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## Vessel fleet analysis for maintenance operations at offshore wind farms

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### Abstract

Performing maintenance operations at offshore wind farms involves one major challenge compared with the onshore counterpart: All maintenance personnel and spare parts need to be transported from an onshore port or offshore station to the individual wind turbines by vessels or helicopters. The vessels and helicopters required for these tasks will constitute a major part of the maintenance costs for the offshore wind farms, and to reduce the cost of energy it is essential to keep an optimal or near-optimal vessel fleet for this purpose. We study the vessel fleet optimization problem that arises for offshore wind farms and propose an appropriate optimization model. Computational experiments show that our model can be solved to provide decision makers with an optimal vessel fleet within acceptable time limits.

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### 1. Introduction

Renewable energy sources are expected to constitute an increasing part of the total global energy mix [1]. EU plans in the 20-20-20 target to raise the share of EU energy consumption produced from renewable resources to 20 % by 2020 [2] and increasing the installed offshore wind capacity will be one of the means to reach this target.

Offshore wind turbines are more exposed to breakdowns than their onshore counterpart due to facing a rougher environment. To enable growth in installed offshore wind capacity, offshore wind farms need to move further away from shore, to deeper waters. With this move, the cost of operation and maintenance (O&M) will increase due to further travel distances, rougher weather conditions and greater logistic challenges. For example, to execute maintenance operations an operator needs a weather window that at a minimum covers the travel time and repair time at the wind turbine, and with a longer travel distance the length of the required weather window will increase. Logistic options to reduce the travel distance will then be relevant. These can for example be offshore platforms situated at the wind farm site where smaller vessels or helicopters are used to bring personnel from the offshore platform to the individual wind turbines.

The choice of the vessel fleet composition and investments in offshore platforms will have a great impact on the O&M costs for an offshore wind farm (in the following, vessels also include helicopters). A helicopter may have a variable cost of 1000 USD/hour and a crane vessel can amount to 40 000 USD/day. Spot rates for maintenance vessels will deviate from year to year, making the decision of chartering-in or purchasing vessels far from straightforward. Weather conditions at the site of the wind farm, distance to shore and the amount and type of maintenance operations

will all affect the fleet composition. To keep the cost of energy from offshore wind farms down, it will be essential to keep the costs of the vessel fleet to a minimum. This is not straightforward and offshore wind farm operators need tools that can be used for vessel fleet analyses.

Offshore wind is a relatively new technology, and there are not many tools available to support planning activities. A survey of offshore wind energy companies was conducted in [3], and about 70 % of the respondents saw the need for decision support tools whereas only a few of them had such models available for use. In [4] a survey of decision support models for offshore wind farms with a special emphasis on O&M strategies was presented. A total of 49 models were found. Most models used simulation tools to analyze O&M costs, and the use of optimization models and methods was limited. However, [5] and [6] presented a deterministic and a stochastic optimization model for opportunistic maintenance of offshore wind farms.

Studies in the literature have considered the fleet composition problem in both road-based and maritime transportation. Models often include routing decisions as it will be necessary to study also the underlying structure of the operational planning problem, see the discussion in [7]. A survey covering fleet composition and routing problems in road-based and maritime transportation is provided in [8].

In this paper we present the vessel fleet composition problem for maintenance operations at offshore wind farms. The goal is to give offshore wind farm operators a tool that can be used to evaluate which vessel types should be purchased, which should be chartered-in, and also which infrastructure (such as vessel bases both offshore and onshore) that should be used. This is a new problem that has not previously been studied in the literature. A deterministic vessel fleet optimization model for offshore wind farms are developed and presented. This optimization model can be used by decision makers when deciding on which vessel concepts and contracts they should enter, in order to get the necessary vessel fleet for execution of maintenance operations at their offshore wind farms.

The rest of this paper is organized as follows: In Section 2 the vessel fleet optimization problem is described. Section 3 presents a mathematical model formulation for the problem. Numerical results from solving the mathematical model, using a commercially available solver, are presented in Section 4. Finally, some concluding remarks and suggestions for further research are provided in Section 5.

## 2. Problem description

Vessel resources and maintenance infrastructure can be shared between one or more offshore wind farms. The wind farms have a given site with given travel distances to each vessel base and other offshore wind farms. At each offshore wind farm there is a number of wind turbines that require maintenance operations during the planning horizon.

