Optimization of vessel fleet size and mix for offshore wind farm maintenance based on a simulation method

Master thesis

Kangjie Wu

ME54010 - Report number - 2023.MME.8803

TU Delft

Optimization of vessel fleet size and mix for offshore wind farm maintenance based on a simulation method

Master thesis

by

Kangjie Wu

in partial fulfilment of the requirements for the degree of
Master of Science
in Mechanical Engineering

at the Department Maritime and Transport Technology of Faculty Mechanical, Maritime and Materials Engineering of Delft University of Technology

Student number:	5237920	
MSc Track:	Multi-Machine Engineering	
Report number:	2023.MME.8803	
Supervisor:	Prof. Dr. ir. X. Jiang	
	PhD candidate M. Li	
Project duration:	September 15th, 2022 - May 2023	
Thesis committee:	Prof. Dr. ir. X. Jiang	TU Delft supervisor
	Prof. Ir. M.B. Duinkerken	TU Delft committee member
	PhD candidate M. Li	TU Delft supervisor

Acknowledgement

First of all, I would like to express my appreciation from the bottom of my heart to my parents and family members who supported me when I decided to pursue my master's degree in a new country. With their endless love, I have no fear when I encounter any challenges and barriers because I know they are always standing behind me.

Also, I would like to thank every friend I met in the past 2.5 years. They taught me kindness, independence, confidence, patience as well as enthusiasm with their tolerance and behaviors. They are my precious on this long journey and they made me firmly believe that I am never alone. Especially, when there was a tough time during the COVID-19, every new friend and every old friend are all flashlights in the darkness and they used their energy to cheer me up and make my life back to bloom, all of which I would cherish for the rest of my life.

What is more, I would like to thank TU Delft and the professors of the Maritime and Transport Technology department because they provided me with a great chance for this master's study and they shared their knowledge with us students. From each course, I obtained much information related to both the mechanical and logistics areas. Importantly, in this graduation project, Xiaoli and Mingxin used their professional knowledge and abundant experiences to lead me in the right direction each time I am struggling and made me grow in the academic area. Also, thanks to Bas for his sharing brilliant ideas and patiently answering my questions, which inspired me a lot.

Last but not least, I want to say a big thanks to myself, who never gives up no matter how difficult the situation, who always stands up when beaten down, who forever knows, O ever youthful, O ever weeping.

Again, thanks for everything life has brought to me!

Kangjie Wu
Delft, April 2023

Abstract

The research on sustainable energy is growing, among which, wind energy catching growing attention and the potential has been supported by more and more countries. Compared with onshore wind farms, offshore wind farms have more advantages including the abundant wind resource at the offshore location and more possible construction areas. While for an offshore wind farm, the operation and maintenance cost is the most significant part and fleet management contributes a lot to it.

In order to optimize the fleet size and mix problem for an offshore wind farm based on a simulation method, this thesis has performed a few research steps. Firstly, a literature view on the modeling methods of fleet size and mix problems for offshore wind farms is finished. Different modeling methods and different factors considered in the model are viewed. Then, two simulation models, the open-loop simulation model and the feedforward simulation model, are introduced, including the model inputs, model agent and process, and model outputs. Afterward, the simulation-optimization methodology is introduced and the optimization algorithm used in this research is introduced. Next, one case study using two models separately for a long-term optimization and a short-term optimization is executed and followed by the results of these two simulation models as well as the comparison of the results from them.

This thesis aims to combine the optimization method with a simulation model for offshore wind farms, which can be regarded as a decision support tool for fleet size and mix problems and is expected to be a practical technology for the operator/researcher of the offshore wind farm in the future.

Keywords: Offshore wind farm, Operation and maintenance, Logistics, Simulation model, Control model, Optimization, Simulated Annealing, Fleet size and mix problem, Agent, Salabim

Contents

Nomenclature

$N_{\mathrm{C}}^{\mathrm{CTV}}$	The number of chartered CTV
α	The cooling factor of the simulated annealing
C^{*}	The total O&M cost
C_{Cycle}	The cost for the maintenance cycle
C_{Loss}	The cost for the production loss
C_{Task}	The cost for the maintenance tasks
C_{Vessel}	The cost for the vessel related
N_{S}	The number of a set of scenarios
$N_{\mathrm{C}}^{\mathrm{FSV}}$	The number of chartered FSV
$N_{\mathrm{C}}^{\mathrm{HLV}}$	The number of chartered HLV
N_{C}^{V}	The number of chartered vessel type V
N_{F}^{V}	The number of vessel type V in the fleet
$N_{\mathrm{O}}^{\mathrm{CTV}}$	The number of owned CTV
$N_{\mathrm{O}}^{\mathrm{FSV}}$	The number of owned FSV
$N_{\mathrm{O}}^{\mathrm{HLV}}$	The number of owned HLV
N_{O}^{V}	The number of owned vessel type V
$N_{\mathrm{T}}^{\mathrm{CTV}}$	The number of tasks requiring CTV
$N_{\mathrm{T}}^{\mathrm{FSV}}$	The number of tasks requiring FSV
$N_{\mathrm{T}}^{\mathrm{HLV}}$	The number of tasks requiring HLV
N_{T}^{V}	The number of tasks requiring vessel type V
P^{r}	The rated output power at the rated output wind speed
T_0	The starting temperature of the simulated annealing
v^{ci}	Cut-in wind speed
v^{co}	Cut-out wind speeds
v^{r}	The rated output wind speed

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1
Introduction

1.1. Background

Wind energy, as renewable and inexhaustible energy, has been focused on recently and more research is being investigated. The cumulative installed capacity of wind power in the European Union (EU) has been raised from 47.8 GW in 2006 to 153.7 GW in 2016, with an annual 12% increment[1][2]. The share of wind power in the EU's electricity supply was 10.4% in 2016, while it is predicted to achieve 20% by 2030[1][2]. In terms of the future outlook, it is expected that Europe will install 116 GW of new wind farms over the period from 2022-2026, during which EU-27 is expected to build on average 18 GW of new wind farms[3].

