuing delays, denoted by d_m^s and d_M^s, are the sum of 1) the delay due to weather and work shift constraints, 2) transportation and transfer time, and 3) duration of the effective maintenance work r_m or r_M. In the case of major failures, in which a CTV would be required to access the wind turbine, the repair time would be

$$d_M^s = \mathrm{WT}_b^s(r_M) + \left(\frac{D_{\mathrm{WF}}}{v_b}+\tau_b\right) + r_M \tag{3}$$

while in the case of minor failures and partial use of a helicopter, the following results:

$$\begin{aligned} d_m^s = \mathrm{WT}_{b/h}^s(r_m) + (1-U_h^s(r_m))\cdot\left(\frac{D_{\mathrm{WF}}}{v_b}+\tau_b\right)&\\ +U_h^s(r_m)\cdot\left(\frac{D_{\mathrm{WF}}}{v_h}+\tau_h\right)+r_m.& \end{aligned}\tag{4}$$

Note that if a maintenance activity requires more time than a single work shift, it should be divided into subactivities which can be performed within one shift.

The average failure rate and repair time per failure and per season can be calculated as

$$\begin{aligned} \lambda^s &= \lambda_m^s + \lambda_M^s\\ d_{\mathrm{CM}}^s &= \frac{\lambda_m^s\cdot d_m^s + \lambda_M^s\cdot d_M^s}{\lambda^s}. \end{aligned}\tag{5}$$

The average repair rate for a failure is given by

$$\mu^s = \frac{1}{d_{\mathrm{CM}}^s}. \tag{6}$$

C. Queuing of Maintenance Activities

A backlog of maintenance activities may occur when there are not enough maintenance teams to simultaneously perform maintenance on all failed wind turbines. This is especially prevalent during harsh weather conditions, during which failures may accumulate and the existing maintenance workforce may not be sufficiently large to perform work on each failure when wind turbines are accessible.

The backlog of maintenance activities can be represented by a Markov chain as depicted in Fig. 4; see, e.g., [15] for an introduction to the Markov chain. It consists of the states i, in which i represents the number of failed turbines. The failure transitions shown in the upper part of the diagram occur at a rate which is proportional to the number of wind turbines in operation. The repair transitions given in the lower part of the diagram occur at a rate which is proportional to the minimum number of wind turbines in repair and the number of permanent maintenance teams.

The model is solved in steady state, which is assumed to be realistic due to the long lifetime of the wind turbines, high transition rates, and expected similar state probability distributions throughout the different seasons. In steady state, a recursive relationship exists between the probability of being in each state i denoted by $P(i)$

$$\begin{aligned} &P(i)\cdot(N_{\mathrm{WT}}-i)\cdot\lambda^s = P(i+1)\cdot(i+1)\cdot\mu^s,\ \forall \mathrm{i}<\mathrm{n}\\ &P(i)\cdot(N_{\mathrm{WT}}-i)\cdot\lambda^s = P(i+1)\cdot n\cdot\mu^s,\ \forall \mathrm{i}\ge\mathrm{n}\\ &\sum_i P(i) = 1. \end{aligned}\tag{7}$$

The system of equation can be solved to calculate $P(i)$. The average queuing time per failure $Q^s(n)$ can be calculated by using Little's law. It is the ratio of the average length of queuing (average number of failed wind turbines waiting for a maintenance team to perform the repair work) and the average number of failures per time unit [16]

$$Q^s(n) = \frac{1}{\lambda^s} \cdot \frac{\sum\limits_{i>n} P(\mathrm{i}) \cdot (\mathrm{i} - n)}{\sum\limits_{i} P(\mathrm{i}) \cdot (N_{\mathrm{WT}} - i)}. \tag{8}$$