There are two main types of maintenance operations: Preventive and corrective. Preventive maintenance operations are conducted to extend the life of a wind turbine and to keep the number of failures at a reasonable level. Such operations will be scheduled according to the wind farm operator's maintenance strategy and will depend on the type of wind turbines being used. Corrective maintenance operations need to be conducted due to unforeseen failures to the system. In the deterministic model these operations are treated as known, i.e. we will know at the start of the planning horizon when failures occur. Preventive and corrective maintenance operations will require up to three different activities: Transportation of maintenance personnel, shipment of larger parts and equipment, and lifting activities. Each of the activities will require a given vessel type. For some maintenance activities a vessel may have several maintenance teams working on different turbines simultaneously. However, safety regulations limit the number of simultaneously working teams from one vessel to four [9]. Thus an activity may be executed on its own or in a bundle of up to four maintenance activities.

Preventive maintenance activities will have a preferred time window for when to be executed. This is a soft time window that will depend on the operator's maintenance strategy. The activities can be executed outside the soft time window, but within a hard time window, at a penalty cost. This penalty cost is introduced to avoid solutions where there are large deviations from the overall periodic maintenance strategy. It can be considered a fictitious cost to steer the optimal solutions so that most activities are executed within the soft time window, or it can be considered a real cost due to a possible increase of maintenance activities in the long run when executed prior to the soft time window, or the expected downtime cost due to increased probability of failure, if executed after the soft time window. There will always be a penalty cost for corrective maintenance activities based on the actual downtime cost starting from the time of failure. All activities should be executed within their hard time windows, but can be delayed until next planning horizon at a high penalty cost.

There are several types of vessels that can be purchased or chartered-in during the planning horizon. For instance crew transfer vessels (CTVs), supply vessels, crane vessels and helicopters. The planning horizon is divided into several lease terms for vessels that can be chartered-in, and the vessels may be chartered for one or more of these. For

vessels that can be purchased, only one lease term is defined. Adjustments to the vessel fleet can be made at the start of each lease term. Each vessel type will have a given service speed, loading capacity for spare parts and capacity for transporting maintenance personnel. Operational weather requirements limit the time intervals for which a vessel type can operate at a wind turbine, and vessel requirements define when weather conditions are so harsh that the vessel needs to return to a safe haven. The costs for a given vessel type is divided into a fixed component and a variable component that depends on the number of hours in operation and transit. Each vessel will be associated with a given base. The base can be an onshore port or an offshore station. The cost of using a base will vary depending on the type: An offshore station will have a high investment cost in addition to running costs, while for an already existing onshore port there may only be running costs. The total investment costs, in both bases and vessels, will be limited by a budget constraint.

The vessel fleet composition problem is exposed to several uncertain parameters. The major ones are the weather conditions, such as wind speed, wave heights, wave direction and current, as these determine whether an operation can be executed or not, and if any vessels need to return to a safe haven. Wind speed and direction also determines the power production from the wind farms, and will together with the electricity price, which is also an uncertain parameter, affect the revenue from the wind farms. Other uncertain parameters are the spot prices of charter-in contracts and the number of failures that lead to corrective maintenance operations. In our deterministic model, all these parameters are treated as known.

The objective of the vessel fleet composition problem for maintenance operations at offshore wind farms is to determine the minimum cost vessel fleet and infrastructure that can execute all, or most, of the maintenance activities during the planning horizon. The total cost includes fixed and variable costs of vessels and bases as well as penalty costs for maintenance activities that are executed outside their soft time window or delayed until next planning horizon.

### 3. Mathematical model

We will start by introducing all sets, parameters and decision variables used in the mixed integer programming formulation for the vessel fleet composition problem arising in the offshore wind industry. Then we will formulate the objective function, followed by a description of each term that is minimized. All constraints are then presented followed by their explanation.

The following are the sets in the model:

$F$ : Set of wind farms

$M$ : Set of alternative vessel bases that can be both onshore ports and offshore platforms

$V$ : Set of all vessel and helicopter types that can be purchased or chartered

$P$ : Set of all periods in the planning horizon

$A_f$ : Set of maintenance activities to be executed at wind farm  $f$  ( $f \in F$ )

$A_f^t$ : Set of maintenance activities at wind farm  $f$  where  $T_i > T^P$ ,  $T_i$  being the total time required to execute maintenance activity  $i$  and  $T^P$  the length of a single time period ( $f \in F, i \in A_f, A_f^t \subseteq A_f$ )