Compared with onshore wind energy, offshore wind energy has some advantages and it is expected to have great potential to obtain more support in the future. The first one is the wind resource having better quality when away from the land, where wind speed is usually stronger and softer, with the increasing distance to the coast. Also, compared with the limited land onshore, there is more space in the sea and wind farms can be installed, with reducing the environmental noise emission as well as reducing the visual impact from the coast[4].

However, the biggest disadvantage is that the cost of offshore wind farms is much higher than onshore wind farms[4]. Where, operation and maintenance (O&M) cost contributes about one-third of the life cycle cost of an offshore wind farm[5][6][7], which is even triple higher than that of an onshore wind farm[6][8]. What is more, 50% of O&M costs result from acquiring and operating a vessel fleet[9]. Therefore, it is significant to reduce the O&M cost and fleet management should be paid more attention.

1.2. Research question

This thesis's aim and objective lead to the main research question: How to obtain the optimal fleet size and mix for an offshore wind farm based on a simulation model?

The main research question is supported by the sub-research questions as followed:

1. What are the state-of-the-art modeling methods for fleet size and mix problems for offshore wind farms? And what are the research gaps?

2. What inputs are considered in the model and what outputs are expected to obtain from the model?
3. What is the connection between inputs and outputs in the model?
4. What optimization method can be used to find the best solution? And what is the optimization objective of the problem?
5. How to execute the verification of the simulation model?

1.3. Scope

The scope of this thesis revolves around the fleet size and mix problem of O&M activities at offshore wind farms. The focus of this work is to combine the optimization method with the simulation model, which can be used for the optimal fleet management decision while minimizing the O&M costs for an offshore wind farm. The decision describes the number of vessels of each vessel type to be chartered at each maintenance cycle, based on the available number of owned vessels and the status of the wind farm. In this research, The objective is to minimize the cost, including charter costs, production loss costs, technician costs, penalty costs, and operational costs. This study also takes into account uncertainties tied to weather conditions and turbine component failures. The introduction of this model allows offshore wind farm operators or researchers to obtain an optimal result of the fleet size and mix within a decent time. All the inputs are flexible to adjust and all the outputs are detailed to illustrate the information of the offshore wind farm, which makes this model a valuable decision support tool for operators or researchers to execute analysis.

1.4. Scientific contribution

This thesis is part of the collaboration work with Mingxin Li and Bas Bijvoet. Mingxin did the opportunistic maintenance strategy part, which is one of the inputs of the simulation model. After that, together with the maintenance strategy given by Mingxin, Bas built an open-loop simulation model to determine the vessel fleet size and mix for offshore wind farms based on a specific preset time horizon. In this model, by defining the number of tasks for each vessel type, the development of an offshore wind farm from the very beginning can be simulated under the randomly generated scenario till the end of a specific time horizon, and the fleet configurations in different maintenance cycles can be known.

However, there are some limitations of the previous work that could be improved. Firstly, the previous model can only give a sight of the development of an offshore wind farm, the optimal result can only be known when all the decision variable combinations are tried in the simulation model, which is time-consuming and not ideal for the decision-making for the wind farm operator in real life. Secondly, all the simulations can only start from the beginning of the wind farm, when all the turbines are new and none of the components needs repair. What is more, all the simulations can only terminate at the end of the pre-defined time horizon of the wind farm. Thus, the beginning and the ending of the simulation are not flexible. Additionally, the decision variable combinations are used for the whole planning horizon, which means in the different maintenance periods, the decision-making is the same but it might not be suitable for all the periods.

Therefore, as an extension of the previous work and to improve all the disadvantages mentioned above, the first contribution of this thesis is to combine one optimization algorithm with the previous open-loop simulation model to find an optimal result of the vessel fleet size and mix problem for offshore wind farms within a decent time. Afterward, another contribution is to develop a feedforward simulation model based on the open-loop simulation model, and again combine the optimization method with the model to find the optimal result of the vessel fleet size and mix for each maintenance cycle.

1.5. Thesis structure

The thesis aims to answer the research question and the corresponding sub-questions, and the rest of the thesis will be structured as follows: in order to answer sub-question 1, the state-of-the-art of fleet management will be focused, and the literature review will be executed, marked as Chapter 2. Then in Chapter 3, the open-loop simulation model and feedforward simulation model will be in detail introduced, including the simulation input, simulation agents and the simulation output, thus sub-question 2 and sub-question 3 can be answered. Next, in Chapter 4, the simulation-optimization methodology will be introduced and the optimization method to obtain the optimal decision variables will be illustrated, where sub-question 4 will be answered.

Afterward, Chapter 5 will be dedicated to a case study, which provides inputs for both long-term optimization by using the open-loop simulation model with the optimization method, and short-term optimization by using the feedforward simulation model. And all the results, as well as the sensitivity analysis will be given, thus sub-question 5 will be answered. In the last Chapter 6, in light of previous chapters, some conclusions will be made and recommendations for future research will be given.

2
Literature Review

This chapter firstly gives a literature background regarding the framework of the maintenance logistics of offshore wind farms. After that, the modeling methods that have been used for the fleet management of offshore wind farms in the previous research will be reviewed, and some comparisons, as well as conclusions, will be displayed.

2.1. Framework of the maintenance logistics of offshore wind farms

From the classification theme proposed by [10], maintenance logistics in offshore wind farms can be categorized into three echelons, strategic, tactical and operational decision-making. These three echelons focus on various issues and challenges of different levels, which are shown as follows:

1. Strategic: Deal with decisions that have a long-lasting effect on O&M of the offshore wind farms, for example, the cost of the offshore wind farm's whole lifecycle.