The average total downtime per failure and season including queuing is

$$d^s_{\mathrm{CM}} + Q^s(n). \tag{9}$$

D. Supplementary Maintenance Teams and CTVs

For a support organization to be feasible, it is necessary that there are a sufficient number of maintenance teams to perform all the CM and PM activities. To evaluate the need for supplementary maintenance technicians for PM, the effective working time of the technicians needs to be calculated. Since the helicopter is used only for minor failures, this is done in the case of the CTV. When wind turbines are accessible using the CTV, a maintenance technician can perform the work for an effective time of

$$\varepsilon^s_{\mathrm{shift}} = \frac{d^s_{\mathrm{shift}} - 2 \cdot \left(\frac{D_{\mathrm{WF}}}{v_b} + \tau_b\right)}{d^s_{\mathrm{shift}}}. \tag{10}$$

The total number of maintenance team hours to be performed per season using the CTV, therefore excluding the maintenance performed by helicopter is

$$r^s_{\mathrm{tot}} = r^s_{\mathrm{PM}} \cdot N^s_{\mathrm{PM}} + (1 - U^s_h(r_m)) \cdot \lambda^s_m \cdot r_m + \lambda^s_M \cdot r_M. \tag{11}$$

Due to the fact that a small portion of repair work using the helicopter can be carried out during times when the turbines are not accessible by CTV, there is no additional need for technicians for the work performed using the helicopter. The number of supplementary maintenance teams for PM for the season can be estimated as

$$n^s_{\mathrm{PM}}(n) = \max\left(0; \mathrm{int}\left(\frac{4 \cdot r^s_{\mathrm{tot}}}{\varepsilon^s_{\mathrm{shift}} \cdot AC^s_b \cdot d_{\mathrm{team}}} - n \cdot M_{\mathrm{shift}}\right) + 1\right). \tag{12}$$

Herein, $\mathrm{int}(\cdot)$ is the integer function, 4 is the number of seasons per year, AC^s_b the probability of accessibility using the CTV, and d_{team} the working time for each team per year.

It is assumed that a CTV may be chartered each season. The number of CTV per season can then be calculated as

$$b^s(n) = \mathrm{int}\left(\left(n + \frac{n^s_{\mathrm{PM}}(\mathrm{n})}{M_{\mathrm{shift}}}\right) \cdot \frac{N_{\mathrm{team}}}{N^{\mathrm{max}}_b}\right) + 1. \tag{13}$$

E. Availability and Economic Model

The availability per season can be calculated as follows:

$$A^s(n) = 1 - \frac{1}{2190} \cdot \left(\lambda^s \cdot (d^s + Q^s(n)) + r^s_{\mathrm{PM}}\right) \tag{14}$$

where the dominator 2190 represents the total number of hours during a season.

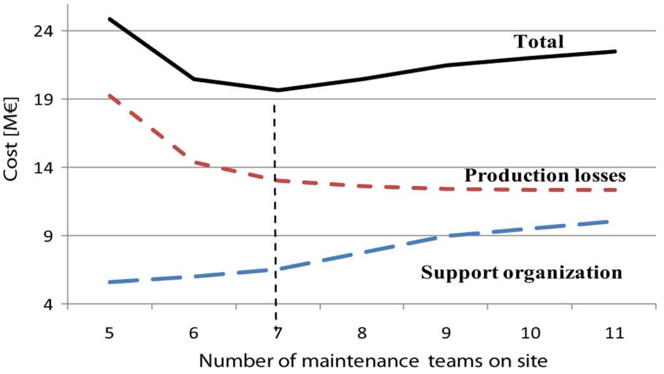

Fig. 5. Cost based on the organization scenario 1 (see Table IV) as a function of the number of maintenance teams. The optimal number of maintenance teams is $n^* = 7$.

The yearly availability is calculated as

$$A(n) = \frac{1}{4} \cdot \sum_{s \in S} A^s(n). \tag{15}$$

For estimating the total yearly cost of using the CTV, it is assumed that the CTV travels to the wind farm every day the wind farm is accessible

$$C^{\mathrm{tot}}_b(n) = \frac{1}{4} \cdot \sum_{s \in S} b^s(n) \cdot \left(C^{\mathrm{yr}}_b + 365 \cdot AC^s_b \cdot C^{\mathrm{day}}_b\right). \tag{16}$$

Herein, 365 refers to the number of days per year, and 4 to the number of seasons.

