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Optimal chartering decisions for vessel fleet to support offshore wind farm maintenance operations

Mingxin Li [a,b,*,1], Bas Bijvoet [a,1], Kangjie Wu [a,1], Xiaoli Jiang [a], Rudy R. Negenborn [a]

[a] *Department of Maritime and Transport Technology, Delft University of Technology, Delft, The Netherlands*
[b] *Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, United Kingdom*

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ABSTRACT

Offshore wind energy is expected to be the most significant source of future electricity supply in Europe. Offshore wind farms are located far from the shores, requiring a fleet of various types of vessels to access sites when maintaining offshore wind turbines. The employment of the vessels is costly, accounting for the majority of the total O&M costs for offshore wind energy. Therefore, configuring the size and mix of the vessel fleet to support maintenance operations in a cost-effective manner is an issue of importance to enhance economics of offshore wind sector. In this paper, a discrete event simulation based model is proposed to present how a mixed vessel fleet with the specific configuration, including crew transfer vessels, field support vessels, and heavy lift vessels, performs maintenance for an offshore wind farm. The economic performance of the vessel fleet under a predetermined condition-based opportunistic maintenance strategy is investigated by using the model. A metaheuristic algorithm, simulated annealing, is employed to find the optimal fleet size and mix to make leasing decisions with the minimum costs. The performance of the developed approaches is evaluated by using a generic offshore wind farm in the North Sea. The sensitivity analysis is performed to investigate the most influential O&M factors.

1. Introduction

The blue economy is one of the most important elements in modern society and the development of renewable and sustainable energy is considered as a cornerstone of net-zero (Li and Kim, 2022; Li et al., 2022a). In Europe, in order to reach carbon neutrality, an installed offshore wind capacity of at least 300 GW is expected by 2050, becoming the most significant source of future electricity supply (Nielsen, 2022; Li et al., 2021). With the rapid development of offshore wind power, enhancing its economics is becoming a vital issue deserving attention. In 2020, the Levelized Cost Of Energy (LCOE) of fixed-bottom and floating offshore wind are approximately 86 €/MWh and 184 €/MWh, which were expected to decline to 37 €/MWh and 40 €/MWh in the middle of this century (ETIPWind and WindEurope, 2021). The cost reduction comes from upscaling of turbine sizes, grid technology improvements, better installation, operation, and maintenance techniques, etc. However, the trend towards reducing costs has not been realized as expectation, and it is expected that these costs will be higher now (ORE Catapult, 2023).

As a typical offshore structure, offshore wind turbines suffer from failure events and harsh marine environments, thus effective maintenance is required to restore faulty wind turbine to operational state or extend the service life of components. Operation and Maintenance (O&M) makes up a substantial portion of the overall life cycle cost of offshore wind projects (Shafiee, 2015a). According to the findings in (Vieira et al., 2022), O&M expenditures contribute to approximately 20% of the total LCOE. The execution of maintenance activities depends on a hybrid maintenance vessel fleet comprising various vessels essential for inventory transformation, technician deployment, and maintenance operations. Reduction in the costs related to the vessel fleet is essential to lower the LCOE of offshore wind power, which will further make it more economical and boost the installed capacity of this renewable energy source (Li et al., 2020a). The portion of O&M costs accounted for by vessel-related costs can be found in the literature (Dalgic et al., 2015c; Smart et al., 2016).

Offshore wind farms are located far from shores. Different types of vessels are employed to configure a vessel fleet, which is required to load and transport necessary wind turbine components, access offshore wind farm sites, assist in implementing maintenance tasks, and provide accommodation for crew and technical personnel (Centeno-Telleria et al., 2023). For instance, the typical service vessels used for maintenance implementation, including Heavy Lift Vessel (HLVs),

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[*] Corresponding author at: Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, United Kingdom.
E-mail address: mx.li@strath.ac.uk (M. Li).

[1] Co-first authors, these authors contributed equally to this work.

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(a) (b) (c)

Fig. 1. Different types of service vessels: (a) HLVs, (b) FSVs, (c) CTVs.

Table 1
Literature on vessel fleet management for offshore wind farm maintenance.

Year	Literature	Maintenance strategy			Vessel type				Modelling methods		Solving tools/ methods
		CM/TM	CBM	OM	CTV/HL	FSV/OAV /SV/SOV	HLV/ Jack-up	Others	Mathematical programming	Simula-tion	
2013	Besnard et al. (2012)	✓			✓			✓	Queuing		
2013	Halvorsen-Weare et al. (2013)	✓			✓	✓	✓	✓	MIP		FICO Xpress
2014	Endrerud et al. (2014)	✓			✓	✓	✓			✓	
2015	Dalgic et al. (2015a)	✓			✓	✓	✓	✓		✓	
2015	Gundegjerde et al. (2015)	✓			✓	✓	✓	✓	SP		FICO Xpress
2015	Dalgic et al. (2015c)	✓			✓					✓	
2015	Dalgic et al. (2015d)	✓					✓			✓	
2015	Dalgic et al. (2015b)	✓			✓		✓	✓		✓	
2016	Stålhane et al. (2016)	✓			✓	✓	✓	✓	SP		FICO Xpress
2017	Stålhane et al. (2017)	✓					✓		SP		SAA
2017	Halvorsen-Weare et al. (2017)	✓			✓			✓	MILP		GRASP
2017	Gutierrez-Alcoba et al. (2017)	✓						✓	MILP		CPLEX
2019	Stålhane et al. (2019)	✓			✓	✓	✓		SP		FICO Xpress
2019	uit het Broek et al. (2019)	✓					✓			✓	
2020	Stålhane et al. (2021)	✓			✓				SP		L-shaped
2022	Bolstad et al. (2022)	✓			✓				SP		GRASP
2023	This paper		✓	✓	✓	✓	✓			✓	SA

Field Support Vessels (FSVs), and Crew Transfer Vessels (CTVs), are shown in Fig. 1. A HLV is a vessel with a specific crane that has a large lifting capacity of up to thousands of tonnes to handle the major offshore wind turbine parts. A FSV operates as a means of transport containing large quantities of spare parts and tools, but it also operates as in-field accommodations for workers and platform assist for wind turbine servicing and repair work. A CTV is used to transport wind farm technicians and other personnel out to sites on a daily basis.

The maintenance implementer usually owns a mixed fleet of vessels to carry out maintenance tasks and chooses to temporarily lease vessels when faced with overwhelming maintenance tasks exceeding the current work capacity of the fleet. In this context, making suitable leasing decisions to configure the vessel fleet is significant. Unavailable transportation means or lack of technicians lead to a delay in maintenance activities and subsequently, long downtimes of the wind farm and excessive costs. On the contrary, maintaining an excessive vessel fleet results in significant original investment and chartering costs. A sound configuration of the mixed vessel fleet is to find a trade-off between excessive and insufficient vessels, so as to complete the required maintenance tasks efficiently and economically.

Over the past decade, the vessel fleet size and mix problem has gradually gained attention. A literature review on the fleet size and mix problem is concluded in Table 1 and Table 2. In the table, the studies are concluded based on the following indicators: (1) maintenance strategies; (2) variety of vessels used; (3) methods and tools for modelling and solving; (4) accounting for uncertainty factors; and (5) performance indicators.

It is found that all the past studies consider Corrective Maintenance (CM) or Time-based Maintenance (TM) strategies, but no paper before developed the model under a novel maintenance strategy such as Condition-Based Maintenance (CBM) or Opportunistic Maintenance (OM) strategy. From the perspective of vessel types in the fleet, most of the studies focus on a hybrid fleet composed of CTVs/helicopters (represented by 'HLs'), FSVs/Offshore Assistance Vessels (OAVs)/Supply Vessels (SVs)/Service Operation Vessels (SOVs), and HLVs/Jack-up vessels. The vessel types concerned in the studies relies on the requirement of maintenance tasks. If the model involves multiple types of maintenance, such as replacement, major repair, and basic repair, a hybrid vessel fleet is necessary (Li et al., 2023a). In case that only basic repair is considered, the vessel fleet is mainly configured by CTVs. Moreover, various types of novel transportation methods can be introduced to discuss about their influence on maintenance logistics. Helicopters are usually used to perform minor maintenance tasks (Dalgic et al., 2015b). Compared to CTVs, helicopters are able to bring and hoist the technicians and the material needed to maintain the wind farm quickly, and handle the rough sea condition, but the drawback is that the helicopter is a kind of costly tool.

Multi-purpose crane vessels, surface effect ships, small accommodation vessel, mother vessels, and daughter vessels are categorized into 'others' in the table. A mother vessel, which is a large vessel that can accommodate multiple CTVs alongside, can provide a possible solution for operators with daughter vessels. Surface effect ships are special types of vessels that are a combination of hovercrafts and catamarans, allowing them to have greater speed on sea water. Multi-purpose crane vessels are designed to carry a wide diversity of cargo types. They are combined with crane capacity, offering a wide operational flexibility depending on the mission. Accommodation vessels are primarily used to provide accommodation for personnel during the establishment or maintenance of an offshore structure/wind farm. Accommodation vessels are moored or floating close to the construction site to minimize

Table 2
Continued: Literature on vessel fleet management for offshore wind farm maintenance.

Year	Literature	Uncertainty factors					Performance					
		Failure	Metocean	Vessel charter	Electricity price	Other	Cost	Revenue loss	Power yield	Availability/ downtime	Vessel utilization	Other
2013	Besnard et al. (2012)	✓	✓			✓	✓	✓		✓		
2013	Halvorsen-Weare et al. (2013)	✓	✓	✓	✓		✓					
2014	Endrerud et al. (2014)	✓	✓				✓		✓	✓	✓	
2015	Dalgic et al. (2015a)	✓	✓				✓	✓	✓	✓	✓	
2015	Gundegjerde et al. (2015)	✓	✓	✓	✓		✓					✓
2015	Dalgic et al. (2015c)	✓	✓				✓	✓	✓			
2015	Dalgic et al. (2015d)	✓	✓				✓				✓	✓
2015	Dalgic et al. (2015b)	✓	✓				✓			✓	✓	
2016	Stålhane et al. (2016)	✓	✓				✓					
2017	Stålhane et al. (2017)	✓	✓		✓		✓					
2017	Halvorsen-Weare et al. (2017)	✓	✓				✓					
2017	Gutierrez-Alcoba et al. (2017)	✓	✓				✓					
2019	Stålhane et al. (2019)	✓	✓			✓	✓			✓		
2019	uit het Broek et al. (2019)	✓	✓				✓			✓	✓	
2020	Stålhane et al. (2021)	✓	✓		✓	✓	✓					
2022	Bolstad et al. (2022)	✓	✓			✓	✓					
2023	This paper	✓	✓				✓	✓	✓	✓		

transport time to the offshore structure and maximize personnel work time.

The modelling methods of the maintenance vessel fleet size and mix problems are categorized as mathematical programming methods and simulation methods. In mathematical programming methods, a mathematical model involving variables and constraints is formulated and solved by minimizing/maximizing an objective function. The mathematical programming methods are further classified into solving deterministic problems (Halvorsen-Weare et al., 2013) and stochastic problems (Gundegjerde et al., 2015). In deterministic problems, all the parameters are assumed to be known. In Halvorsen-Weare et al. (2017, 2013), Gutierrez-Alcoba et al. (2017), deterministic vessel fleet optimization models for offshore wind farms are developed by using Mixed-Integer Programming (MIP), Mixed-Integer Linear Programming (MILP), aiming to give offshore wind farm operators a tool to determine which types of vessels to buy, which and how many vessels to charter, and which vessel bases (onshore and offshore) to use. A MIP problem is one where some of the decision variables are constrained to be integer values, and a MIP problem without any quadratic features is often referred to as a MILP problem. In MIP/MILP problems, factors including metocean conditions, electricity price, vessels charter rates, and maintenance tasks are all treated as deterministic parameters which have been known in advance.