$A_f^B$ : Set of activity bundles at wind farm  $f$  ( $f \in F, A_f^B \subseteq A_f$ )

$A_{if}^B$ : Set of activity bundles at wind farm  $f$  that include maintenance activity  $i$  ( $f \in F, i \in A_f, A_{if}^B \subseteq A_f^B$ )

$L_v$ : Set of lease terms for vessels of type  $v$  ( $v \in V$ )

$V_j$ : Set of vessel types that are using base  $j$  ( $j \in M, V_j \subseteq V$ )

$V^O$ : Set of vessel types that can only stay offshore for one period before returning to the base ( $V^O \subseteq V$ )

$V^S$ : Set of vessel types that can stay offshore several periods before returning to the base ( $V^S \subseteq V$ )

$V_{if}^A$ : Set of vessel types that can execute maintenance activity  $i$  at wind farm  $f$  ( $f \in F, i \in A_f, V_{if}^A \subseteq V$ )

$P_{if}^A$ : Set of periods where maintenance activity  $i$  at wind farm  $f$  can be executed, ( $f \in F, i \in A_f, P_{if}^A \subseteq P$ )

$P_{vl}^L$ : Set of periods in lease term  $l$  for vessels of type  $v$  ( $v \in V, l \in L_v, P_{vl}^L \subseteq P$ )

$P_{vl}^{Ll}$ : The last period in lease term  $l$  for vessels of type  $v$  ( $v \in V, l \in L_v, P_{vl}^{Ll} \subseteq P$ )

$K$ : Set of types of weather restrictions, i.e. wind speed and wave height

The parameters in the mathematical model formulation are as follows:

$C^B$ : Investment budget for vessels, ports and offshore stations

$C_j^F$ : Fixed cost for port/offshore station  $j$  over the planning horizon given as the investment costs less the salvage value, depreciated over the life time of the offshore wind farms ( $j \in M$ )

- $C_{vl}^F$ : Fixed cost of charter-in or purchasing a vessel of type  $v$  in lease term  $l$ . Only one lease term is defined for vessels that are purchased, and the fixed costs are then the investment costs less the salvage value depreciated over the expected life time of the wind farms ( $v \in V, l \in L_v$ )
- $C_v^V$ : Variable cost for vessels of type  $v$  per hour of operation ( $v \in V$ )
- $C_{ipf}^D$ : Expected downtime cost if maintenance activity  $i$  at wind farm  $f$  is executed in period  $p$  ( $f \in F, i \in A_f, p \in P$ )
- $C_{if}^P$ : Penalty cost for not completing maintenance activity  $i$  at wind farm  $f$  within the planning horizon ( $f \in F, i \in A_f$ )
- $Q_{jv}$ : Maximum vessel capacity at port/offshore station  $j$  for vessels of type  $v$  ( $j \in M, v \in V_j$ )
- $T_{if}^A$ : Number of hours required to execute maintenance activity  $i$  at wind farm  $f$  ( $f \in F, i \in A_f$ )
- $T^P$ : Available number of operating hours during a period (e.g. if a period is one day  $T^P$  can typically be 12 or 24 hours depending on the use of night shifts)
- $T_{vf}^T$ : Time to transfer a vessel of type  $v$  from its base to wind farm  $f$  and back again, base being either a port or an offshore station ( $v \in V^O, f \in F$ )
- $T_{vfg}^T$ : Time to transfer a vessel of type  $v$  from wind farm or port/offshore station  $f$  to wind farm or port/offshore station  $g$  ( $v \in V^S, f, g \in F \cup M$ )
- $P_v^M$ : Maximum number of periods vessels of type  $v$  can stay offshore before returning to base ( $v \in V^S$ )
- $W_{vk}^O$ : Operational requirement for vessels of type  $v$  and weather category  $k$ , vessels of type  $v$  cannot operate if weather conditions exceed this level, but can stay offshore until weather conditions improve ( $v \in V, k \in K$ )
- $W_{vk}^S$ : Vessel requirements for vessels of type  $v$  and weather category  $k$ , vessels of type  $v$  need to return to a safe haven if weather conditions exceed this level ( $v \in V, k \in K$ )
- $W_{pk}$ : Value of weather category  $k$  in period  $p$  ( $p \in P, k \in K$ )
- $H_{vif}$ : Number of maintenance personnel from a vessel of type  $v$  working on maintenance activity  $i$  when at wind farm  $f$  when achieving highest possible efficiency ( $v \in V, f \in F, i \in A_f$ )
- $B_{vif}$ : Constant based on the efficiency of a vessel of type  $v$  when working on an activity bundle, and the minimum number of maintenance personnel needed on activity  $i$  at wind farm  $f$  ( $v \in V, f \in F, i \in A_f$ )