The total yearly cost of the helicopter is the sum of the fixed cost and cost of each event when the helicopter is used

$$C^{\mathrm{tot}}_h = C^{\mathrm{yr}}_h + N_{\mathrm{WT}} \cdot C^f_h \cdot \sum_{s \in S} \lambda^s_m \cdot U^s_h(r_m). \tag{17}$$

The total cost for the technicians is calculated as

$$C^{\mathrm{tot}}_{\mathrm{tech}}(n) = C_{\mathrm{tech}} \cdot \left(n \cdot M_{\mathrm{shift}} + \frac{\sum\limits_{s \in S} n^s_{\mathrm{PM}}(n)}{4}\right). \tag{18}$$

The cost for the maintenance support organization is the sum of the cost of the overhead, technicians and transportation

$$C^{\mathrm{tot}}_{\mathrm{org}}(n) = C_{\mathrm{over}} + C^{\mathrm{tot}}_{\mathrm{tech}}(n) + C^{\mathrm{tot}}_b(n) + C^{\mathrm{tot}}_h. \tag{19}$$

F. Optimal Number of Permanent Maintenance Teams

The optimal number of permanent teams for the support organization is determined by minimizing the sum of the cost for the support organization and the production losses

$$n^* = \underset{n \in Z^+}{\arg\min} \left\{C^{\mathrm{tot}}_{\mathrm{losses}}(n) + C^{\mathrm{tot}}_{\mathrm{org}}(n)\right\}. \tag{20}$$

For each support organization scenario investigated, the optimal number of permanent technicians is determined numerically by calculating the cost of the support organization and the cost of the production losses for a range of possible numbers of maintenance teams, and by selecting the solution based on the lowest total cost, as illustrated in Fig. 5. Note that due to the effect of the number of boats, the cost for the support organization is not linear.

TABLE I
RELIABILITY DATA AND CAPACITY FACTOR

Season	λ_m^s [1/yr]	λ_M^s [1/yr]	r_{PM}^s [h]	C_f [%]
Winter	5	1,2	6	53
Spring	3	0.8	30	41
Summer	3	0.8	30	38
Autumn	5	1.2	6	48

TABLE II
ACCOMMODATION AND WORK SHIFT ARRANGEMENTS

Location	D_{WF} [km]	Work shift	d_{team} [h]	M_{shift}	C_{tech} [€/yr]	C_{over} [k€/yr]
onshore	60	12/7	1450	3	60 000	-
offshore	10	12/7	2100	2	80 000	3 400
offshore	10	24/7	2100	4	80 000	4 000

IV. CASE STUDY

The proposed model has been demonstrated by means of a case study of a fictitious offshore wind farm consisting of $N_{\mathrm{WT}} = 100$ wind turbines located 60 km from a harbor. Each turbine has a rated capacity of $P = 5$ MW. The season-dependent capacity factors are provided in Table I.

Wind and wave data are based on real data from the 160-MW Horns Rev offshore wind farm located 15 km off the coast of Esbjerg in Denmark. The time series covers five years and, therefore, provide a sound basis for statistical analysis. The time step is set to $\Delta_t = 3$ h.

The generic set of reliability and service maintenance data used for the case study are summarized in Table I and corresponds to an average of four minor failures and one major failure per turbine and year. The durations of the minor and major repairs are $r_m = 8$ h and $r_M = 16$ h, respectively.

Each maintenance team is assumed to consist of $N_{\mathrm{team}} = 3$ technicians, which is recommended for safety reasons. The technicians work in shifts of a duration of $d_{\mathrm{shift}}^s = 12$ h.

Offshore wind turbines are generally serviced once a year during spring or summer. The scheduled maintenance includes condition-based maintenance activities assumed to be 6 h per season, with the yearly service maintenance employing 48 hours with two maintenance teams. It includes such activities as the following [21], [22]:

1) change of lubrication systems and oil filters;
2) checkup of brushes and slip ring for DFIG machines;
3) test of safety systems, strength testing of bolts;
4) oil sampling and analysis of the gearbox lubricant;
5) visual inspection of the blades.