The deterministic problems assume that all the parameters are known, which is a simplification of the real maintenance planning full of uncertainty. The significant variations in vessel fleets resulting from different scenarios with uncertainty will pose challenges for decision-makers. Several work tends to investigate the optimal fleet configuration in the scenarios incorporating uncertainty, namely as stochastic problems. In Gundegjerde et al. (2015), a Stochastic Programming (SP) model for the fleet size and mix problem for offshore wind farms is proposed. SP is a framework for modelling an optimization problem in which some or all problem parameters are uncertain, but follow known probability distributions. This framework contrasts with deterministic optimization, in which all problem parameters are assumed to be known exactly. The uncertainty in charter rates of vessels and helicopters, metocean conditions (wind speed and wave height), electricity prices, and failures is introduced. The SP model is solved by transforming it into its scenario tree node-based deterministic equivalent, where all decision variables affected by the uncertain parameters are transferred into node-based equivalents. Each realization of the uncertain parameters is referred to as a scenario in which all the parameters are deterministic. Similarly, in Stålhane et al. (2019), Bolstad et al. (2022), Stålhane et al. (2017, 2016, 2021), SP models are developed to consider various types of uncertain variables including metocean conditions, components failures, electricity prices, and vessel chartering rates. The study (Gundegjerde et al., 2015) reveals that, compared to a stochastic approach, deterministic methods where all uncertain parameters are replaced by their expected value underestimates the required vessel fleet result in fewer maintenance tasks being completed in rougher metocean conditions.

Simulation methods are typically used to model and analyse the complex organization of vessel fleet in order to understand how they work and make predictions about the output. For one specific realization of the decision variables (configuration of the vessel fleet), the outputs (e.g., total costs and wind farm availability) are estimated after simulating the maintenance activities. By performing simulations for different fleet configurations, the most favourable fleet size and mix can be determined. In Dalgic et al. (2015c), different fleet compositions in different scenarios with realizations of the stochastic parameters involving metocean conditions and turbine failures are evaluated. The objective was to find the fleet composition resulting in the minimum total O&M costs. Simulation methods have also been used in Dalgic et al. (2015a), uit het Broek et al. (2019), Dalgic et al. (2015d), Endrerud et al. (2014), Dalgic et al. (2015b) to investigate the optimum chartering strategies for jack-up vessels, mother vessels, and hybrid vessel fleet consisting of helicopters, CTVs, OAVs, and jack-up vessels.

According to the literature review on the different modelling methods for fleet management of offshore wind farms, two main differences (advantages and disadvantages) are identified. First, the deterministic models solve a certain problem where all information is known priorly. For example, the corrective maintenance tasks (sudden failures) of wind turbines and metocean conditions are assumed to be known over the planning horizon. Thus, optimal decisions can be determined by anticipating future events, while in practice the failures and metocean conditions are not known in advance. Consequently, deterministic methods may underestimate the required fleet size and costs of O&M since in practice there is incomplete information. Simulation methods and SP methods can deal with information to be revealed over time, so the problem can be modelled more realistically. Second, the results of using a specific fleet can be analysed in much greater detail with simulation methods compared to mathematical programming methods.

A simulation method allows the results of multiple fleet configurations to be evaluated and compared, whereas with an mathematical programming method only the result of the optimal solution is obtained. For example, one specific fleet composition resulting in the lowest expected costs may have significantly more risks in extreme cases than another fleet composition with somewhat higher average costs. These considerations can be taken into account by analysing the results of a simulation model, useful for assessing the risks versus the benefits of different fleets.

The solving methods/tools selected in the studies is related to the modelling methods. When using mathematical programming methods, metaheuristic algorithm, such as Greedy Randomized Adaptive Search Procedure (GRASP), commercial optimization tool, such as FICO Xpress and CPLEX, and Sample Average Approximation (SAA) are the commonly used solving methods and tools (Stålhane et al., 2016; Gutierrez-Alcoba et al., 2017). On the other hand, when dealing with the problems using simulation methods, the common approach is to use an exhaustive method or a large number of comparisons of different fleet configurations to determine the optimal solution (Dalgic et al., 2015a).

The fleet size and mix problem involves various types of uncertainty factors, e.g., metocean conditions, component failures, vessel chartering rates, electricity prices, working shift (Gundegjerde et al., 2015; Stålhane et al., 2017). The optimization objectives or the performance indicators which decision makers concern about are mainly set as minimum costs, including fixed costs of maintenance bases, chartering costs of vessel resources, variable costs of executing maintenance tasks, downtime costs, penalty costs, transportation costs, and technician costs (Halvorsen-Weare et al., 2017; Stålhane et al., 2019; Dalgic et al., 2015c). Moreover, revenue loss, power production, and availability, downtime, vessel utilization, hazard rates and mean time to failure can also be used to evaluate the performance of the vessel fleet (Dalgic et al., 2015a,d).

Based on the above literature review, the limitations in the past research are identified. First, the past studies study the fleet configuration under a corrective or time-based maintenance strategy, but the model under a novel maintenance strategy such as condition-based or opportunistic maintenance strategy still lacks. O&M decisions can be generally categorized into long-term, medium-term, and short-term decisions (Shafiee, 2015b). The maintenance strategy is a long-term decision, providing guidance for wind farm O&M over the lifetime and directly impact the number of maintenance tasks in each maintenance cycle, thus exerting a significant influence on maintenance fleet size and mix. Maintenance cycles refer to the sequence of events from the definition to the completion of maintenance tasks. More specifically, when a maintenance cycle is triggered, the following steps include mobilizing vessels to prepare for repairs, dispatching the maintenance teams and vessels to the site, and repairing the components requiring maintenance. This series of operations constitutes a maintenance cycle. The vessel fleet management is determined at the beginning of each maintenance cycle, so this is a medium-term decision. Although there is no difference between tasks under novel maintenance strategies and conventional maintenance strategies for the vessels from the point of view of vessel dispatching, previous studies lacked the ability to integrate vessel fleet configuration with maintenance strategies and failed to realize the interaction between long-term and medium-term decisions. Moreover, the influence of the maintenance strategy on maintenance fleet management has never been investigated.

Second, the past studies using simulation-based methods commonly use an exhaustive method or a large number of comparisons of different fleet configurations to search for the optimal maintenance fleet. This is a common problem in all studies that use simulation methods to model the operation of maintenance vessel fleets. This method is not efficient enough, especially considering that the offshore wind farms will keep scaling up in the future. The problem will also become more complex when considering more factors, such as various types of uncertainty including stochastic metocean conditions and uncertain failure events. The computation time by using the exhaustive method to solve this complex problem is anticipated to increase significantly, bringing difficulties in decision-making.

Considering the above research gaps, in this paper, a discrete event simulation-based model is proposed to present how a mixed vessel fleet with the specific configuration carries out maintenance operations for an offshore wind farm, where uncertainty such as environmental conditions and component failures is included. The performance of the vessel fleet is evaluated in terms of costs under a predetermined condition-based opportunistic maintenance strategy. By employing a metaheuristic algorithm, Simulated Annealing (SA), the optimal maintenance fleet is found to provide suggestions on leasing decisions to minimize total costs.

The remainder of the paper is organized as follows. The methodology for modelling maintenance fleet optimization problems is formalized in Section 2. In Section 3, the employed simulated annealing optimization method is introduced. In Section 4, the proposed approach is applied on a generic offshore wind farm to evaluate its performance. The results and sensitivity analysis are also presented. In Section 5, concluding remarks and future research directions are provided.

2. Methodology

In this section, as a long-term decision guiding maintenance operations, the condition-based opportunistic maintenance strategy is firstly introduced. The maintenance strategy is recognized as a criteria to determine when to perform which type of maintenance on which component and turbines over the lifetime. In other hands, the maintenance strategy has a direct influence on the timing of maintenance cycles and the number of diverse maintenance tasks within maintenance cycles. Thus, the configuration of maintenance fleet and organization of logistics activities is determined while considering the predetermined maintenance strategy. An O&M model based on discrete event simulation is then used to formalize the maintenance logistics activities for three types of vessels when maintaining an offshore wind farm, as demonstrated in Fig. 2(a). Discrete event simulation is a method used to model real world systems that can be decomposed into a set of logically separate processes that autonomously progress through time. In the model, operations and actions for a specific maintenance fleet to conduct maintenance are simulated. The development of the O&M model aims to provide decision-making basis for decision-makers (wind farm owners or maintenance service providers). Fig. 2(b) demonstrates the flow chart of solving the maintenance fleet mix and size problem. Given an offshore wind farm in operation, the decision-maker uses the O&M model to evaluate the efficiency and cost-effectiveness of a maintenance fleet to carry out the required tasks in maintenance cycles. The performance evaluation is input into the SA method to assist searching for a better fleet configuration. The new fleet configuration is input into the O&M model to evaluate the corresponding performance. Finally, the optimal fleet is found after repeating a number of these cycles until satisfying the stopping criteria.

2.1. Assumptions

In order to better understand this problem and ensure that it is representative of the reality, the following assumptions are made in the model.

1. The metocean conditions considered to constrain the vessel operations are wave height and wind speed. Wind speed and wave height are independent of each other. The current metocean condition is independent from previous metocean conditions.

2. The travelling time between the base and the offshore wind farm and repair times are constant. The inter-transit time between turbines is constant, ignoring the detailed layout of the wind farm.

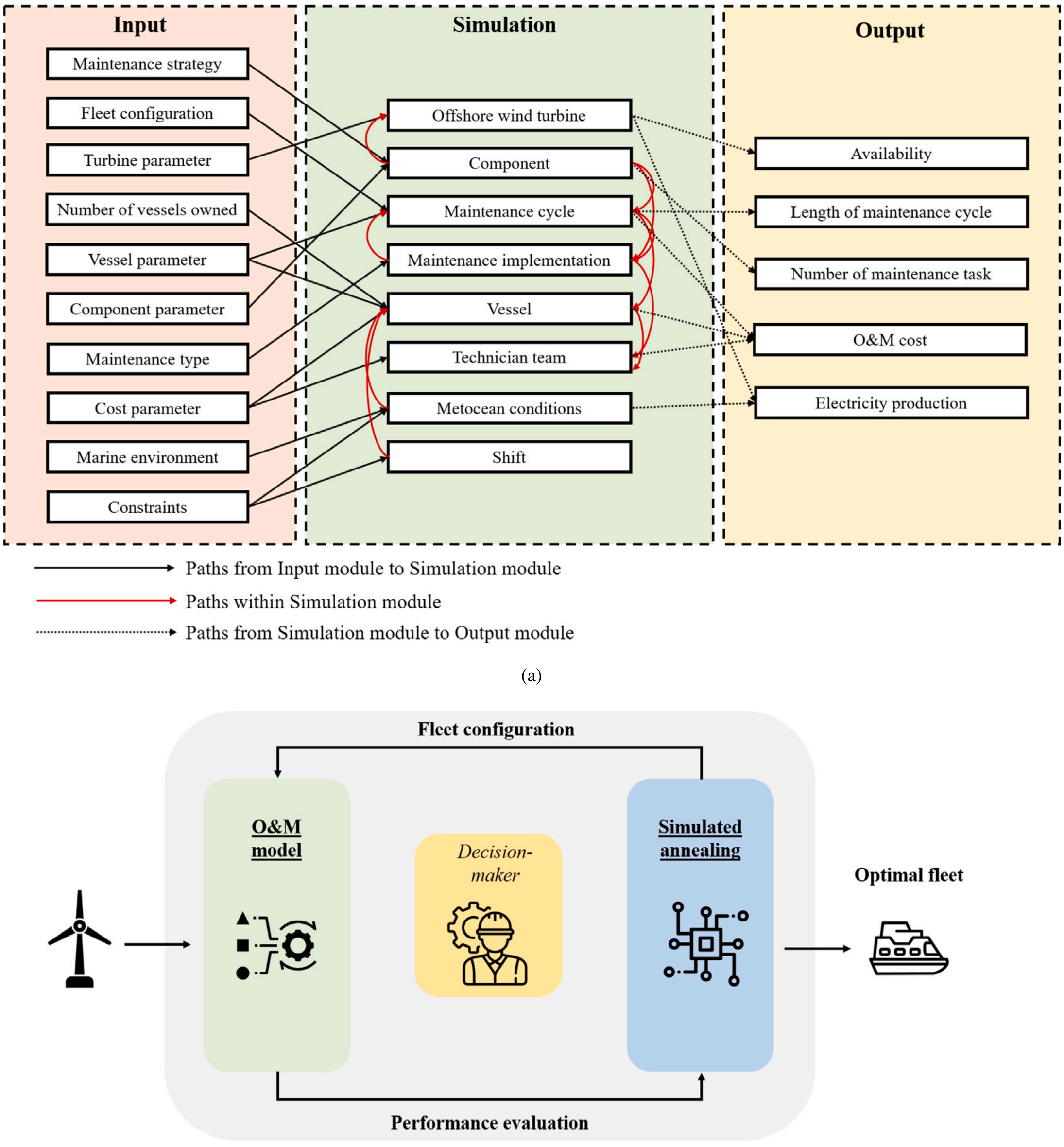

Fig. 2. (a) Schematic diagram of the developed O&M model based on discrete event simulation methods. (b) Flowchart of solving the maintenance fleet mix and size problem.