The decision variables are:

- $\delta_j$ : Binary variable that equals 1 if base  $j$  is used  $\delta_j$  and 0 otherwise ( $j \in M$ )
- $x_{vl}$ : Number of vessels of type  $v$  to charter-in or purchase in lease term  $l$  ( $v \in V, l \in L_v$ )
- $x_{vp}^E$ : Number of vessels of type  $v$  entering the fleet in period  $p$  ( $v \in V, p \in P$ )
- $x_{vp}^L$ : Number of vessels of type  $v$  leaving the fleet in period  $p$  ( $v \in V, p \in P$ )
- $y_{vpf}$ : Number of vessels of type  $v$  located at position  $f$  in period  $p$  ( $v \in V, p \in P, f \in F$ )
- $w_{vpfg}$ : Number of vessels of type  $v$  travelling from position  $f$  to position  $g$  in period  $p$  ( $v \in V, p \in P, (f, g) \in F \cup M$ )
- $t_{vipf}$ : Time spent on maintenance activity  $i$  at wind farm  $f$  by vessels of type  $v$  in period  $p$  ( $f \in F, i \in A_f, v \in V_{if}^A, p \in P_{if}^A$ )
- $t_{vpfg}^M$ : Time used in transit at the start of period  $p$  from position  $f$  to position  $g$  for vessels of type  $v$  ( $v \in V, (f, g) \in F \cup M, p \in P$ )
- $t_{vpfg}^E$ : Time used in transit at the end of period  $p$  from position  $f$  to position  $g$  for vessels of type  $v$  ( $v \in V, (f, g) \in F \cup M, p \in P$ )
- $z_{if}$ : Part of maintenance activity  $i$  at wind farm  $f$  being postponed to next planning horizon ( $f \in F, i \in A_f$ )

The objective function minimizes all the fixed costs of vessels and vessel bases, variable costs of using the vessels at the wind farm, expected downtime costs of delayed preventive maintenance tasks and corrective maintenance tasks, penalty costs and transportation costs. It can be modeled as follows:

$$\begin{aligned}
 \min \quad & \sum_{j \in M} C_j^F \delta_j + \sum_{v \in V} \sum_{l \in L_v} C_{vl}^F x_{vl} & (1a) \\
 & + \sum_{f \in F} \sum_{i \in A_f} \sum_{v \in V_{if}^A} \sum_{p \in P_{if}^A} C_v^V t_{vipf} & (1b) \\
 & + \sum_{f \in F} \sum_{i \in A_f} \sum_{v \in V_{if}^A} \sum_{p \in P_{if}^A} C_{ipf}^D t_{vipf} + \sum_{f \in F} \sum_{i \in A_f \setminus A_f^B} C_{if}^P z_{if} & (1c) \\
 & + \sum_{v \in V^S} \sum_{p \in P} \sum_{(f,g) \in F \cup M | f \neq g} C_v^V (t_{vpfg}^M + t_{vpfg}^E) + \sum_{v \in V^O} \sum_{p \in P} \sum_{f \in F} T_{vf}^T C_v^V y_{vpf}. & (1d)
 \end{aligned}$$

Terms (1a) are the fixed costs of vessel bases and vessels that are chartered-in or acquired in lease term  $l$ . Term (1b) are the variable costs of using the vessels to execute maintenance activities. The first term in (1c) is the penalty cost

for the preventive maintenance tasks that are not executed within their soft time windows when  $i$  represent a preventive maintenance activity, and an estimate of the real downtime cost of corrective maintenance tasks when  $i$  represent a corrective maintenance activity. The second term gives a penalty cost for any maintenance activity that is not completed within the planning horizon and represents the expected cost of delaying an activity until the next planning period. Finally, (1d) is the travel costs for the vessels. The first term is for vessel types that can stay offshore for several time periods, and sums up all travel costs from a vessel base or wind farm to another vessel base or wind farm. The second term is for vessel types that can only be used in one period before returning to its base and is the variable costs of using the vessels multiplied with the return-time from base to wind farm per period the vessels are used.