2. Tactical: Typically include decisions that are updated anywhere between once a year and once every five years.

3. Operational: Refer to day-to-day decisions within offshore wind farms.

In the strategy echelon, Shafiee[10] summarizes four categories: wind farm design for reliability, location and capacity of maintenance accommodations, selection of wind farm maintenance strategy, and outsourcing the repair services.

In the tactical echelon, three categories are identified by Shafiee[10]: spare parts inventory management, maintenance support organization, and Purchasing or leasing decisions.

In the operational echelon, another three categories are mentioned by Shafiee[10]: scheduling of maintenance tasks, routing of maintenance vessels, and measuring the maintenance performance.

2.2. Fleet size and mix problem

In the tactical echelon, in order to solve the fleet size and mix problem, different solution methods are used in past research. Generally speaking, all these methods can be categorized into three main modeling methods, deterministic optimization modeling, stochastic programming modeling and simulation modeling. In the first two modeling methods, a mathematical model with an objective function and some corresponding constraints is built and solved. While for the simulation modeling, the results can be obtained after the maintenance activities are simulated. A literature review based on these three modeling methods will be researched and the analysis will be shown as follows:

2.2.1. Deterministic optimization modeling

In deterministic optimization modeling, all the parameters are assumed to be known and used in mathematical expressions. Halvorsen-Weare et al.[11] developed a deterministic optimization model for vessel fleet used for the offshore wind farm. In this paper, they used Mixed Integer Programming (MIP) to determine vessel types to purchase, vessel types to charter in, and some infrastructure, such as onshore and offshore vessel based, to use. Under the preventive and corrective maintenance strategy, the weather conditions, electricity price, the spot prices of charter-in contracts, the number of failures that lead to corrective maintenance operation and the characteristics of different vessels are all assumed as deterministic parameters. By considering soft and hard time windows for preventive maintenance activities, their model is trying to minimize the sum of many costs, including all the fixed costs of vessels and vessel bases, variable operating costs using at the wind farm, downtime costs of delayed preventive maintenance tasks and corrective maintenance tasks, penalty costs and transportation cost.

Similarly, in another paper[12], Gutierrez et al. also use a deterministic optimization model for the optimal fleet composition of vessels for offshore wind farm maintenance. In their proposed two-level model, what vessels to charter can be obtained at the first stage decisions, after that, the results can be used for the second stage decision, that is, how to support maintenance tasks. At the first level, what can be decided is which bases to use and which vessels should be available during the time horizon period. After that, for every possible scenario, in every period of the planning horizon, which maintenance activities to support by which vessel type can be known at the second level. By solving the Mixed-integer linear programming (MILP) problem, their objective is to minimize many costs which are very similar to the previous paper[11]. However, more constraints are taken into account in [12], for example, two shifts a day is considered, and three fixed bases with different capacities are also considered. Also, identically, in terms of the maintenance strategy, preventive and corrective maintenance are considered.

2.2.2. Stochastic programming modeling

Even though deterministic optimization models can be a useful tool to solve the fleet size and mix problem, the important uncertainty aspect of the real-life problem is ignored. In order to solve highly relevant real-life problems, stochastic programming

(SP) has been introduced, where the uncertainty is considered in many equivalent scenarios from a node-based scenario tree.

Gundegjerde et al.[13] first introduce stochastic programming for fleet size and mix problems. As a continuation of work done by Halvorsen-Weare et al.[11], a 3-stage stochastic programming model is proposed in this paper. The uncertainty in vessel spot rates, weather conditions, electricity prices and failures in the system are represented by four random variables and considered in the mixed integer programming (MIP) formulations. The objective function is to minimize the various costs of 3 stages. At the first stage, with the known spot rates from today's perspective, which offshore bases to acquire, the number of vessels of each vessel type to acquire, as well as the number of vessels to charter can be obtained. At this stage, no uncertainty is considered, thus, there is only one node in the scenario tree. In the second stage, some adjustments can be executed and the decision maker can decide to charter more vessels with new spot rates. Where, the uncertainty in vessel charter-in rates is deterministically considered to be high, medium, or low. While at the third stage, how the maintenance activities are executed by the available fleet can be known. And at this stage, uncertainty in weather conditions, electricity prices, and failures are deterministically sampled from a probability distribution. By doing this way, one scenario in paper[11] can be increased to many scenarios, ranging from 3 to 36. In this paper, preventive and corrective maintenance are considered.

Stalhane et al. in the paper[14] proposed a 2-stage stochastic optimization model. Compared with the work done by Gundegjerde et al.[13], they only consider the uncertainty of the weather data and the occurrence of corrective activities. Ignoring the uncertainty in the electricity price and vessels' charter rates can be acceptable because according to the paper [15] by Sperstad, vessels' limiting significant wave height for turbine access is found particularly sensitive, the vessel day rate is moderately sensitive while electricity price is less sensitive. Very similarly, the first stage decisions are about which bases to use, and which vessels to charter both on long time horizon and short time horizon, and the second stage decisions are about the decision of which vessel to support which maintenance activities on each day of each scenario, by using MILP(with vessel number variables relaxed). In terms of maintenance activities, preventive and corrective maintenance are both considered but in a different way in this paper.