The present study compares several maintenance support organizations with respect to different locations of the maintenance accommodation, work shift arrangements, and transportation means, for the purpose of identifying the most cost-effective solution. The accommodation locations and work shift arrangements investigated are summarized in Table II. The difference in the work shift arrangements between onshore- and offshore-based organizations is related to working hour regulations in Europe, which differ for onshore and offshore accommodations.

TABLE III
VESSELS AND HELICOPTER CHARACTERISTICS

	$H_{b/h}$ [m]	$W_{b/h}$ [m/s]	$v_{b/h}$ [km/h]	$\tau_{b/h}$ [min]	$N_{b/h}^{\max}$	$C_{b/h}^{yr}$ [k€/yr]	C_b^{day}
CTV1	1.5	15	40	30	12 pers.	900	1.2 [k€/day]
CTV2	2	15	40	30	12 pers.	1200	1.6 [k€/day]
Heli.	n.a.	17	220	5	1 team	1200	1 [k€/h]

The overhead costs only include the relative difference in the cost of accommodation and work shift supervision.

Two different types of CTVs are investigated, CTV1 and CTV2. The main difference between the vessels is that the CTV2 is equipped with an access system, in the form of a gangway or stabilizing platform to enable access to the wind turbine at higher significant wave height. Table III summarizes the features of the transportation means investigated in the present study.

The electricity price is assumed to be 150 €/MWh guaranteed price in Germany [17] for offshore wind power. The costs of the CTVs and helicopter were kindly provided by Vattenfall and are summarized in Table III.

V. RESULTS AND DISCUSSION

The main results obtained from the analysis of the maintenance support organizations investigated are presented in Table IV. The results are in the range of the observed availability of 95%–97% at the Horns Rev wind farm [23], whose support organization is similar to that in scenario 3. Moreover, the availability results seem consistent with the advantages of the logistic solution investigated.

It can be observed that the organization scenario 10, which consists of an offshore accommodation with 24/7 work shifts and the use of CTV2, offers the most cost-efficient solution closely followed by the options 12, 2, and 4. All options include the use of CTV2, clearly more cost-beneficial than using CTV1.

The cost-benefit of using the helicopter differs with the type of CTV as well as the work shift arrangement. The yearly availability increase is in the range of 0.2%–0.7% for an organization with 24/7 work shifts and type CTV2 vessels as well as for an organization with 12/7 work shifts and CTV1, respectively. The use of the helicopter is cost-beneficial in all cases except for the case of an offshore accommodations with 24/7 work shifts and CTV2.

It can also be observed that an offshore accommodation is cost-beneficial only in the case of the 24/7 work shift. This can be attributable to the relatively low increase in the availability and work efficiency due to the location of the accommodation alone. The benefit would increase with a longer distance from the shore and harsher weather conditions. It can be noted that the availability increases by almost 1% for each logistic solution by using 24/7 work shifts instead of 12/7 work shifts.

A major parameter influencing the results is the electricity price, which varies considerably between different countries and depending on the local incentive system may be constant or variable over time. The effect of the electricity income on the results is depicted in Fig. 6. Although the optimal number of maintenance teams was recalculated as a function of the electricity income, the total cost is almost linearly dependent