$$x_{vl} \leq Q_{jv} \delta_j, \quad j \in M, v \in V_j, l \in L_v. \tag{2}$$

Constraints (2) restrict the number of vessels that can be based at vessel base  $j$ . Vessel base  $j$  can be a port or an offshore station and the capacity on an offshore station will be quite restricted compared with a port. The constraints also ensure that a vessel base needs to be acquired if any vessels are to be associated with it.

$$\sum_{v \in V} \sum_{l \in L_v} C_{vl}^l x_{vl} + \sum_{j \in M} C_j^l \delta_j \leq C^B. \tag{3}$$

Constraint (3) restricts the investments in vessels and vessel bases to the budget limit  $C^B$ .

$$\sum_{v \in V_{if}^A} \sum_{p \in P_{if}^A} H_{vif} t_{vpif} + \sum_{i \in A_{if}^B} \sum_{v \in V_{if}^A} \sum_{p \in P_{if}^A} B_{vif} t_{vpif} + T_{if}^A z_{if} \geq T_{if}^A, \quad f \in F, i \in A_f \setminus A_f^B. \tag{4}$$

Constraints (4) ensure that all maintenance activities are executed within their hard time windows or are postponed until the next planning horizon. A maintenance activity may be executed on its own (first term), as a part of an activity bundle (second term) or be postponed (third term).

$$\sum_{v \in V_{if}^A} t_{vpif} \leq T^P, \quad f \in F, i \in A_f^L, p \in P_{if}^A. \tag{5}$$

Constraints (5) limit time spent on an activity in one period to the maximum amount of time available in a period. These constraints are necessary to avoid solutions where more than one vessel is assigned to work on a maintenance activity at the same time to reduce the execution time of the activity.

$$\sum_{f \in F} \gamma_{vpf} \leq x_{vl}, \quad v \in V^O, l \in L_v, p \in P_{vl}^L. \tag{6}$$

Constraints (6) determine the number of vessels with ability to stay offshore for one time period ( $V^O$ ) that should be chartered-in or purchased in each lease term. The total number of vessels used in a given time period cannot exceed the number of chartered-in or purchased vessels for that time period.

$$\sum_{f \in F \cup M} \gamma_{vpf} = x_{vl}, \quad v \in V^S, l \in L_v, p \in P_{vl}^L, \tag{7}$$

$$x_{vl} - x_{v(l+1)} = x_{vp}^L - x_{vp}^E, \quad v \in V^S, l \in L_v \setminus \{|L|\}, p \in P_{vl}^{|L|}, \tag{8}$$

$$\sum_{g \in M} \gamma_{vpfg} - \sum_{g \in M} \gamma_{v(p+1)g} = \sum_{f \in F} \sum_{g \in M} (w_{vpfg} - w_{vpfg}) + x_{vp}^L - x_{vp}^E, \quad v \in V^S, l \in L_v \setminus \{|L|\}, p \in P_{vl}^{|L|}, \tag{9}$$

$$\gamma_{vpf} - \gamma_{v(p+1)f} = \sum_{g \in F \cup M | f \neq g} (w_{vpfg} - w_{vpfg}), \quad v \in V^S, l \in L_v, p \in P_{vl}^{|L|}, f \in F, \tag{10}$$

$$\gamma_{vpf} - \gamma_{v(p+1)f} = \sum_{g \in F \cup M | f \neq g} (w_{vpfg} - w_{vpfg}), \quad v \in V^S, l \in L_v, p \in P_{vl}^L \setminus P_{vl}^{|L|}, f \in F \cup M. \tag{11}$$

Constraints (7)-(11) are balancing constraints for the vessel types that can stay offshore for several periods ( $V^S$ ). The first set of constraints (7) determines the number of each vessel type located at either a vessel base or at a wind farm in each lease term. Then constraint set (8) determines the vessel balance between each lease term. Constraints (9)-(11) determine the flow of vessels from location  $f$  to location  $g$ . Adjustments to the fleet can only occur at a vessel base, thus constraints (9) only apply for vessel bases and the time periods in which adjustments may occur. Constraints (10) apply for all wind farms in time periods where adjustments to the fleet can occur, and constraints (11) apply for all wind farms and vessel bases for the time periods in which there can be no adjustments.