Based on paper[14], Stalhane et al.[16] improve the 2-stage stochastic optimization model with a new decomposition method, ad-hoc Dantzig–Wolfe decomposition. By firstly introducing this method, different from classical decomposition methods like L-shaped or dual decomposition, parts of the second-stage problem still remain in the master problem. In order to solve this decomposed model, Stalhane et al. develop a matheuristic where a subset of the possible extreme points from the Dantzig–Wolfe sub-problems is apriorily generated. And in order to test the stability of the model, they adopt in-sample and out-of-sample tests based on the case from[17]. In terms of the maintenance strategy, this paper is also based on a combination of preventive and corrective maintenance tasks. However, Stalhane et al. mention a recent trend in the offshore wind industry is that moving from a preventive maintenance strategy to a condition-based maintenance strategy is expected by operators. Also, in a recent paper[18], Stalhane et al. propose a dual-level stochastic model considering uncertainties of both levels, including the first-level uncertainty related to electricity prices and subsidy levels, second-level uncertainty of weather conditions and demand for corrective maintenance handled, by solving many operational scenarios with a low number of time periods, rather than few scenarios with a large number of time periods, which is significantly different from earlier work. To solve the proposed model, one L-shaped method has been developed.

What is more, together with stochastic programming models, some heuristic and metaheuristic methods are combined. Elin E. Halvorsen et al.[19] introduce a metaheuristic solution method based on the stochastic mathematical model formulation of [14], which is a version of a greedy randomized adaptive search procedure - GRASP. They compared the GRASP results with the exact results of [14] and they found that the optimal vessel fleets are almost identical but GRASP methods has a great advantage in computation time. However, they only considered the number of vessels to charter in and out, but different charter lengths or changes to the wind farm over time are not considered. In paper [20], Kamilla et al. design the reactive GRASP heuristic for the stochastic programming model based on [18], with considering the same uncertainties of both levels as [18].

2.2.3. Simulation modeling

Very different from the previous two methods, without many mathematical expressions, the simulation modeling method is achieved by reconstructing the detailed development of discrete events, and the outputs, such as the total maintenance cost, will be determined after the maintenance activities simulation is done. By executing specific simulations for different fleet configurations, the optimal fleet size and can be known.

In the paper[21], Yalcin Dalgic et al. propose a Monte-Carlo-based simulation model, in which climate parameters, failure characteristics of different failure modes and different transportation systems conditions are simulated, to investigate the most cost-effective resource allocations including helicopter, crew transfer vessels(CTV), offshore access vessels(OAV), and jack-up vessels. Finally, they obtain the best 10 offshore wind farm O&M planning configurations and worst 10 configurations. In each configuration, shift start, OAV charter length, Jack-up vessel charter type, Jack-up vessel charter length, helicopter contract hour, preventive maintenance start month, technician allocation order, power based availability, total O&M cost are included and should be inputted before the simulation begins. In terms of the maintenance strategy, three different orders are considered: Corrective maintenance or preventive maintenance, Preventive maintenance after corrective maintenance, Preventive maintenance only after corrective maintenance.

Similarly, with the Monte-Carlo simulation process, Yalcin Dalgic et al. in the paper [22] introduce the mothership concept into a simulation model. After simulating 20 configurations of mothership, daughter and various chart types as well as different start/final chart months, the result of different cost distributions shows that mothership can greatly improve performance, thus authors suggest that in the future, a mothership needs to be considered in the far offshore wind farm. In the paper [9], Yalcin Dalgic et al. introduce an extensive methodology in the simulation for CTV fleet selection, and the result tells the importance of CTV capability. Thus it is suggested that, in the future, new generation CTVs with higher operational capabilities need to be considered, instead of simply increasing the size of the CTV fleet. While in the paper [6], Yalcin Dalgic et al. execute the investigation of optimum chartering strategy for jack-up vessels. From the simulation result, they suggest that jack-up mobilization time might be the main cause of the significant delays, therefore, it might be considered that chartering the vessel for the entire project life cycle for the non-small wind farms.

In the paper[17], Dinwoodie et al. compare four different operation and maintenance simulation models from [7][23][24][25]. The result shows that different modeling approaches and assumptions have a great influence on differences on the simulation results. They draw a conclusion that the modeler should pay high attention to four modeling assumptions that have an effect on the simulation results significantly, those are (1) possibility to perform parallel maintenance tasks in a shift, (2) approach of modeling failures(failures generated on a wind turbine with/without considering if the turbine is operating or not), (3) possibility to assign maintenance tasks to vessels when offshore, and (4) approach on modeling of charter options for heavy-lift vessels (A minimum HLV charter length of one month, or only charter an HLV for the minimum required period).

Resource sharing is also taken into account in some simulation model research. In [26], Michiel A.J. et al. present a simulation model to analyze two types of resource sharing between offshore wind farm service providers, one is vessel purchasing and sharing and another one is the combined use of vessel and harbor sharing. The results show that, the cost-sharing of jack-up vessels is possible to lower costs compared to the vessel leasing policy. The benefits of harbor sharing are relatively small to vessel sharing but become more significant if there is considerable congestion in the network.

2.3. Summary and conclusion

A summary of the previously mentioned literature is shown in Table 2.1, including the maintenance strategy, vessel types considered in the research, as well as the modeling methods and the corresponding solver. What is more, different costs involved in the literature and different time horizon are also listed in Table 2.1.

It can be seen from Table 2.1 that, in past research on the fleet size and mix problem for offshore wind farms, the quantity of the literature is limited. In terms of the modeling methods, most research used mathematical programming including deterministic optimization modeling or stochastic programming modeling. Only 6 papers used simulation models, in which most solver and their modeling processes are unknown. The combination of corrective maintenance and preventive maintenance is the most used maintenance strategy, while CTV and HLV are the most considered vessel types. Different costs can be considered in the model, depending on the modeling methods and the assumptions in the model. Plus, in order to obtain the decision on fleet size and mix, all papers used Monte–Carlo approach, with which the optimal result is found among all the scenarios they created. But such a method can only find the optimal solution among the given limited simulations.