3. Once a maintenance task starts, the FSVs and HLVs can only be assigned to a new task after the task is finished. Maintenance tasks for different components on the same turbine can be performed simultaneously. The chartered vessel should finish the assigned maintenance tasks even though its charter period has ended, and its late return leads to the extra cost based on late-return days. Either a minor repair or a major repair cannot be performed twice on one component within the same maintenance cycle. After the end of a charter period, it is necessary to decide to extend the charter period of a vessel if there are still excessive number of maintenance tasks to be performed relative to the number of owned vessels and currently chartered vessels.

4. The degradation of components are independent. The failure times of components are modelled as a two-parameter Weibull distribution.

5. The spare parts are available and each vessel is equipped with sufficient spare parts to complete its maintenance tasks.

6. The charter rates are fixed and the charter period can be extended when necessary. Once a charter period starts, the entire charter period will be charged. The costs of non-maintenance personnel have been included in the charter rate.

7. During each maintenance cycle, the charter period of vessels may need to be extended due to a large number of remaining tasks. Once a charter period is ended, the vessel always returns to base, regardless of whether the charter period will be extended. In this process, technicians on board need to be renewed and the vessel needs to be resupplied. If one vessel is decided to extend the charter period of, after it arrives at the base, it will return to the site after the next day's shift starts if weather permits.

8. Each vessel is equipped with sufficient number of technicians. The cost for technicians of an owned vessel is paid based on the entire duration of each maintenance cycle, and the cost for technicians of a chartered vessel counts from the start of the charter period until the day when the vessel is returned.

9. For the maintenance tasks that need the same type of vessels, the more degraded components are given priority, indicating they will be repaired earlier. For vessels, the on-site vessels are assigned priority to conduct maintenance tasks over the vessels staying at the base. If there are multiple available vessels on site, priority is given to those vessels with a greater number of teams already assigned.

2.2. The long-term maintenance strategy

The long-term maintenance strategy employed in this research is the condition-based opportunistic maintenance strategy, which is briefly introduced here, and more details can be found in Li et al. (2022b). Denote t as the elapsed time since a component begins to operate, the component health is divided into different zones based on the ratio between the current age $u(t)$ and the predicted failure time $f(t)$. A health threshold $A(t)$is introduced as $A(t) = u(t)/(u(t) + f(t)) \cdot 100\%$. The unobservability of the wind turbine component condition and the inaccuracy of the failure prediction are not considered in this study. Three maintenance thresholds A_1, A_2, and A_3 are introduced for component condition classification. The maintenance actions are determined according to the classification as follows:

- Corrective replacement: if $A(t)$ reaches 100%, the component is predicted to reach the end of the lifetime. In this case, this component is replaced by a new item.
- Preventive replacement: if $A_1 \leq A(t) < 100\%$ (Zone 4), the component is determined as an aged component, requiring a preventive replacement.
- Major repair: if $A_2 \leq A(t) < A_1$ (Zone 3), the defective component requires a major repair to improve its condition.
- Minor repair: if $A_3 \leq A(t) < A_2$ (Zone 2), the component state is still good, and minor repair is conducted to maintain its current state.
- No maintenance: if $0 \leq A(t) < A_3$ (Zone 1), the component is very young, and there is need to perform maintenance.

After classifying the health state of the components, the decision-maker decides whether to initiate a maintenance cycle. The maintenance cycle is triggered when a turbine stops working or a components reaches Zone 4. In maintenance cycles, the number of corrective replacement, preventive replacement, major repair, and minor repair, required for offshore wind turbine components are determined. The quantity of various maintenance tasks serves as the workload confronting maintenance implementers. If the workload becomes excessively heavy, it becomes necessary to lease additional vessels to ensure the completion of planned maintenance tasks on time. Consequently, the number of maintenance tasks under long-term maintenance strategies will be a crucial input for the maintenance model and a significant basis for decision-making regarding vessel leasing.

2.3. Description of the O&M model

2.3.1. Configuration of vessel fleet

According to the maintenance strategy introduced in Section 2.2, the number of various maintenance tasks can be determined in maintenance cycles. The implementation of corrective replacement and preventive replacement requires HLVs. FSVs and CTVs are necessary to conduct major repair and minor repairs respectively. Therefore, the formation of a mixed vessel fleet consisting of HLVs, FSVs, and CTVs is essential during the mobilization phase of maintenance cycles.

In the sth maintenance cycle, the numbers of maintenance tasks requiring HLVs, FSVs, and CTVs are represented by N_s^{HLVT}, N_s^{FSVT}, N_s^{CTVT}, respectively. The number of three types of vessels owned are N_s^{HLVO}, N_s^{FSVO}, N_s^{CTVO}. The decision variables in this model are $X_{\mathrm{T}}^{\mathrm{HLV}}$, $X_{\mathrm{T}}^{\mathrm{FSV}}$, and $X_{\mathrm{T}}^{\mathrm{CTV}}$, which are introduced to indicate how many tasks one vessel is 'desired'. The number of vessels to be chartered in each maintenance cycle is determined based on the number of tasks and these decision variables. The number of chartered vessels in sth maintenance cycle, N_s^{HLVC}, N_s^{FSVC}, N_s^{CTVC}, is determined by the number of maintenance tasks to be completed in the maintenance cycle and the number of the corresponding type of vessel owned as

$$N_s^{\mathrm{HLVC}} = \left\lceil \frac{N_s^{\mathrm{HLVT}}}{X_{\mathrm{T}}^{\mathrm{HLV}}} \right\rceil - N_s^{\mathrm{HLVO}}, \tag{1}$$

Table 3
Constraints for three types of vessels.

No	Name	HLV	FSV	CTV
1	Stay on-site for multiple days	✓	✓	
2	Constrained by shift hours		✓	✓
3	Constrained by wave height	✓	✓	✓
4	Constrained by wind speed at sea	✓	✓	✓
5	Constrained by wind speed at hub	✓		

$$N_s^{\mathrm{FSVC}} = \left\lceil \frac{N_s^{\mathrm{FSVT}}}{X_{\mathrm{T}}^{\mathrm{FSV}}} \right\rceil - N_s^{\mathrm{FSVO}}, \tag{2}$$

$$N_s^{\mathrm{CTVC}} = \left\lceil \frac{N_s^{\mathrm{CTVT}}}{X_{\mathrm{T}}^{\mathrm{CTV}}} \right\rceil - N_s^{\mathrm{CTVO}}. \tag{3}$$

2.3.2. Wind turbine failure and maintenance actions

Offshore wind turbines consist of a number of components. Four types of critical components, rotor & blades, generators, gearboxes, and main bearings, are considered in this model. Considering that the wind turbine is a series system, the component failure causes the wind turbines to stops operation.

Due to the variability and uncertainty in the factors including manufacturing processes, operating conditions, stress and fatigue, the lifetime of components are random. The random component lifetime is generated by using the Weibull distribution with specific shape parameters and scale parameters. According to the lifetime and operational time of components, the type of the maintenance action is decided as mentioned in Section 2.2.

Corrective and preventive replacement is conducted on the component which has failed or is predicted to be close to failure. The component is completely replaced to a component of the same type. The component is brand new, and the component age is reset to zero. The major repair can effectively improve the component health. The component is recovered to the state between 'as good as new' and 'as bad as old'. Minor repair is performed to maintain the current state of components, without changing the component age. Depending on the type of the maintenance and the component, the repair times and costs vary.

2.3.3. Maintenance vessels and metocean conditions

Three types of maintenance vessels, HLVs, FSVs, and CTVs, are employed to carry out maintenance at the offshore wind farm. Different types of vessels have different characteristics and their operations are affected by varying conditions. These characteristics are the constraints shown in Table 3. HLVs and FSVs can stay offshore for multiple days, while the CTV has to return to the base every day. In terms of shift hours, only HLVs can work 24 h a day with 12 h shift, and FSVs and CTVs can only work within the shift hours. All the vessel types are constrained by the wave height and the wind speed at sea level, and only HLVs are also constrained by the wind speed at the hub level.

The number of owned vessels is pre-defined as inputs in the simulation model, because the decision-makers have known how many vessels have been available at the beginning. On the basis of the number of owned vessels, the decision-maker can make decisions to charter vessels.

The two main metocean conditions, wind speed and wave height, are considered in this model, and synthetic climate datasets can be generated by using the Weibull distribution. Referring to the wind power law shown as Eq. (4) in Dalgic et al. (2015a), Justus and Mikhail (1976), the wind speed at different height at sea can be calculated based on the value of wind speed at the reference level.

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\partial}, \tag{4}$$

where v_2 is the wind speed at height h_2, v_1 is the wind speed at height h_1, and ∂ is the constant coefficient for the wind power law equation.

2.3.4. Order of maintenance operations

As depicted in Fig. 2(a), the orders of maintenance operations start with determining health states of offshore wind turbines and components. The turbines produce electricity in operational state and stops working due to failure or maintenance implementation. Each turbine in the offshore wind farm consists of four critical components and each critical component has an individual lifetime. Referring to its current age and lifetime, the components are categorized in zone 1, zone 2, zone 3, zone 4, or failed components in maintenance cycles, as mentioned in Section 2.2.

A maintenance cycle can be initiated when the number of components in zone 4 equals or exceeds one or when a wind turbine stops operating due to failure. Once the maintenance cycle starts, vessels are leased at the start of the maintenance cycle or during the cycle if additional vessels are determined to be chartered.

The operations for chartered and owned vessels in the fleet are different. An owned vessel stays idle at the base if maintenance cycles are not triggered. If a decision is made to charter a new vessel, the chartered vessel is available and added to the vessel fleet after the mobilization is finished. If the maintenance cycle has ended, all chartered vessels are removed from the fleet. In case the charter period of a chartered vessel has ended during the maintenance cycle, it is checked in advance whether the charter period should be extended before the charter expires. If the charter period is not extended, the chartered vessel is removed from the fleet.

The vessel is subject to metocean conditions and it is necessary to check whether the weather window is sufficient for vessels to travel to the site for maintenance activities. Before dispatching the vessel, the time required for the upcoming maintenance task and the vessel's capacity to withstand wind and wave conditions will be compared. Only if the weather requirements are met will the vessel be sent. If maintenance task is interrupted due to limitations imposed by shift schedule, it will be resumed when the next shift starts and metocean conditions permit.

The operations of HLVs in maintenance activities are illustrated in Fig. 3. For both preventive and corrective replacement tasks, the HLV is required to drop off a team at the turbine and lift heavy parts to the hub level of the turbine. The HLV is not restricted by shift hours and can stay offshore (on-site) for multiple days. The HLV is equipped with multiple teams of technicians that take turns completing maintenance tasks. Before parts are lifted to the wind turbine hub, the HLV needs to be stabilized, which is done by stationing its legs on the seabed. Then the hull can be raised over the sea surface, providing a stable setting for lifting operation under rough metocean conditions. Jacking up/down is constrained by the wind speed at sea and wave height. Therefore, the HLV will only jack up/down if the limits for wind speed at sea and wave height are not exceeded for the required time to jack up/down. In case the metocean window is not sufficient, the HLV will wait before jacking up/down until the conditions are met. Once the HLV is jacked-up, it can stay jacked up under any metocean condition. After jacking up, the maintenance task starts if the metocean conditions for lifting operations are sufficient. The lifting operation is constrained by wind speed at hub level. Therefore, the HLV can only start a maintenance task if the wind speed at hub level does exceed the limit for wind speed at hub level for the duration of the minimum working window plus a safety margin. The minimum working window of the HLV is the entire time required for the maintenance activity. The safety margin for the HLV ensures that the team of technicians has time to leave the turbine and enter the HLV before the weather limit is exceeded. The safety margin can be regarded as the required time for a team of technicians to leave the turbine and enter the vessel.