$$\sum_{f \in F} y_{vpf} \leq \sum_{\bar{p} \in \{p, \dots, p+P_v^M-1\}} \sum_{f \in F} \sum_{g \in M} w_{v\bar{p}fg}, \quad v \in V^S, p \in \{1, \dots, |P| - P_v^M + 1\}, \tag{12}$$

$$y_{vpf} \leq \sum_{\bar{p} \in \{p, \dots, p+P_v^M-1\}} \sum_{g \in F \cup M} w_{v\bar{p}fg}, \quad v \in V^S, p \in \{1, \dots, |P| - P_v^M + 1\}, f \in F. \tag{13}$$

Vessels that can stay offshore for several time periods need to return to their onshore vessel bases after a certain number of time periods. Constraints (12) force the required number of vessels to return to their vessel bases. If the distances from the vessel base to the wind farms vary, only vessels at the wind farm closest to the vessel base will return. Thus, constraints (13) are added to ensure a constant movement of vessels between the wind farms. Constraint sets (12) and (13) will be sufficient for problems of up to two wind farms. When there are more than two wind farms there may be internal movements only between wind farms, but as the nature of the model is strategic, this is an acceptable simplification.

$$T_{vfg}^T w_{vpfg} \leq t_{vpfg}^E + t_{vpfg}^M, \quad v \in V^S, p \in \{1, \dots, |P| - 1\}, (f, g) \in F \cup M | f \neq g. \tag{14}$$

Constraints (14) determine when vessels that can stay offshore for several time periods travel from a base to a wind farm, between wind farms, or from a wind farm and back to base, how much time that is spent in such transit and whether the vessels travel in the beginning or the end of a period.

$$\sum_{g \in F \cup M | g \neq f} w_{vpfg} \leq y_{vpf}, \quad v \in V^S, p \in P, f \in F \cup M, \tag{15}$$

$$\sum_{g \in F \cup M | g \neq f} w_{vpfg} \leq y_{v(p+1)f}, \quad v \in V^S, p \in \{1, \dots, |P| - 1\}, f \in F \cup M. \tag{16}$$

If a number of vessels travel from location  $f$  to  $g$  in period  $p$ , constraints (15) ensure that the vessels were located at  $f$  in period  $p$ . Similarly, constraints (16) ensure that the number of vessels that travel to wind farm  $f$  in period  $p$  are located at that wind farm in period  $p+1$ . These constraints are added to avoid that constraints (12) and (13) lead to vessels travelling from location  $f$  to  $g$  in the end of period  $p$  and back to  $f$  in the beginning of period  $p+1$ .

$$\sum_{i \in A_f} t_{vipf} \leq T^P y_{vpf} - \sum_{g \in F \cup M | g \neq f} (t_{vpgf}^M + t_{vpfg}^E), \quad v \in V^S, p \in P, f \in F, \tag{17}$$

$$\sum_{i \in A_f} t_{vipf} \leq (T^P - T_{vf}^T) y_{vpf}, \quad v \in V^O, p \in P, f \in F. \tag{18}$$

Constraints (17) reduce the available operation time on wind farm  $f$  for vessel types that can stay offshore for several time periods with the time in transit between wind farms and between wind farms and vessel bases. Similarly, constraints (18) reduce the available operational time on a wind farm for vessel types that can stay offshore only for one single time period with the transit time between base and wind farm.

$$(W_{vk}^O - W_{pk}) \sum_{f \in F} \sum_{i \in A_f} t_{vipf} \geq 0, \quad v \in V, p \in P, k \in K, \tag{19}$$

$$(W_{vk}^S - W_{pk}) \sum_{f \in F} y_{vpf} \geq 0, \quad v \in V, p \in P, k \in K. \tag{20}$$

Constraints (19) are operational constraints that ensure that maintenance activities cannot be executed if the weather conditions are worse than the operational requirements. Constraints (20) are vessel constraints that force vessels to return to a safe haven whenever the weather conditions are worse than the vessel requirements for staying at sea. The operational requirements for executing maintenance (19) will always be at least as restrictive as the vessel requirements (20). In this deterministic model constraint sets (19) and (20) will be pre-processed by setting the  $t_{vipf}$  and  $y_{vpf}$  variables to zero whenever the weather conditions requires no operations and/or return to safe haven.