Table 2.1: Literature summary

Year	Literature	time horizon	Maintenance strategy	Vessel type	Modeling methods: Mathematical programming	Modeling methods: Simulation	Solver	Cost: Charter	Cost: Fuel	Cost: Technician	Cost: Mobilisation	Cost: OEM	Cost: Fixed	Cost: Penalty	Cost: Production
2015	[21]	5 years	CM, PM	CTV, FSV, HLV, Helicopter		✓	/	✓	✓	✓	✓	✓	✓		✓
2019	[26]	20 years	CM	HLV		✓	/	✓	✓	Replacement cost			✓		✓
2015	[9]	/	CM, PM	CTV		✓	/	✓	✓	✓		✓			✓
2015	[6]	1 year	CM	HLV		✓	/	✓	✓	✓	✓	✓		✓	✓
2014	[23]	2 years	CM, PM	CTV, HLV, SOV		✓	AnyLogic	✓		✓		✓	✓		✓
2015	[22]	25 years	CM	CTV, HLV, Mothership, helicopter		✓	/	✓	✓	✓	✓	✓	✓		✓
2017	[19]	1 year	CM, PM	CTV, Mothership, Daughter ship SES, Small accommodation vessel	MILP		GRASP	✓		✓	✓	✓	✓	✓	✓
2019	[16]	1 year	CM, PM	CTV, FSV, HLV	SP model		Xpress	✓	✓	✓		✓	✓	✓	✓
2015	[13]	1 year	CM, PM	CTV, FSV, HLV, Helicopter, Multipurpose vessel	SP model		FICO™ Xpress	✓	✓	Operation variable cost			✓	✓	✓
2013	[11]	1 year	CM, PM	CTV, FSV, HLV, Helicopter, Multipurpose vessel	MIP		Xpress-IVE	✓	✓	Operation variable cost			✓	✓	✓
2022	[20]	1 year	CM, PM	CTV	SP model		GRASP	✓	✓	Operation variable cost			✓	✓	✓
2017	[27]	1 year	CM	HLV	SP model		SAA method	✓					✓	✓	✓
2016	[28]	25 years	CM, PM	CTV, FSV, HLV, Helicopter, Multipurpose vessel	SP model		FICO™ Xpress	✓	✓	Operation variable cost			✓		✓
2017	[12]	1 year	CM, PM	4 self-defined vessel	MILP		CPLEX solver	✓		Operation variable cost			✓	✓	✓
2020	[18]	1 year	CM, PM	CTV	SP model		L-shaped method FICO™ Xpress	✓	✓	Operation variable cost			✓	✓	✓

HLV = Heavy Lift Vessel, FSV = Field Support Vessel, CTV = Crew Transfer Vessel, CM = Corrective Maintenance, PM = Preventive Maintenance, GRASP = Greedy Randomized Adaptive Search Procedure, OEM = Original Equipment Manufacturers, SOV = Service Operation Vessels, SES = Surface Effect Ship, MILP = Mixed-Integer Linear Programming, SP = Stochastic Programming, SAA = Sample Average Approximation

In this research, the simulation method will be chosen and focused on as it has some outstanding advantages compared with the mathematical method.

Firstly, the simulation model is more realistic and dynamic, and this is its irreplaceable advantage compared with the mathematical method. The details of the discrete events are revealed and all the information and process can be traced back. On this point, however, the mathematical method needs some priorly known information, such as the annual corrective failure rate, which is unknown in reality and not realistic. Secondly, when using the simulation method, different fleet configurations can be simulated and the corresponding costs can be known after simulating the maintenance activities within the whole horizon. Some different fleet configurations can lead to similar costs, which can be a useful reference for the operators to make an analysis. Nevertheless, the mathematical method can only give one and only optimal result based on its objective function, and more potential analysis between different fleet configurations is not possible. Lastly, there is one characteristic of the simulation model is that, the detailed modeling is not publicly available but the other two models are publicly available and described in detail in their papers. This could be a double-edged sword because, on the one hand, the development and improvement of simulation model development will meet some barriers. But on the other hand, the model's uniqueness can be protected and have more potential commercial value in the future.

However, in this research, instead of using the Monte-Carlo approach, one optimization method will be introduced and used to find the optimal result of the simulation model in a wide range of possible decisions.

3

Simulation Modeling

In this chapter, the detail of both the open-loop simulation model and the feedforward simulation model will be detailed introduced. Firstly, a brief introduction of different control loops will be given. Afterward, the open-loop simulation model will be detailed introduced, including assumptions, simulation model inputs, simulation model agents and process, and simulation model outputs. Next, a developed feedforward simulation model, which is an extension of the previous simulation model, will be introduced with explanations.

3.1. The introduction of different control loops

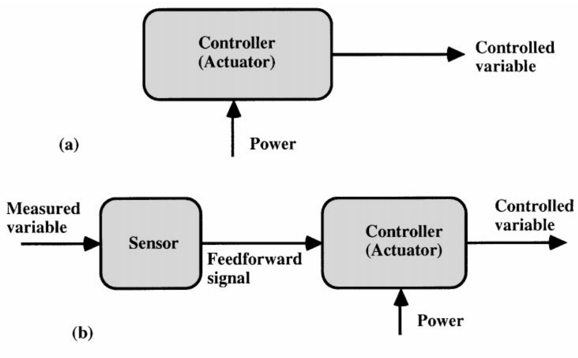


Figure 3.1: Different control loops for active flow control. (a) predetermined, open-loop control; (b) reactive, feedforward, open-loop control.

In terms of the control loops, Mohamed Gad-el-Hak proposes the classification scheme[29][30] for active flow control, and "active" here means auxiliary power for the energy expenditure. In this research, such a classification is applied to both simulation models in a similar way. The simulation models are regarded as controllers/actuators in the control loop, and the decision variable combination is similar to the power to the flow control loops.