Once a maintenance task is finished, it is checked at which turbine the next task is. In case the next task is at another turbine, the HLV will jack down (if the weather window is sufficient) and it will travel to the next turbine. In case the next task is at the same turbine, the HLV will stay jacked up and start the new maintenance tasks if the weather window is sufficient. In case the HLV is not assigned to a new maintenance task (in which case there are no more unassigned remaining tasks for HLVs), the HLV will travel back to base and stay idle at the base. It will stay idle at the base until the end of the maintenance cycle, until the end of the charter period, or travel to the site if it is assigned to a maintenance task at a later time.

The operations of FSVs are shown in Fig. 4. The FSV is used for major repair tasks requiring lifting medium-weighted parts onto the wind turbine platform. This type of vessel is equipped with dynamic positioning systems and a motion-compensating gangway system through which technicians can be transferred on the turbine in rougher metocean conditions. The FSV type can only work within shift hours and can stay offshore for multiple days. The FSV is equipped with multiple teams of technicians that take turns completing maintenance tasks.

The FSV is constrained by conditions of wave height and wind speed at sea. These metocean conditions are operational conditions, meaning that if any of these metocean conditions exceed the limits, the FSV and its teams cannot work on a maintenance task. During rough metocean conditions, the FSV can stay on-site at the turbine or travel. The FSV will only drop off a team of technicians and start working at a turbine if the weather window is sufficient. Similar to the HLV, the FSV has a safety margin of one period that ensures that the team of technicians has time to leave the turbine and enter the FSV before the weather becomes rough.

In case the FSV and a team of technicians is working on a maintenance task and the shift has ended, the maintenance operation will be ceased and the team of technicians will enter the vessel. The maintenance operation is resumed at the shift starting at the next day if the weather window is sufficient. If a maintenance operation was ceased due to rough weather, the maintenance task will be resumed if and the weather window becomes suitable again and the remaining time in the current shift is greater or equal to the minimum working window. If there are no remaining maintenance tasks for the FSV, the FSV will travel back to base and stay idle at the base until the end of the maintenance cycle, until the end of the charter period, or until it is assigned to a new maintenance task in which case it will travel to the site.

The operations of FSVs are shown in Fig. 5. The CTV is used for minor repair task which only requiring dropping off a team of technicians at the turbine. This vessel type is significantly smaller than an FSV and HLV and, therefore, has a higher chance of capsizing in rough metocean conditions. Consequently, the weather limits for the CTV are stricter compared to the FSV and HLV. The CTV can only operate within shift hours and cannot stay offshore for multiple shifts.

If maintenance tasks have been assigned to more than one team of the CTV, the CTV delivers the first team at a turbine and travels to the next turbine until all teams have been delivered. The priority of delivery is according to the repair time. The team with the least required time for a repair will be delivered first. Once all teams have been delivered, the CTV travels back to the turbine of the first delivered team, because the first delivered team is the first to finish its task. This is the most time-efficient manner to operate the CTV. If the CTV arrives at the turbine of the first delivered team before this team has finished its task, the CTV will wait (stay idle on-site at this turbine) until the team has finished its task. Once the team has finished its task, the team will be picked up by the CTV, a new task will be assigned to this team (if any tasks are left) and the CTV will travel to the turbine of this new task (if the task is at another turbine).

At the end of the shift, the CTV will pick up every team that is working on a maintenance task. The maintenance task of each team is ceased once the team leaves the turbine. Once all teams have been picked up, the CTV will travel back to base. When the shift at the next day starts, the CTV will travel back to the site and deliver all teams that have been interrupted. Some teams of the CTV may not have been interrupted (since they were not working on a maintenance task at shift

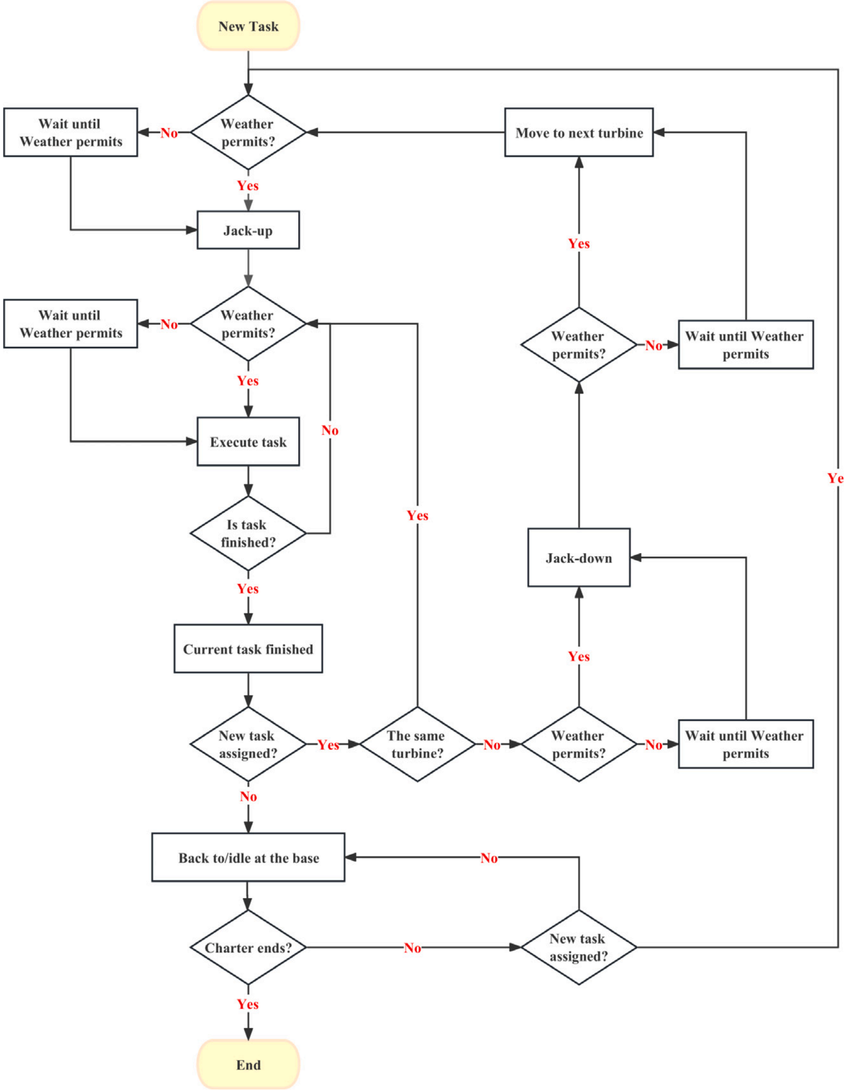

Fig. 3. Flowchart of maintenance operations of HLVs.

end) but may be assigned to a new maintenance task at the start of the shift. The CTV can only be at sea if the metocean conditions of wave height and wind speed at sea do not exceed the CTV limits. In other words, at the moment any of the metocean conditions exceed the limit, the CTV must be at the base. This implies that the CTV picks up teams and travels back to base ahead of rough metocean conditions.

When assigning maintenance tasks to technician teams and vessels, the remaining maintenance tasks is checked and the maintenance priority is sorted, as explained in Section 2.1. Then, the maintenance tasks are assigned to technician teams and vessels based on the maintenance priority. If all maintenance tasks are completed and all the vessels are back at base, the maintenance cycle ends.

2.3.5. Outputs

In the discrete event simulation model, the process of all O&M activities is modelled as a series of discrete events. The consequences of the events are finally concluded to estimate the output results. The start and end of maintenance cycles are tracked to calculate the length of maintenance cycles and penalty costs related to prolonged maintenance cycles. For exceeding the prescribed length of maintenance cycles, the calculation of penalty cost is based on the number of days exceeding the limit multiplied by the daily fine. When a maintenance task is completed, the outputs on the maintenance task is traced, including the maintenance type which is performed on components and the corresponding costs and times.

Based on the daily operation of offshore wind turbines, the total production losses due to failure and maintenance implementation can be calculated. To estimate the wind farm's total production losses, wind turbines' electricity production is calculated individually and finally accumulated. The relationship between the wind speed at the hub level w_l and the generated power P_l^{w} at day l is given as

$$P_l^{\mathrm{w}} = \begin{cases} 0, & v_l < v^{\mathrm{ci}} \text{ or } v_l > v^{\mathrm{co}} \\ P^{\mathrm{r}}(a + b v_l + c v_l^2), & v^{\mathrm{ci}} \le v_l \le v^{\mathrm{r}} \\ P^{\mathrm{r}}, & v^{\mathrm{r}} \le v_l \le v^{\mathrm{co}}, \end{cases} \tag{5}$$

where v^{ci} and v^{co} are the cut-in and cut-out wind speeds respectively; v^{r} is the rated output wind speed; P^{r} is the rated output power; parameters a, b, and c are given as

$$a = \frac{1}{\left(v^{\mathrm{ci}} - v^{\mathrm{r}}\right)^2}\left[v^{\mathrm{ci}}\left(v^{\mathrm{ci}} + v^{\mathrm{r}}\right) - 4 v^{\mathrm{r}} v^{\mathrm{ci}}\left(\frac{v^{\mathrm{ci}} + v^{\mathrm{r}}}{2 v^{\mathrm{r}}}\right)^3\right], \tag{6}$$

$$b = \frac{1}{\left(v^{\mathrm{ci}} - v^{\mathrm{r}}\right)^2}\left[4\left(v^{\mathrm{ci}} + v^{\mathrm{r}}\right)\left(\frac{v^{\mathrm{ci}} + v^{\mathrm{r}}}{2 v^{\mathrm{r}}}\right)^3 - \left(3 v^{\mathrm{ci}} + v^{\mathrm{r}}\right)\right], \tag{7}$$

$$c = \frac{1}{\left(v^{\mathrm{ci}} - v^{\mathrm{r}}\right)^2}\left[2 - 4\left(\frac{v^{\mathrm{ci}} + v^{\mathrm{r}}}{2 v^{\mathrm{r}}}\right)^3\right] \tag{8}$$

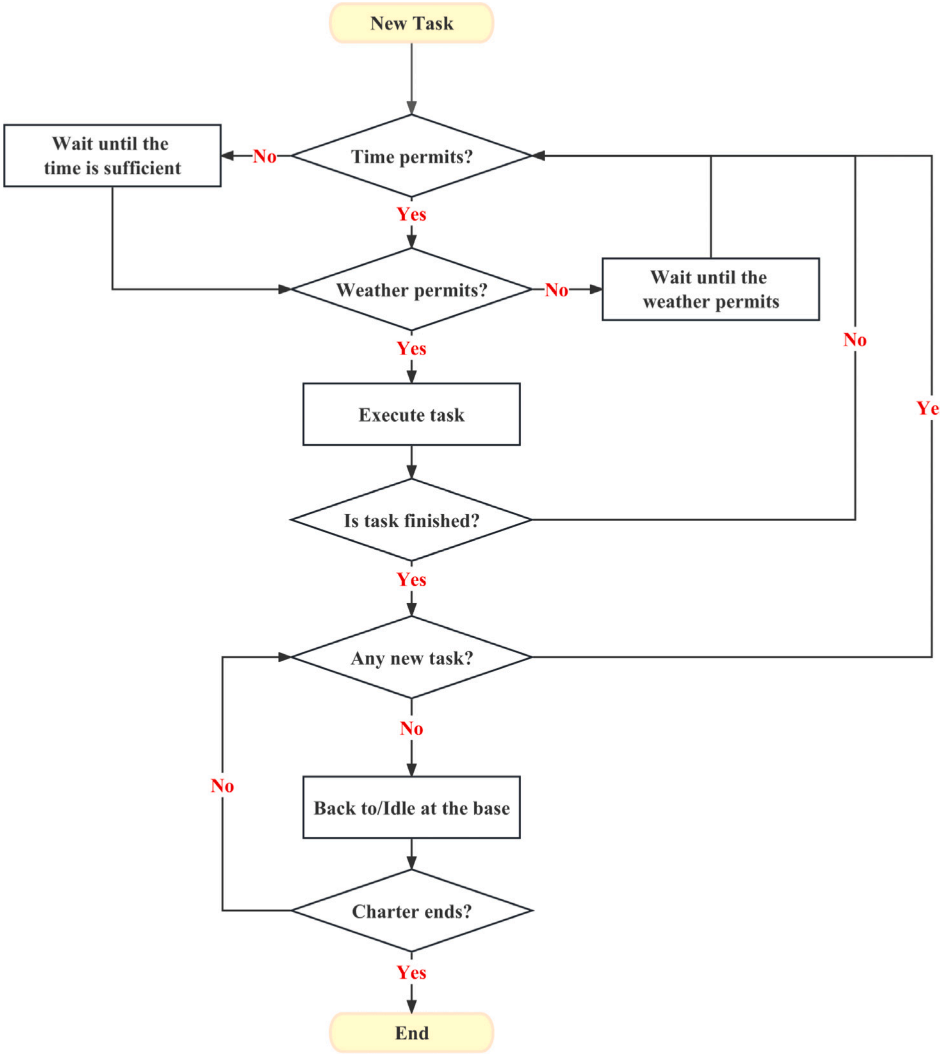

Fig. 4. Flowchart of maintenance operations of FSVs.