$$\delta_j \in \{0,1\}, \quad j \in M, \tag{21}$$

$$x_{vl} \in \mathbb{Z}^+, \quad v \in V, l \in L_v, \tag{22}$$

$$x_{vp}^E, x_{vp}^L \in \mathbb{Z}^+, \quad v \in V^S, l \in L_v \setminus \{|L_v|\}, p \in P_v^{|L|}, \tag{23}$$

$$y_{vpf} \in \mathbb{Z}^+, \quad f \in F \cup M, v \in (V^O | f \neq M) \cup V^S, p \in P, \tag{24}$$

$$w_{vpfg} \in \mathbb{Z}^+, \quad (f, g) \in F \cup M | f \neq g, v \in V, p \in P, \tag{25}$$

$$t_{vipf} \geq 0, \quad f \in F, i \in A_f, v \in V_{if}^A, p \in P_{if}^A, \tag{26}$$

$$t_{vpfg}^M, t_{vpfg}^E \geq 0, \quad (f, g) \in F \cup M, v \in V, p \in P, \tag{27}$$

$$z_{if} \geq 0, \quad f \in F, i \in A_f \setminus A_f^B. \tag{28}$$



Finally, constraints (21)-(28) set the binary, integer and non-negativity requirements for the problem variables.

#### 4. Computational study

The mathematical model formulation from Section 3 has been implemented in Xpress-IVE. It has been tested on 15 problem instances to check the model formulation and to demonstrate its use. Since offshore wind is a relatively new technology, the access to relevant vessel concepts and data is limited. The data used in this section are therefore based on some available data sources and some expert opinion and is solely for the purpose of demonstrating how the model can be used. The model itself is, however, general and can handle various vessel types and concepts. In Section 4.1 we describe some details for the 15 problem instances and in Section 4.2 we present the numerical results.

##### 4.1. Problem instances

All problem instances have a planning horizon of 360 periods where one period is 24 hours. Data for vessel types are based on [9] and [10], and data for helicopters are based on [9] and [11]. A set of reasonable costs for vessels and an offshore station concept that do not exist as of today is included. Investment costs, time charter costs and variable costs for the vessel types are based on expert opinions. There is one onshore base and one offshore base in our problem instances where both or one of them can be included in the solution. There is an investment cost for the offshore base but not for the one onshore. An overview of some characteristics for the available vessel types that are used in the 15 problem instances is given in Table 1.

Table 1. Characteristics of vessel types included in the generated problem instances generated.

Vessel number	Vessel type	Personnel	Base	Lift capacity [Metric tons]	Max periods offshore	Lease length [periods]	Wave restriction (operation/vessel) [m]	Wind restriction (vessel) [m/s]
1	CTV (small)	12	Offshore	0	1	360	1.5/1.5	20
2	CTV (large)	24	Onshore	0	1	30	2.0/2.5	25
3	CTV (small)	12	Onshore	0	1	30	1.5/1.5	30
4	Supply vessel (small)	40	Onshore	0	20	30	2.5/3.5	30
5	Supply vessel (large)	70	Onshore	0	20	30	2.5/4.0	30
6	Helicopter 1	7	Onshore	0	1	30	-	20
7	Helicopter 2	9	Offshore	0	1	360	-	20
8	Multipurpose vessel	100	Onshore	250	20	360	2.0/3.5	30
9	Jack-up rig	150	Onshore	400	20	360	2.5/4.0	35

In each problem instance, each turbine has two planned preventive maintenance operations over the planning horizon. The number of corrective maintenance operations for the wind farms is generated based on the probabilities of four selected types of failures (gearbox, hydraulic, electric, brakes) for land-based wind turbines [12]. Each of the maintenance operations are divided into up to three maintenance activities, as explained in Section 2, which will be included in the input data. Preventive maintenance activities with overlapping hard time windows are combined into activity bundles, so that these activities can either be executed on their own or as part of a bundle.

In this computational study we only focus on the weather parameters wind speed and wave height, although our model can accommodate for a number of different weather parameters. For each problem instance, wind speed and wave heights for each period of the planning horizon is generated from historical data from the Ekofisk field in the North Sea in the years 2005 to 2010 [13].

Downtime cost for preventive maintenance activities are based on the expected cost involved with executing the activity before or after the optimal execution point, and the loss in earnings during the time the maintenance activity is executed due to turbine shut down. For corrective maintenance activities, the downtime cost represents the loss in earnings due to turbine break down. Penalty cost for not completing an activity within the planning horizon is set to a value that is high enough so that the activity will be executed if possible without having to increase the vessel fleet capacity significantly.