3.2. The open-loop simulation model

The proposed methodology of the open-loop simulation model, as one control loop seen as Fig 3.1a, is applied in this research, and it means a model can directly run and give the output after users give the decision variables as power. It consists of three main sections: Inputs, Simulation, and Outputs. In the inputs section, in order to build the simulation environment, all the information about the simulation is defined and the information is delivered to the specific simulations section where different agents work. Afterward, agents will use the given information and interact with each other, in this way the development of the discrete event process is simulated based on the specific information and the behaviors are counted. And finally, in the output section, the average results of the operational simulations are obtained. The framework of the open-loop simulation model can be seen in Fig.3.2, which shows the flowchart illustrating the information flow between different parts. All the details of each part in each section will be given later.

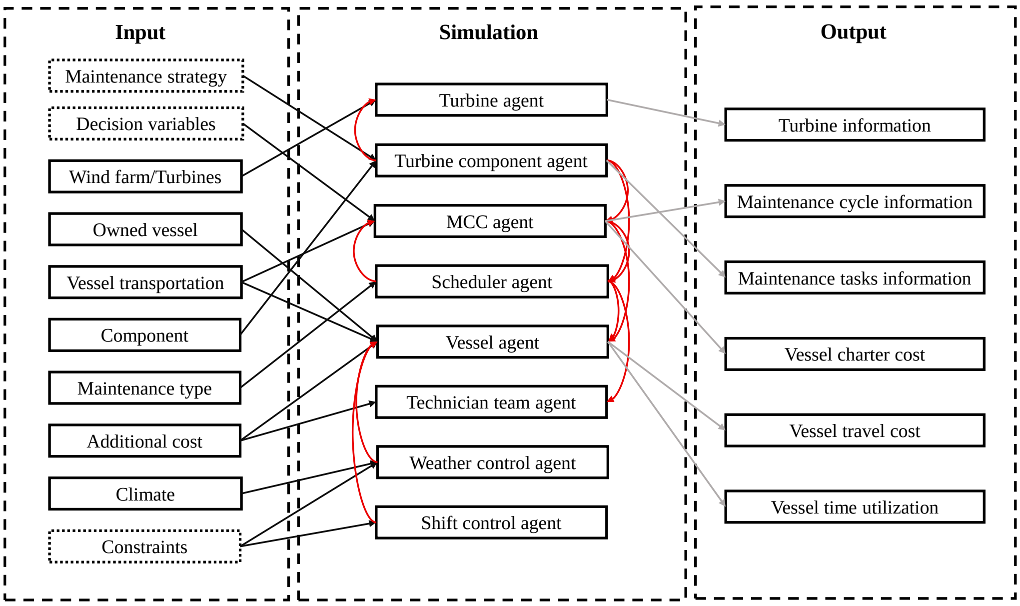


Figure 3.2: The open-loop simulation model framework

3.2.1. Assumptions

Because of the complexity of the maintenance system and due to many reality factors being considered into the system, it is necessary to make some assumptions for a better understanding of the system. Thus, the following assumptions are made when building the simulation model in this paper:

1. **Simulation resolution** The simulation resolution is the least time unit in this research. Each resolution is equal to 20 minutes, and it is called *period* in the later content. The length of one period is determined based on the least time considered in the simulation model and detailed information on the discrete event can be updated after every period.

2. **Maintenance cycle** Within a specified time frame, referred as the maintenance cycle in this study, maintenance tasks can be completed. When one of the triggers for a maintenance task is reached, a maintenance cycle is initiated. And a maintenance cycle is ended when all maintenance tasks are completed.

3. **Weather condition** The weather conditions, wave height and wind speed, are independent. While the formula is used to determine the wind speed at sea level/hub level, the wind speed of 21m level serves as a reference. Additionally, the current weather is independent of the preceding weather. The weather conditions are assumed to be constant for 2 hours (equal to 6 periods).

4. **Maintenance time** Any maintenance time for tasks is thought of as constant and unaffected by the weather.

5. **Traveling time** The travel speed of a vessel is assumed to be constant. Additionally, it is assumed that the distance between the base and the wind farm is constant and unaffected by the weather. While the intricate design of the wind farm is disregarded, and the duration of transit between two turbines is considered to be constant.

6. **Maintenance tasks** It is possible to undertake maintenance on different components of a turbine simultaneously. Once a maintenance task is started by a vessel, the vessel cannot be allocated to a new assignment before the maintenance task is completed. And once the maintenance task starts, the chartered vessel should always finish it even after the charter period has expired, and its late return will lead to the additional cost based on late-return days. A vessel will never be given a new maintenance task once a charter period has ended.

7. **Component** One component's lifetime is unrelated to that of any other component. A turbine can only function when none of its components is being maintained and none of its components is defective. A component cannot undergo a minor repair or a major repair twice during the same maintenance cycle. While a component that has been replaced can be again repaired in the same maintenance cycle because it is regarded as a new component.

8. **Technicians** Each vessel is equipped with technicians of the maximum number. And the technicians are assumed to be always adequate when any vessel is chartered. The cost for technicians of an owned vessel is paid based on the full length of each maintenance cycle, while the cost for technicians of a chartered vessel counts from the beginning of a charter period until the day when the vessel is returned.

9. **Spare parts** It is assumed that spare parts are expected to be always available and every vessel is equipped with sufficient spare parts for its maintenance tasks.

10. **Vessel charter** It is assumed that the charter rates are fixed for the simulation time horizon. And the charter period can be extended indefinitely. Once the charter period starts, the complete charter period will be charged. The costs of the non-maintenance crew are assumed to be included in the charter rate.

11. **Vessel mobilization** When mobilization is initiated, if one maintenance cycle is ended before the mobilization of any vessel is finished, the mobilization activity needs to be stopped and the full mobilization cost is charged.