In addition, the outputs including the start and end time of mobilization and charter periods, whether the charter period is ended by the end of a maintenance cycle or by the end of the charter period, whether the chartered vessels are returned on time or late as well as the length of delay, and whether mobilization is stopped by the end of a cycle, are calculated. The technicians on the chartered vessels are paid based on the duration of the charter period while the technicians on an owned vessel are paid for the duration of the maintenance cycles. Then the costs of chartered vessels, mobilizations, and technicians can be calculated. Based on the number of round trips from base to the site and the number of inter-transits, the fuel cost for travelling can be calculated.

3. Optimization method

After inputting a specific configuration of the maintenance vessel fleet, a set of stochastic scenarios is generated with varying component lifetimes and metocean conditions by using Monte Carlo methods. The average total O&M costs in these stochastic scenarios are used to evaluate the expected economic performance of this fleet configuration. In order to make leasing decision to minimize costs, the optimization objective is set as

$$\begin{aligned} \min \quad & A_{\mathrm{c}}(X_{\mathrm{T}}^{\mathrm{HLV}}, X_{\mathrm{T}}^{\mathrm{FSV}}, X_{\mathrm{T}}^{\mathrm{CTV}}) = \frac{\sum_{s \in S}\left(C_s^{\mathrm{task}} + C_s^{\mathrm{penalty}} + C_s^{\mathrm{vessel}} + C_s^{\mathrm{loss}}\right)}{L_{\mathrm{P}}}, \\ \text{s.t.} \quad & N_s^{\mathrm{HLVC}}, N_s^{\mathrm{FSVC}}, N_s^{\mathrm{CTVC}} \in \mathbb{Z}, \end{aligned} \tag{9}$$

where C_s^{task} is the cost for maintenance tasks in sth maintenance cycle; C_s^{penalty} is the penalty cost once the maintenance cannot be completed within the required time period; C_s^{vessel} is the vessel-related costs, including the cost caused by charter, charter extension, mobilization, delayed return, fuel and technicians; C_s^{loss} is the cost caused by production losses; L_{P} is the length of offshore wind farm lifetime.

In order to find optimal solutions out of all possible solutions of this optimization problem, a metaheuristic algorithm, SA method, is used to evaluate potential solutions and perform a series of operations to find different and better solutions. The SA method is a versatile and robust heuristic solution strategy which offers a good balance between exploration and exploitation, making it a valuable tool for solving a wide range of optimization problems, and an acceptable answer for typical problems can be obtained in a reasonable time (Rutenbar, 1989; Li et al., 2023b; Centeno-Telleria et al., 2021). The algorithm is inspired by the physical process of annealing, which involves heating and then slowly cooling a material to reduce its defects and increase its stability.

First, an initial temperature is set, and an initial solution presenting the configuration of the vessel fleet is generated by randomly assigning values to each variable within the allowed range. The value of variables indicates the number of chartered vessels of various types. By applying this solution to the model, the simulation is executed to calculate the average total costs, representing the performance of this solution which is used as the energy of the current move.

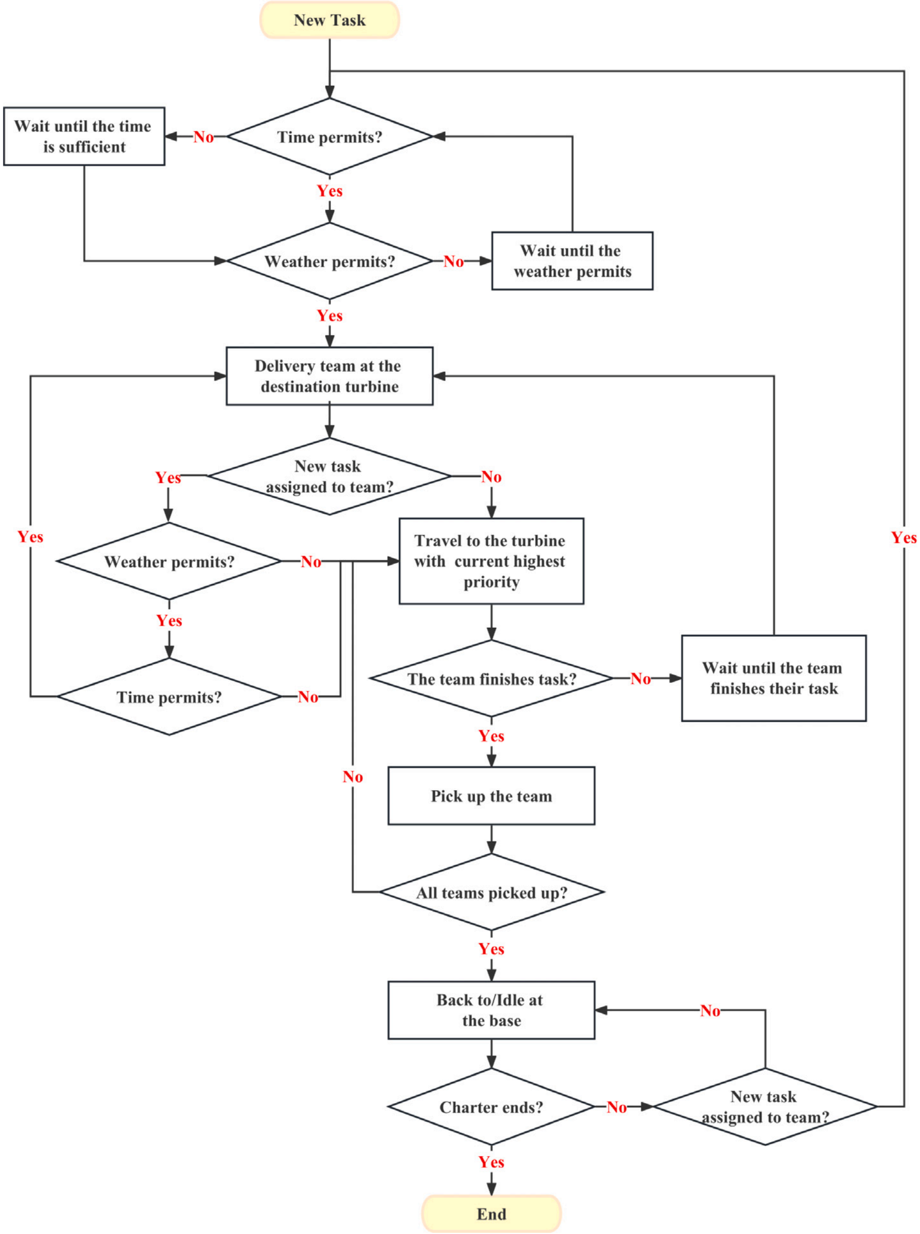

Fig. 5. Flowchart of maintenance operations of CTVs.

Next, a neighbouring solution is generated by making small, local changes to the current solution in order to explore the solution space. Again, by applying this new solution to the simulation model, the total costs, which is the energy of the new move, can be obtained. This function quantifies how good or bad the solution is in terms of the optimization goal.

Then a comparison between the initial solution and the new solution is performed by comparing their average costs obtained from the simulation, which are priorly mentioned as the energy at each move. If the new energy is lower than the initial energy, it means the average cost of the new solution is lower than that of the initial solution. The acceptance probability is 1, which means the new solution is definitely accepted. However, if the new energy is not lower than the initial energy, the solution is not directly rejected. By using the energy difference and the current temperature, the current acceptance probability can be calculated and its value is between 0 and 1. Based on the Metropolis criterion, another random variable from distributed uniform over (0,1) is used to make a probabilistic decision. If the acceptance probability is greater than the random variable, the new solution leading to larger energy will be accepted, while if not, the new solution will be rejected (Brooks and Morgan, 1995). The acceptance probability can be calculated as follows (Rutenbar, 1989):

$$P = \begin{cases} 1, & E(n+1) < E(n) \\ e^{-\frac{E(n+1)-E(n)}{T(n)}}, & E(n+1) \geq E(n), \end{cases} \tag{10}$$

where $E(n+1)$ is the energy of the next move and $E(n)$ is the energy of the current status, both of them are the evaluation results from the simulation; $T(n)$ is the current temperature.

Then the current temperature is updated according to the cooling rate as

$$T(n) = T_0 y^n, \tag{11}$$

where the starting temperature is T_0; the cooling factor is y; the cooling step is n. The cooling factor and cooling step are parameters that control the annealing schedule, specifically how the temperature decreases over time during the optimization process.

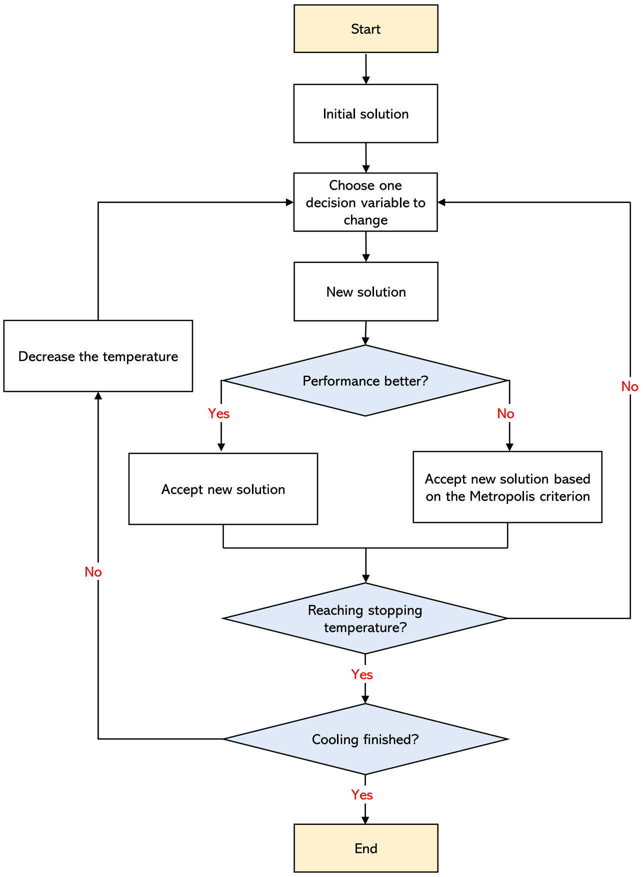

Fig. 6. The flow chart of the simulated annealing process.

The new temperature should be compared with the stopping temperature before starting the iterations. If the new temperature is still higher than the stopping temperature, it means the search for the optimal solution still goes on. Then based on the currently accepted solution, the previous steps will be repeated. One of the decision variables of the current solution is chosen for a change, a new solution will be generated and the energy at the new move will be compared with energy at the current move and based on which, it is decided whether the new solution will be accepted or not.

The above iterations of the algorithm keep running until reaching the stopping temperature, and the system is considered to have frozen (Brooks and Morgan, 1995). The final iteration ends when the final temperature is lower than the stopping temperature T_f, which can serve as the stopping criterion (Youssef et al., 2001), and the maximum number of cooling steps N can be calculated as

$$N = \left[\frac{\ln T_f - \ln T_0}{\ln y} \right] . \tag{12}$$

The procedure of the SA in this research is illustrated as the flow chart shown in Fig. 6.