TABLE IV
SUMMARY OF RESULTS OF ANALYZING MAINTENANCE SUPPORT ORGANIZATION SCENARIOS

Scenario description					**Results**							
Org.	Location	Workshift	CTV	Heli.	n^*	$n_{PM}^{spr}(n^*)$	b^{win}/b^{spr}	U_h^{yr}	$A(n^*)$	$C_{org}^{tot}(n^*)$	$C_{losses}^{tot}(n^*)$	**Total cost**
1	onshore	12/7	CTV1	No	7	0	2 - 2	n.a.	95.7%	6.6	12.9	19.5
2	onshore	12/7	CTV2	No	6	0	2 - 2	n.a.	96.8%	6.9	9.6	16.5
3	onshore	12/7	CTV1	Yes	6	0	2 - 2	25%	96.3%	7.3	11.2	18.5
4	onshore	12/7	CTV2	Yes	4	5	1 - 2	14%	96.6%	6.6	10.0	16.7
5	offshore	12/7	CTV1	No	6	0	2 - 2	n.a.	96.0%	9.0	11.9	21.0
6	offshore	12/7	CTV2	No	4	4	1 - 2	n.a.	96.8%	8.5	9.7	18.2
7	offshore	12/7	CTV1	Yes	6	0	2 - 2	25%	96.7%	10.3	9.7	19.9
8	offshore	12/7	CTV2	Yes	4	4	1 - 2	14%	97.2%	9.8	8.2	18.0
9	offshore	24/7	CTV1	No	4	0	1 - 2	n.a.	97.0%	10.9	9.2	20.0
10	offshore	24/7	CTV2	No	3	0	1 - 1	n.a.	97.9%	9.6	6.2	15.8
11	offshore	24/7	CTV1	Yes	3	0	1 - 1	12%	97.5%	10.2	7.5	17.7
12	offshore	24/7	CTV2	Yes	3	0	1 - 1	7%	98.1%	10.8	5.6	16.4

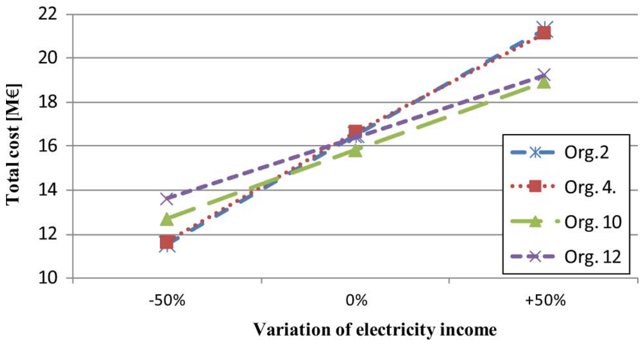

Fig. 6. Sensitivity of the total cost of variations in the electricity price for different organization scenarios (see Table IV).

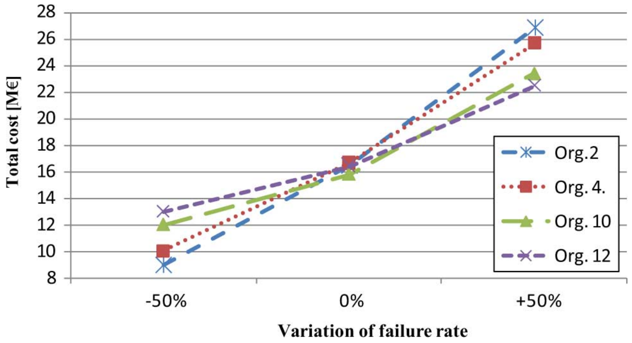

Fig. 7. Sensitivity of the total cost to variations in the wind-turbine failure rate for different organization scenarios (see Table IV).

on the electricity income. As expected, due to a higher resulting availability of the wind turbines, the solutions with offshore accommodation and 24/7 work shift are more cost-beneficial as the electricity income increases.

In addition, a sensitivity analysis was performed on the input parameter afflicted with the highest uncertainty, the failure rate. The analysis was performed with a variation of $+/-50\%$ for the organization scenarios 2, 4, 10, and 12; the results are depicted in Fig. 7

As expected, the benefits of the offshore accommodation and the benefits of using the helicopter increase with increasing failure rates. It can also be observed that the results are more sensitive to variations in turbine reliability than variations in electricity income.

VI. CONCLUSION

An analytical model for the cost-based optimization and selection of a maintenance support organization for an offshore wind farm was presented in this paper. The model considers decisions regarding the location of the maintenance accommodation, the number of technicians, the choice of transfer vessels, and the use of a helicopter. The model includes an analysis of the transportation strategy using alternative transportation means, a queuing model of maintenance activities, and an economic model of the maintenance support organization.

The model was demonstrated by means of a case study of a generic 100 wind turbines 5-MW wind farm located 60 km from shore was presented. The results of the case study show the cost-benefit of the various options and the sensitivity of the results to variations in electricity price and turbine reliability. The most cost-efficient maintenance support organization in this case study consisted of an offshore accommodation using technicians on service 24 hours a day, 7 days a week, and a crew transfer vessel with a motion compensated access system.

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