12. **Charter extension** Regardless of whether the charter period will be extended, the vessel always returns to base when a charter period is ended. Through this process, technicians on board need to be renewed and the vessel needs to be restocked. If one vessel is decided to extend the charter period, after arriving at the base, it will, weather permitting, return back to the site after the start of the following day's shift.

13. **Maintenance priority** When two vessels require the same maintenance, the component with the higher age is given priority. The vessels that are on-site are given preference over those staying at the base. And if there are multiple available vessels on site, the vessels with more assigned teams are prioritized.

3.2.2. Simulation model inputs

Simulation inputs have the significant function to introduce the information, with which simulations can run successfully. In this section, the name of each input, its values used in this report as well as its unit are provided in the tables, and the explanations come after each table.

3.2.2.1 Maintenance Strategy

All components of offshore wind farm turbines age over time and eventually fail at the end of their life. When a component reaches a certain percentage of its age, which is the fraction of the consumed age relative to the components' lifetime, it falls into a predefined zone and the appropriate maintenance type should be performed on that component. In this report, four types of maintenance, minor repair, major repair, preventative replacement, and corrective replacement, require different maintenance resources, such as different vessel types and different numbers of technicians. After completion of maintenance activities, minor repair from zone 2 and major repairs from zone 3 lead to different age degradation of the components, and preventive replacement from zone 4 and corrective replacements from zone failed lead to new component replacements, whose lifetime is generated from the Weibull distribution of the components.

In terms of the vessel types, inspired by [21], three vessels with different functions are considered for different maintenance types. For minor repairs, conventional crew transfer vessels (CTV) are utilized to transfer technicians to the site. For major repairs, medium-weight components are needed to transfer, and field support vessels (FSV) are designed where cranes are on vessels to provide ability. For replacement operations in the offshore wind energy market, heavy lift vessels (HLV) are the most utilized vessels. By raising hulls above the water's surface and anchoring legs to the bottom, a very stable environment is created and the replacement of damaged components can be performed even in choppy seas. All this maintenance strategy information is organized in Table 3.1.

As the assumption previously states, a maintenance cycle can be initiated when the number of components in zone 4 equals or exceeds a pre-defined threshold, or

Table 3.1: Maintenance strategy

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	$\geq$ 100	Failed	New component	HLV	8

when the number of failed components equals or exceeds a defined threshold. The threshold values for starting a maintenance cycle are listed in Table 3.2.

Table 3.2: Threshold for starting a maintenance cycle

The trigger of starting a maintenance cycle	Threshold value
The number of zone 4 components	1
The number of failed components	1

3.2.2.2 Decision variables

Based on the specified owned vessel in the fleet, the simulation models seek to optimize the fleet size and mix, which includes HLVs, FSVs, and CTVs, for O&M activities of an offshore wind farm. Both in the open-loop simulation model and feedforward simulation model, the decision logic is utilized to determine the number of vessels, and these dynamic decisions are made based on the number of maintenance tasks per vessel type to be accomplished, as opposed to directly determining the number of vessels to be chartered. Before running a simulation, the values of the following decision variables must be defined:

- $X_{\mathrm{T}}^{\mathrm{HLV}}$
- $X_{\mathrm{T}}^{\mathrm{FSV}}$
- $X_{\mathrm{T}}^{\mathrm{CTV}}$

Each of them displays the estimated number of tasks that one vessel is expected to do during the maintenance cycle for each decision variable. Based on the number of tasks of each vessel type, $N_{\mathrm{T}}^{V}(V = \mathrm{HLV/FSV/CTV})$, which can be known from the model, and the given number of owned vessels of each type, $N_{\mathrm{O}}^{V}(V = \mathrm{HLV/FSV/CTV})$, which is given before simulation, the general equations used to decide how many vessels of each type to charter can be expressed as:

$$N_{\mathrm{C}}^{\mathrm{HLV}} = \left\lceil \frac{N_{\mathrm{T}}^{\mathrm{HLV}}}{X_{\mathrm{T}}^{\mathrm{HLV}}} \right\rceil - N_{\mathrm{O}}^{\mathrm{HLV}} \tag{3.1}$$

$$N_{\mathrm{C}}^{\mathrm{FSV}} = \left\lceil \frac{N_{\mathrm{T}}^{\mathrm{FSV}}}{X_{\mathrm{T}}^{\mathrm{FSV}}} \right\rceil - N_{\mathrm{O}}^{\mathrm{FSV}} \tag{3.2}$$

$$N_{\mathrm{C}}^{\mathrm{CTV}} = \left\lceil \frac{N_{\mathrm{T}}^{\mathrm{CTV}}}{X_{\mathrm{T}}^{\mathrm{CTV}}} \right\rceil - N_{\mathrm{O}}^{\mathrm{CTV}} \tag{3.3}$$

Where $\lceil * \rceil$ denotes the ceiling operation in equation 3.1-3.3.

For example, if at the current time point, the number of tasks requiring CTV is 100, then $N_{\mathrm{T}}^{\mathrm{CTV}} = 100$. If the estimation of the task capacity for CTV in one maintenance cycle is 40, then $X_{\mathrm{T}}^{\mathrm{FSV}} = 40$, thus the number of the CTV needed in this maintenance cycle is

$$\left\lceil \frac{N_{\mathrm{T}}^{\mathrm{CTV}}}{X_{\mathrm{T}}^{\mathrm{CTV}}} \right\rceil = \left\lceil \frac{100}{40} \right\rceil = \lceil 2.5 \rceil = 3 \tag{3.4}$$