4. Case study

4.1. Scenario set-up

In this section, a generic offshore wind farm is used to evaluate the performance of the developed model. The parameters for offshore wind farms and turbines as well as critical components are listed in Tables 4 and 5 (Dalgic et al., 2015a; Sarker and Faiz, 2016).

The number of vessels owned by the decision maker is one CTV when the offshore wind farm begins to operate. The vessel-related parameters are concluded in Table 6 (Dalgic et al., 2015a). Inter-transit time is the time for different vessels to move between two turbines inside offshore wind farms, and the time of a maintenance team entering turbines is included. Minimum working window means the time window that must be available for a vessel or team to work on a maintenance task before it starts/resumes. The maximum number of parallel teams indicates the number of teams on each vessel that can work on different maintenance tasks simultaneously. The daily penalty factor is the extra cost of the exceeded days for those chartered vessels that return after the charter period has ended. Safety margin is the required time for a team of technicians to leave the turbine and enter the vessel in terms of safety.

Table 4
Parameters of wind farms, wind turbines, and maintenance cycles (Dalgic et al., 2015a; Sarker and Faiz, 2016).

No	Input	Value	Unit
1	Number of turbines	50	turbine
2	Distance from shore	50	km
3	Simulation time horizon	15	year
4	Shift start	08:00	hh:mm
5	Shift end	20:00	hh:mm
6	Rated power output	3.6	MW
7	Rated output wind speed	13	m/s
8	Cut in speed	4	m/s
9	Cut out speed	25	m/s
10	Hub height	77.5	m
11	Prescribed length of maintenance cycles	60	day

Table 5
Lifetime parameters for critical components (Dalgic et al., 2015a; Sarker and Faiz, 2016).

Component	Weibull shape parameter (days)	Weibull scale parameter
Rotor	3	3,000
Bearing	2	3,750
Gearbox	3	2,400
Generator	2	3,300

Table 6
Maintenance vessel-related parameters (Dalgic et al., 2015a).

No	Input	Value			Unit
		HLV	FSV	CTV	
1	Travel speed	11	13.5	24	knot
2	Inter-transit time	40	40	20	min
3	Minimum working window	X	120	60	min
4	Technicians on-board	24	12	12	person
5	Maximum parallel teams	1	1	4	team
6	Limit wave height	2.8	2	1.7	m
7	Limit wind speed at sea	36.1	25	25	m/s
8	Limit wind speed at hub	15.3	–	–	m/s
9	Jack-up time	3	–	–	h
10	Jack-down time	3	–	–	h
11	Mobilization time	30	21	7	day
12	Charter length	30	30	30	day
13	Extend charter period length	15	15	15	day
14	Regular charter check	15	15	15	day
15	Cost coefficient for delayed return	2	2	2	–
16	Fuel consumption	0.55	0.2	0.24	mt/h
17	Safety margin	20	20	Y	min

X: The minimum working window for HLV is equal to the time required for its maintenance task.

Y: The safety margin of CTV is the total time of the maximum number of parallel teams times the inter-transit time, as well as the time required to travel back to base.

The inputs describing the maintenance strategy is summarized in Table 7 (Li et al., 2022b). The maintenance-related inputs include

Table 7
Classification of component health and corresponding vessel type (Carroll et al., 2016; Le and Andrews, 2016; Li et al., 2022b).

Maintenance type	Component age (%)	Zone	Age reduction	Vessel type	Technician number
No maintenance	[0, 50)	Zone 1	–	–	–
Minor repair	[50, 80)	Zone 2	30%	CTV	3
Major repair	[80, 95)	Zone 3	50%	FSV	6
Preventive replacement	[95, 100)	Zone 4	New component	HLV	8
Corrective replacement	≥100	Failed	New component	HLV	8

Table 8
Parameters for repair time and cost for maintenance actions on components (Li et al., 2022b, 2020b).

Component	Minor repair		Major repair		Preventive replacement		Corrective replacement	
	Time (h)	Cost (k€)	Time (h)	Cost (k€)	Time (h)	Cost (k€)	Time (h)	Cost (k€)
Rotor	9	4	18	15	70	60	100	185
Bearing	6	1	12	3.75	50	15	70	45
Gearbox	8	5	16	18.75	70	75	100	230
Generator	7	1.5	14	5	60	20	81	60

Table 9
Vessel cost-related parameters (Dalgic et al., 2015a).

No	Input	Value	Unit
1	Electricity price	150	€/MWh
2	HLV charter rate	110,000	€/HLV/day
3	FSV charter rate	10,000	€/FSV/day
4	CTV charter rate	2500	€/CTV/day
5	HLV mobilization cost	800,000	€/mobilization
6	FSV mobilization cost	200,000	€/mobilization
7	CTV mobilization cost	50,000	€/mobilization
8	HLV fuel cost	450	€/mt
9	FSV fuel cost	300	€/mt
10	CTV fuel cost	300	€/mt
11	HLV technician cost	100,000	€/technician/year
12	FSV technician cost	10,0000	€/technician/year
13	CTV technician cost	60,000	€/technician/year
14	Penalty cost	50,000	€/day

Table 10
Parameters of wave and wind conditions (Wagenaar and Eecen, 2009; Dalgic et al., 2015a).

No	Item	Value	Unit
1	Weibull shape parameter of wind speed (at 21 m)	2.43	–
2	Weibull scale parameter of wind speed (at 21 m)	8.58	m/s
3	Weibull shape parameter of wave height	1.58	–
4	Weibull scale parameter of wave height	1.1	m
5	Relevant height above sea	5	m
6	Wind speed coefficient	0.1	–

repair time and cost, which is listed in Table 8 . The parameters are collected and estimated from Carroll et al. (2016), Le and Andrews (2016), Li et al. (2022b, 2020b). The vessel costs are listed in Table 9 (Dalgic et al., 2015a). The metocean conditions are listed in Table 10 (Wagenaar and Eecen, 2009; Dalgic et al., 2015a).

The model is developed by using Salabim, a discrete event simulation package in Python, running on an Intel Xeon 40-core-80-threads processor with 192 GB ddr4 memory. The scenarios are randomly generated 20 times by Monte Carlo methods to estimate the performance of the maintenance fleet. The range of $X_{\mathrm{T}}^{\mathrm{HLV}}$, $X_{\mathrm{T}}^{\mathrm{FSV}}$, $X_{\mathrm{T}}^{\mathrm{CTV}}$ is [1,200]. The SA parameters are set as: initial temperature is 100 °C; stopping temperature is 4 °C; cooling factor is 0.5; cooling step is 5; inner loops at each temperature is 40; number of iterations is 200 (Olberts, 2021).

4.2. Results

The computational time for solving the optimization problem is about 30.3 h. The optimal number of HLVs, FSVs, and CTVs which are chartered in each maintenance cycle are shown in Table 11. The obtained values of variables are $X_{\mathrm{T}}^{\mathrm{HLV}} = 6$, $X_{\mathrm{T}}^{\mathrm{FSV}} = 24$, $X_{\mathrm{T}}^{\mathrm{CTV}} = 150$. In Table 11, the combination of three numbers illustrates the chartered number of each type of vessel. For example, the result is (1,2,0) in 14th cycle in SET1 simulation, indicating one HLV and two FSVs are charted. Given that one CTV has been owned, the vessel fleet in this maintenance cycle is composed of one HLV, two FSVs, and one CTV.

The results indicate that HLV is necessary in every maintenance cycle since both preventative replacement and corrective replacement, which are the two triggers that initiate maintenance cycles. The number of chartered HLVs is always one, because the required number of replacements is small. In most maintenance cycles, one FSV and one CTV are sufficient to complete maintenance on time. Since there has been one owned CTV, the number of the chartered CTV is zero. More than one FSVs and CTVs are still required in a few situations, which usually happen at the middle or end of the wind farm lifetime. The reason is that the maintenance can keep up with the degradation of the components at the early stage. With the degradation of components, more maintenance actions are demanded and the required number of vessels rises consequently.

Table 12 lists the O&M costs of the optimal solution compared to other solutions. The decision variables in this model are $X_{\mathrm{T}}^{\mathrm{HLV}}$, $X_{\mathrm{T}}^{\mathrm{FSV}}$, and $X_{\mathrm{T}}^{\mathrm{CTV}}$, indicating the number of maintenance tasks that the vessel is ‘desired’ to complete. We increase and decrease the values of each variable by 200% and 300%, respectively, and also decrease them by 50% and 33%. It is noted that the range of variables are [1,200]. Thus, even though the value of $X_{\mathrm{T}}^{\mathrm{CTV}}$ increases to 200% and 300%, the values can only been taken up to the upper limit of 200. Solution 1 is the optimal solution. The remaining solutions are based on Solution 1 and represent unoptimized solutions or the decision maker’s decision basis for leasing vessels based on historical experience.

The decrease in each variable represents a reduction in the vessel’s capacity to complete tasks, resulting in the deployment of more vessels to handle the same amount of work. Conversely, the increase in each variable represents an increase in the vessel’s capacity to complete tasks, resulting in the deployment of fewer vessels for the same workload. However, the decrease of values of the variables does not necessarily mean that fewer vessels will always be deployed in all cases. When the workload is low, an increase in the value of the decision variables does not result in a decrease in the number of vessels deployed, because the vessels’ capacity may already exceed the workload. For example, in solution 3 and 5, the increase of the

Table 11
Optimal mixed fleet of leased vessels across different maintenance cycles in random scenarios.

Maintenance cycle	Scenario																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1,0,0	1 0,0	1,0,0	1,1,0	1,1,0	1,1,0	1,0,0	1,0,0	1,0,0	1,1,0	1,0,0	1,0,0	1,0,0	1,0,0	1,0,0	1,0,0	1,1,0	1,0,0	1,0,0	1,1,0
2	1,1,0	1,0,0	1,0,0	1,1,0	1,0,0	1,0,0	1,0,0	1,0,0	1,1,0	1,0,0	1,1,0	1,1,0	1,0,0	1,1,0	1,1,0	1,0,0	1,1,0	1,1,0	1,0,0	1,1,0
3	1,1,0	1,1,0	1,0,0	1,1,0	1,1,0	1,1,0	1,0,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,2,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,0,0	1,1,0
4	1,1,0	1,1,0	1,1,0	1,1,0	1,0,0	1,1,0	1,0,0	1,1,0	1,1,0	1,1,0	1,0,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0
5	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,0,0	1,0,0	1,1,0	1,1,0	1,1,0	1,1,0	1,0,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0
6	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0
7	1,1,0	1,1,0	1,1,0	1,2,0	1,1,0	1,1,0	1,1, 0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,1	1,1,0	1,1,0
8	1,1,0	1,1,0	1,1,0	1,0,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,1	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0
9	1,2,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,1	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0
10	1,2,0	1,1,0	1,1,0	1,2,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,1	1,1,1	1,2,0
11	1,1,0	1,1,1	1,1,0	1,2,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,1	1,1,0	1,1,0	1,1,0	1,2,1	1,1,0	1,2,1	1,1,1	1,2,0
12	1,1,0	1,1,0	1,1,1	1,2,0	1,2,0	1,1,0	1,1,1	1,1,0	1,1,0	1,1,0	1,1,0	1,1,0	1,1,1	1,1,0	1,1,0	1,2,0	1,1,0	1,1,0	1,2,1	1,1,0
13	1,2,0	1,2,0	1,1,0	–	1,1,0	1,1,0	1,2,0	1,1,0	1,1,0	1,1,0	1,2,0	1,1,0	1,1,0	1,2,1	1,1,0	1,2,1	1,2,0	1,2,0	1,2,0	1,2,0
14	1,2,0	1,1,0	1,1,0	–	1,1,0	1,1,0	1,2,0	1,2,0	1,1,0	1,2,0	1,1,1	1,1,0	1,1,0	1,1,1	1,1,0	1,2,0	1,1,0	–	1,1,1	–
15	–	1,2,0	1,1,0	–	1,1,0	1,2,0	1,2,0	1,2,0	1,1,1	1,1,1	1,2,0	–	1,1,1	–	–	–	–	–	1,2,1	–
16	–	–	1,2,0	–	1,1,0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
17	–	–	–	–	1,1,0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

Table 12
O&M costs of the optimal solution compared to other solutions.