Table 2. Overview of problem instances

Problem instance	# wind farms	# wind turbines per wind farm	# preventive maintenance activities	# corrective maintenance activities
1	1	20	40	34
2	1	50	100	85
3	1	100	200	159
4	1	150	300	262
5	1	200	400	341
6	2	20	80	72
7	2	50	200	165
8	2	100	400	328
9	2	150	600	526
10	2	200	800	746
11	3	20	120	114
12	3	50	300	274
13	3	100	600	499
14	3	150	900	771
15	3	200	1200	975

For all problem instances we define a maximum optimality gap of 0.5%: Xpress-Optimizer stops searching for better solutions and report the current solution as optimal when the gap between the cost of the current solution and the best known lower bound for the solution is less than 0.5%. We also set a maximum time limit for execution of 5 hours. Results are obtained on a normal PC.

Table 2 provides an overview of the 15 problem instances.

Table 3. Numerical results

Problem instance	CPU [s]	Bases	Vessel types	# activities not executed
1	6	Onshore, Offshore	1,8	0
2	46	Onshore, Offshore	1,2,8	0
3	42	Onshore, Offshore	1,2,8	0
4	118	Onshore	2,3,4,8	4
5	87	Onshore, Offshore	1,2,3,4,6,8	2
6	11	Onshore, Offshore	1,2,8	0
7	276	Onshore, Offshore	1,2,3,4,8	2
8	700	Onshore, Offshore	1,4,6,9	4
9	1277	Onshore, Offshore	1,2,3,4,6,9	4
10	923	Onshore, Offshore	1,2,4,6,8,9	8
11	313	Onshore	2,3,4,8	3
12	1157	Onshore, Offshore	1,3,4,8	8
13	5317	Onshore	2,3,4,9	6
14	6717	Onshore, Offshore	1,2,3,4,6,9	6
15	18000	Onshore, Offshore	1,2,4,6,8,9	11

#### 4.2. Numerical results

The numerical results in Table 3 show that the CPU times, in general, increase with problem size. Only the largest problem instance was not solved to an optimality gap of less than 0.5 % within the maximum time limit of 5 hours, but the optimality gap for this problem instance was only 0.7 %. We can therefore conclude that our model can solve large



problem instances to optimality or near-optimality within acceptable computational time for a strategic problem of this type.

The penalty cost for activities not executed within the planning horizon is set relatively high for the problem instances, the result can be seen in Table 3 where there are few activities not being executed. The investment cost of the offshore base is set relatively low compared to the actual investment cost for such a base. With an increased cost, the offshore base would in most cases not be used. Our model only considers the investment cost of this base together with the cost of the vessels associated with this base compared with the cost of other vessels and bases, and does not capture any other benefits of having such a base. However, factors not included in the model, such as safety regulations and preferences among maintenance personnel, can make an offshore base more attractive than the actual investment cost implies. Hence we reduce the investment cost used in the model accordingly, to reflect the goodwill resulting from having an offshore base.

## 5. Concluding remarks and further research

We have defined and presented a new problem arising in the offshore wind business: The vessel fleet composition problem for maintenance operations at offshore wind farms. Vessels and helicopters are capital intensive and crucial for the execution of maintenance operations at offshore wind farms. To keep the cost of energy down it is essential to hold an optimal or near-optimal vessel fleet. To attain this goal we have developed and presented a deterministic vessel fleet optimization model.

Our computational study involving 15 problem instances with 1 – 3 wind farms and a total of 20 – 600 wind turbines shows that the proposed optimization model can provide optimal or near-optimal solutions to relevant problems within acceptable computational time. This illustrates that an offshore wind farm operator may use this model for decision support and analysis when facing decision with regards to vessel fleet composition and infrastructure.

Since offshore wind is a relatively new technology our model may not capture all aspects that an offshore wind farm developer find relevant. The model will thus need to be modified as the technology develops and other relevant details are exposed. As the model can solve relatively large problems within short computational time, it is likely that it can handle such extensions without the need to develop other solution methods.

The proposed optimization model has a deterministic nature, i.e. it treats all uncertain parameter as known. This is a simplification of the real world problem that is highly affected by uncertainty. However, the deterministic model can cope with this by solving a problem instance several times with different realizations of the uncertain parameters. If the optimal vessel fleet does not change, or the change is marginal, for the different realizations, an optimal fleet is found. Large changes in vessel fleet will make it difficult for a decision maker to know which one will be the better. Then it will be relevant to investigate ways of incorporating uncertainty to the deterministic model. For example a stochastic modeling approach will be of interest for further research.

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