Solution	Vessel type	Change	Values of variables	Annual cost (k€/year)	Portion (%)
1	-	-	(6, 24, 150)	6354.5	100.0
2	HLV	Decrease to 50%	(3, 24, 150)	6487.3	102.1
3		Increase to 200%	(12, 24, 150)	6354.5	100.0
4		Decrease to 33%	(2, 24, 150)	7085.3	111.5
5		Increase to 300%	(18, 24, 150)	6354.5	100.0
6	FSV	Decrease to 50%	(6, 12, 150)	6590.1	103.7
7		Increase to 200%	(6, 48, 150)	6439.6	101.3
8		Decrease to 33%	(6, 8, 150)	6852.9	107.8
9		Increase to 300%	(6, 72, 150)	6439.6	101.3
10	CTV	Decrease to 50%	(6, 24, 75)	6399.9	100.7
11		Increase to 200%	(6, 24, 300)	6376.2	100.3
12		Decrease to 33%	(6, 24, 50)	6588.8	103.7
13		Increase to 300%	(6, 24, 450)	6376.2	100.3
14	HLV, FSV, CTV	Decrease to 50%	(3, 12, 75)	6728.7	105.9
15		Increase to 200%	(12, 48, 300)	6435.6	101.3
16		Decrease to 33%	(2, 8, 150)	7493.7	117.9
17		Increase to 300%	(18, 72, 450)	6435.6	101.3

variable value relevant to HLV does not bring change in annual costs. The reason is that, in maintenance cycles, the number of replacement tasks does not exceed the optimal solution's variable value. Therefore, even if the value has increased, there is still only one HLV chartered in maintenance cycles. This can also explain why the impact of the increase in the value on the annual cost is greater than the impact of the decrease in the value.

Overall, the changes in decision variables related to HLV and FSV have a greater impact than those related to CTV. A decrease in the values may lead to a tendency for decision makers to charter more vessels. Although repairs are expected to be accomplished in a shorter period of time, additional costs may be resulted in due to redundancy in the number of vessels. Conversely, an increase in the value leads to an insufficient number of vessels being leased and repairs not being completed efficiently. Compared to solution 1, other solutions may result in up to an additional 17.9% O&M costs.

The total electricity production in different scenarios is shown in Fig. 7. The random component lifetime and stochastic metocean conditions, including wave height and wind speed, vary in various scenarios, thus electricity production is different consequently. When offshore wind turbines operate well under wind speeds which are appropriate for power production, the value of electricity produced can be higher than in unfavourable situation. Fig. 8 displays the time-based and power-based availability, which are important outputs. Time-based availability represents the average of the ratio of total operating time to lifetime for wind turbines. The power-based availability further considers the influence of weather conditions on wind power to estimate the power production capacity.

Fig. 9 illustrates the time of occurrence of maintenance cycles in simulated scenarios. In the figure, the relative location of each maintenance cycle in scenarios to the entire time horizon is shown from a down-to-up perspective to the vertical axis. The width of each bar depicts the length of each maintenance cycle. Table 13 shows the length of maintenance cycles in different scenarios. It is clear that the number of maintenance cycles vary depending on the circumstances. The lifespan of each turbine component varies in different scenarios, and the component with a longer lifetime has a lower likelihood of replacement, making it less frequently to initiate the maintenance cycle, thus the amount of maintenance cycles is less.

In addition, it can be found that the length of maintenance cycles also vary. The workload during maintenance cycles and the metocean conditions have a direct impact on this result. Maintenance tasks can be completed more efficiently when the weather is suitable for maintenance implementation. Maintenance cycles require less time if there are fewer maintenance tasks to be completed. The length of maintenance cycles required by decision makers is 60 days. The majority of the

Table 13
Length of maintenance cycles in scenarios.

	Scenario (days)																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Cycle 1	37	34	75	38	45	38	37	45	38	46	34	48	33	39	45	39	64	37	33	43
Cycle 2	47	39	33	38	38	55	48	33	89	34	43	35	44	35	37	54	48	48	37	45
Cycle 3	75	66	77	43	55	52	60	61	44	34	40	36	112	50	41	41	51	34	75	42
Cycle 4	37	41	33	40	37	64	42	42	37	38	35	49	58	39	40	34	70	60	68	39
Cycle 5	40	103	42	50	42	65	33	109	52	33	64	42	35	39	85	45	39	39	50	96
Cycle 6	49	68	67	52	50	39	39	36	38	46	41	51	59	42	63	49	37	39	44	34
Cycle 7	48	42	37	55	42	45	45	33	47	42	40	50	49	104	49	56	44	46	48	41
Cycle 8	57	42	42	42	82	104	51	47	61	54	48	68	43	47	52	47	48	64	38	52
Cycle 9	60	41	44	52	66	55	44	52	56	46	64	69	49	60	44	50	52	53	54	56
Cycle 10	44	45	51	45	47	51	44	51	56	52	53	52	51	66	50	54	52	48	48	56
Cycle 11	55	56	46	55	47	45	52	48	50	47	56	44	56	42	47	51	51	43	59	51
Cycle 12	47	54	56	67	52	51	54	55	59	47	50	51	49	50	48	49	51	62	46	60
Cycle 13	52	46	50	–	52	50	57	54	60	66	47	56	60	60	54	49	46	45	47	46
Cycle 14	46	55	56	–	59	61	47	45	43	48	51	53	57	59	51	59	56	–	42	–
Cycle 15	–	60	59	–	55	47	48	62	57	33	50	–	43	–	–	–	–	–	44	–
Cycle 16	–	–	49	–	51	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
cycle 17	–	–	–	–	53	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Total	694	792	817	577	873	822	701	773	787	666	716	704	798	732	706	677	709	618	733	661

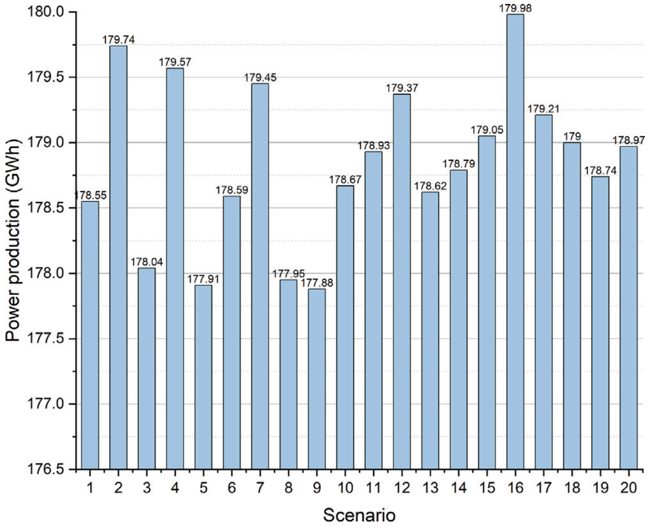

Fig. 7. Electricity production of offshore wind farms.

maintenance cycles last less than this length. When the maintenance cycle is shorter than the prescribed length, the penalty cost is zero; conversely, there will be additional penalty costs incurred.

Fig. 10 demonstrates the number of each type of maintenance tasks and associated costs. In each scenario, the bottom of four stacked bar graphs show the number of tasks for the corresponding maintenance type. Among all the maintenance tasks, the number of minor repairs dominates, followed by major repairs, preventative replacements, and corrective replacements. The maintenance strategy, where the component age and the related zone and age reduction are determined, have an impact on this result. The portion of each maintenance type fluctuates as the range of each zone changes. The component lifetime also has an impact on how many tasks are performed. For the components with longer lifetime, it takes more time to enter their repair zones. In addition, the major repair postpones the ensuing maintenance tasks, since the major repair improves the condition of components with longer lifetime more significantly. From the perspective of maintenance costs, the proportion of costs spent on different maintenance tasks varies less significantly. The reason is various types of maintenance on different components consume much different costs. For instance, the cost of the corrective replacement is far higher than minor repairs, causing an increase in the proportion on cost bars, despite the fact that the number of corrective replacement is very small.

4.3. Sensitivity analysis

As the outputs of the simulation model are affected by many inputs, a sensitivity analysis on important inputs is performed to test different values for the verification as well as to evaluate how these inputs influence the results, which could serve as a reference for wind farm developers/researchers.

The concerned input parameters are Weibull scale parameter of climate input, maximum parallel teams number on CTV, penalty cost, charter length, range of component age zone. These inputs are key parameters in the model, directly affecting the vessel organization and leasing decisions, thus a sensitivity analysis is performed on these input parameters. The values of the parameters increase by 50% and decrease by 50%. The results of sensitivity analysis are shown in Table 14, where the upward arrow presents the increased value and where the downward arrow presents the decreased value.

The balance between the number of chartering vessels and the lengths of maintenance cycles is significant to the total costs. If more vessels are chartered, maintenance tasks are performed more efficiently and the length of maintenance cycles is shorter. However, in this case, more vessels lead to more charter costs. On the other hand, if the fleet size is not sufficient enough for the maintenance tasks, the maintenance cycle has to be prolonged, thus the penalty cost will be charged when the required date is exceeded. It can be seen that the changes in penalty have no influence on the costs except for the annual penalty cost, hence the total O&M costs are very close.

In terms of the changes in the climate Weibull scale parameter, when the parameter decreases to be 0.5 times, there is a general decrease in every costs, and the cost of production loss decreases outstandingly. Nevertheless, when the scale parameter becomes larger, meaning that the metocean conditions become worse, the influence is very significant. The costs of the vessel travelling, vessel chartering, penalty and production loss are extremely different from the original results. Under extreme metocean conditions, the weather changes drastically, the minimum working window of HLV can never be satisfied and it keeps waiting for suitable conditions. Thus, once the maintenance cycle starts, no maintenance cycle is completed and it lasts until the end of the wind farm lifespan. Minor repairs contribute the most to the cost of maintenance tasks while replacement will never be performed.

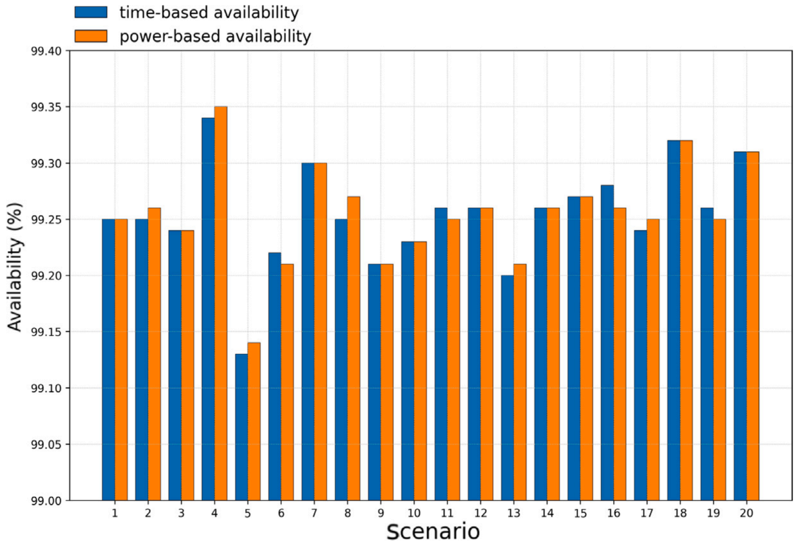

Fig. 8. Time-based and power-based availability of the offshore wind farm.

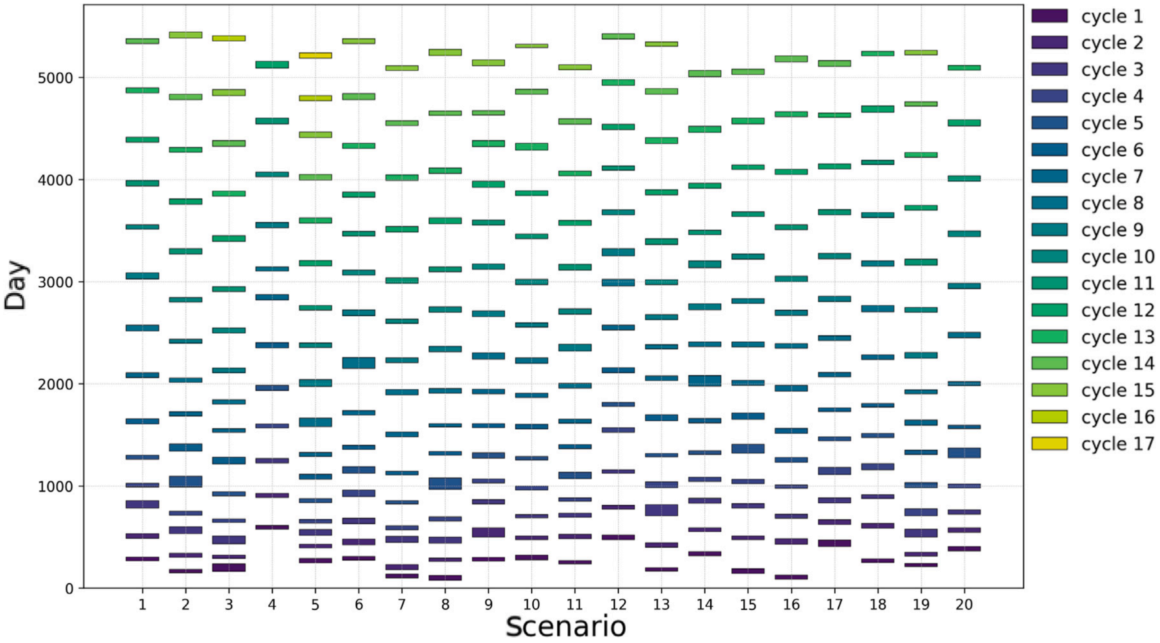

Fig. 9. Time of occurrence of maintenance cycles in simulated scenarios.

Table 14
Influences of different factors on annual costs.

Description	Change	Annual cost (k€/year)					
		Vessel travelling	Vessel chartering	Repair tasks	Penalty	Production loss	Total
Benchmark	–	19.2	5052.8	522.8	88.0	671.6	6354.5
Climate parameter	↑	6.8	15 908.8	110.1	17 205.2	89 655.1	122 886.0
	↓	15.4	4670.8	513.4	40.8	49.2	5289.7
Component zone	↑	27.0	4755.9	666.4	63.5	867.6	6380.4
	↓	15.8	6543.8	517.4	429.0	712.1	8218.1
Charter length	↑	19.2	6653.4	522.9	87.5	672.4	7955.4
	↓	19.6	3879.1	525.0	106.0	673.9	5203.6
Penalty cost	↑	19.2	5052.8	522.8	44.0	671.6	6310.5
	↓	19.2	5052.8	522.8	132.0	671.6	6398.5
CTV teams	↑	17.5	5094.0	520.9	93.7	699.0	6425.1
	↓	24.9	5290.8	515.1	1020.0	682.6	7533.4

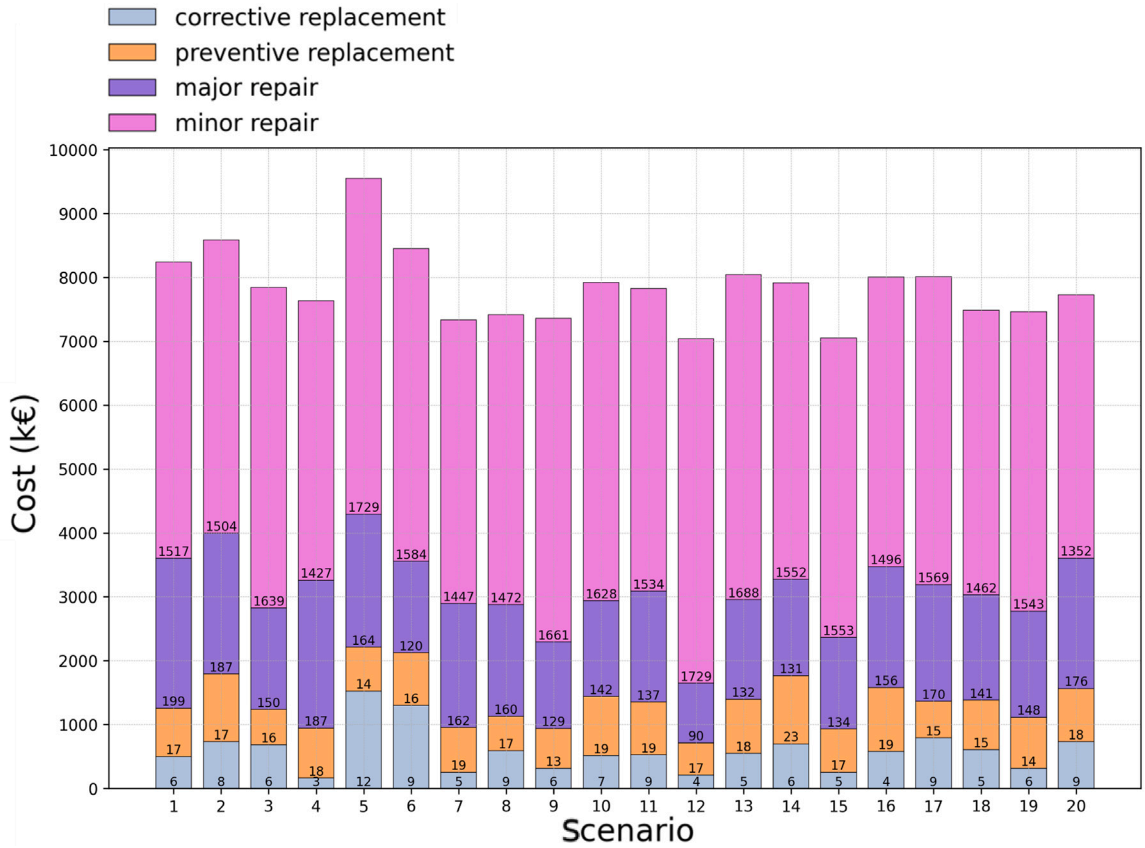

Fig. 10. Number of different types of maintenance tasks and associated costs.

In the aspect of the charter length, the differences reveal important information. Compared with the benchmark, the cost of maintenance tasks when the charter length is longer is not significantly different. However, the longer charter length means that in the first several maintenance cycles with a low number of tasks, vessels quickly finish the tasks and have to wait until the end of the charter length, during which the charter cost is still charged. When meeting a similar number of tasks, the longer charter length will lead to the waste of vessel utilization and lead to an obvious increment of the total charter cost. Conversely, the short charter length goes in another direction where the charter is more flexible. Given a shorter initial charter length, the charter length can be extended when needed, and each charter can be made good use of, leading to the remarkable saving on the total charter cost.

The changes in the range of the component age zone also result in different costs. When the length of each component zone becomes 1.5 times larger, this implies that the scope of maintenance has increased, and there are more components that require repair or replacement within the scope. What happens in this situation is that, components have fewer possibilities to fail because they can be fixed at an early age, thus, the number of the most expensive maintenance task, i.e., replacement due to failure, substantially decreases, and the cost can be saved a lot. However, the amount of minor repairs and major repairs increases, leading to a sharp increase in their costs for maintenance tasks. Also, due to the frequent repair, more turbines need to stop running and the production losses climb. In contrast, shortening the component zone results in the accumulation of maintenance tasks because each component could only be repaired/replaced when its situation is very bad. Therefore, more vessels need to be used and longer maintenance cycles are needed to address this situation of increased tasks.

The changes in the maximum parallel team also result in fluctuations in the output results. The decrease in team number leads to insufficient resources for maintenance tasks, therefore, more time is needed and maintenance cycles need to be prolonged. More frequent activities are required and the travelling cost increases. On the other hand, the increment in the maximum parallel team does not mean a decrease in the total O&M cost. The number of maintenance cycles might increase due to the fact that maintenance tasks are completed faster and more triggers of starting a maintenance cycle can be reached. The reason is that the influence of maintenance activities on components, namely the value of age reduction, is more influential when the component is more aged. For example, at the beginning of a maintenance cycle, there are two components both with a lifetime of 1000 days. If a major repair reducing 50% current age is performed on the first component at day 1, its current age is reduced to $1000 \cdot 50\% =$ 500 days. If the other component is repaired at day 40, its current age is reduced to $(1000 + 40) \cdot 50\% = 520$ days. At this moment, the current age of the first component is $500 + 40 = 540$ days. In other words, it is not better to repair the parts earlier and faster in this case. If maintenance is performed too efficiently, the component will degrade sooner, potentially resulting in more failures and more maintenance cycles.

5. Conclusions

The high cost of O&M for offshore wind farms poses a challenge for the future development of the wind industry. This paper contributes to solving this problem, aiming to reduce O&M costs by configuring a sound maintenance vessel fleet, and finally enhances performance and competitiveness of offshore wind.

Given the number of available owned vessels, the decisions involve determining the number of each type of vessels to be chartered at various moments throughout the wind farm lifetime. Random component failures and stochastic metocean conditions are uncertainties affecting decision-making. In this paper, an O&M model based on discrete event simulation is developed to present how a mixed vessel fleet performs a series of maintenance operations under a long-term maintenance strategy. Under a specific fleet configuration, the overall O&M costs are evaluated by using the developed model. A metaheuristic algorithm, SA method, is used to search for the optimal solution. The most economical leasing decisions are made to configure a mixed maintenance vessel fleet to support the implementation of maintenance activities with minimum total costs including vessel costs, production losses, repair costs, and penalty cost.

A computational study was conducted to investigate the value of the model. The results show that the model can be used to solve the fleet mix and size problem. The sensitivity analysis shows the offshore environment is the most influential factor for maintenance implementation and directly affects the progress of conducting tasks, followed by the length of the charter contract, the team configuration of CTV, and penalty costs. The proposed model can be used as a decision-making tool to manage maintenance fleet and improve the O&M for offshore wind sector.

However, there are still limitations in this research, resulting in gaps between O&M simulations and reality. These gaps and potential directions for future developments are listed below:

(a) While this study mainly considers short-term rentals of 15 and 30 days, vessel rental contracts is more diverse in practical situations. Rental contracts can last for months or even years in reality. Similarly, the impact of personnel rental contracts on O&M has not been considered in this paper. Personnel can be further divided based on their skills and task types, which is worth further research in the future.

(b) This paper has not considered the situation where multiple teams work on site during maintenance operations. In reality, O&M may be accomplished through collaboration among teams such as the Original Equipment Manufacturer (OEM) teams, substation and export cable teams, Balance Of Plant (BOP) teams. The potential synergy and conflicts among these teams are worth studying.

(c) In actual O&M, many repair campaigns are a result of regular summer inspections and some repairs occur at the beginning of the turbine's lifespan due to installation errors. These factors should be taken into account in future models to make the model more realistic.

(d) The metocean condition is one of the most critical influencing factors in actual O&M. While it is assumed that metocean conditions are known in advance in this paper, metocean conditions are highly unpredictable in reality and may introduce significant uncertainty and challenges to maintenance operations. Maintenance tasks may be interrupted due to inclement weather in practice, which has not been considered in this paper. In addition, a maintenance task may involve multiple stages, such as lifting parts, personnel boarding the turbine, and personnel performing maintenance. The safety regulations for each stage should be followed to determine whether the maintenance task can proceed. The maintenance tasks in this study have not been further divided into these stages. This is also a limitation of this study. Future research should take these factors into account.

(e) The installation of wind turbines requires a vessel fleet that is similar to the one used for O&M. In the future, it would be interesting to modify the model to adapt to offshore wind farm installation.

(f) It is assumed that repair times are constant in this paper, but maintenance is carried out in complex and dynamic conditions, making repair times random in reality. This is an interesting factor worthy future research.

(g) This paper has not fully considered the lack of vessels in the rental market and the unavailability of spare parts. Delays and cancellations in maintenance activities due to the unavailability of maintenance resources are worth consideration in future.

CRediT authorship contribution statement

Mingxin Li: Writing – original draft, Methodology, Investigation, Conceptualization. **Bas Bijvoet:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Kangjie Wu:** Writing – original draft, Software, Investigation, Formal analysis. **Xiaoli Jiang:** Writing – review & editing, Supervision. **Rudy R. Negenborn:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Xiaoli Jiang reports financial support was provided by Nederlandse Organisatie voor Wetenschappelijk Onderzoek. Mingxin Li reports financial support was provided by Chinese Scholarship Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Further reading

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