If the number of owned CTV is 1, then $N_{\mathrm{O}}^{\mathrm{CTV}} = 1$ and the number of vessels to be chartered is 3 - 1 = 2, and this is the value of $N_{\mathrm{C}}^{\mathrm{CTV}}$. In another case, if the number of tasks requiring CTV is still 100, but the estimation of the task capacity for CTV in one maintenance cycle is 50, then $N_{\mathrm{T}}^{\mathrm{CTV}} = 100$ and $X_{\mathrm{T}}^{\mathrm{FSV}} = 50$, thus the number of the CTV needed in this maintenance cycle is

$$\left\lceil \frac{N_{\mathrm{T}}^{\mathrm{CTV}}}{X_{\mathrm{T}}^{\mathrm{CTV}}} \right\rceil = \left\lceil \frac{100}{50} \right\rceil = \lceil 2 \rceil = 2 \tag{3.5}$$

If the number of owned CTV is still 1, then $N_{\mathrm{O}}^{\mathrm{CTV}} = 1$, meaning that the number of vessels to be chartered is 2 - 1 = 1 and $N_{\mathrm{C}}^{\mathrm{CTV}}$ is equal to 1.

Similarly, all the calculation logic for the number of chartered CTV can be applied to the number of chartered FSV, $N_{\mathrm{C}}^{\mathrm{FSV}}$, and the number of chartered HLV, $N_{\mathrm{C}}^{\mathrm{HLV}}$.

Apart from all three decision variables set before the simulation starts, during each maintenance cycle, the charter period of each vessel type may need to be extended throughout each maintenance cycle due to the substantial backlog of tasks. Then, the decision logic for determining whether to prolong a charter time is therefore provided as follows:

$$\text{Charter extension} = \begin{cases} \text{Yes} & N_{\mathrm{C}}^{V} + N_{\mathrm{O}}^{V} \geq N_{\mathrm{F}}^{V} \\ \text{No} & N_{\mathrm{C}}^{V} + N_{\mathrm{O}}^{V} < N_{\mathrm{F}}^{V} \end{cases} \tag{3.6}$$

Where, $N_{\mathrm{C}}^{V} (V = \mathrm{HLV/FSV/CTV})$ is the number of the chartered vessel of each type, N_{O}^{V} is the number of the owned vessel of each type, $N_{\mathrm{F}}^{V} (V = \mathrm{HLV/FSV/CTV})$ is the number of each vessel type in the current fleet, including the vessel that must be determined if the charter period will be extended.

For example, at the current time point, if the number of CTV in the fleet is 2 and there is only 1 owned CTV in the fleet, then $N_{\mathrm{F}}^{\mathrm{CTV}} = 2$ and $N_{\mathrm{O}}^{\mathrm{CTV}} = 1$. By using the previous logic to calculate the number of CTV to be chartered, if the number is 0, then $N_{\mathrm{C}}^{\mathrm{CTV}} = 0$. Then according to the charter extension logic:

$$N_{\mathrm{C}}^{\mathrm{CTV}} + N_{\mathrm{O}}^{\mathrm{CTV}} = 0 + 1 < 2 = N_{\mathrm{F}}^{\mathrm{CTV}} \tag{3.7}$$

Then the decision for the charter extension is No. While if the number of CTV in the fleet is still 2 and there is still only 1 owned CTV in the fleet, however, the number of CTV to be chartered is calculated as 1, then $N_{\mathrm{C}}^{\mathrm{CTV}} = 1$, and according to the charter extension logic:

$$N_{\mathrm{C}}^{\mathrm{CTV}} + N_{\mathrm{O}}^{\mathrm{CTV}} = 1 + 1 \geq 2 = N_{\mathrm{F}}^{\mathrm{CTV}} \tag{3.8}$$

Then the decision for the charter extension is Yes. The charter extension will be checked periodically, and its frequency is the input 13 of Table 3.5.

3.2.2.3 Wind farm and turbines inputs

For the wind farm-specific inputs, all the values are defined in Table 3.3. The input [1] shows the number of turbines in the offshore wind farm. Input [2] displays the distance between the based onshore and the offshore wind farm. Input [3] indicates the simulation time horizon for the open-loop simulation model.

Table 3.3: The values of wind farm and turbine inputs

No	Item	Unit
1	Number of turbines	turbine
2	Distance from shore	km
3	Simulation time horizon	year
4	Shift start	hh:mm
5	Shift end	hh:mm
6	Rated power output	MW
7	Rated output wind speed	m/s
8	Cut in speed	m/s
9	Cut out speed	m/s
10	Hub height	m
11	Soft time window	day

Inputs [4-5] are the shift start and shift end of the wind farm, and all the maintenance tasks can only be executed within this period if the required vessels are constrained by shift hours. The inputs [6-10] are the specification of every turbine. Input [11] is the soft time window for each maintenance cycle. This is an artificial value of time limit, which aims to push each maintenance cycle to be completed within the specified time as soon as possible, which also makes the simulation model close to real life. The soft time window can be set to different values according to the actual situation. Once the number is exceeded, the daily penalty cost will be taken into account.

3.2.2.4 Owned vessels inputs

The number of owned vessels of each type in Table 5.3 should be pre-defined as inputs in both two simulation models. These values can be changed by offshore wind farm operators or developers according to the specific situation. In this research, the number of owned vessels of each vessel type is the same for all the scenarios.

Table 3.4: The values of owned vessels inputs

No	Item	Unit
1	Number of owned HLVs	vessel
2	Number of owned FSVs	vessel
3	Number of owned CTVs	vessel

3.2.2.5 Vessel transportation inputs

For the vessel-related inputs of 3 vessel types, all the values are listed in Table 3.5.

Input [1] is different travel speeds. Input [2] is the inter-transit time for different vessels to move between two turbines, where the time of a team entering the turbine is included. Inputs [1-2] are independent of the weather condition and assumed to be constant according to the prior assumption section. Input [3] is the minimum working window, which means that, the time window that at least must be available for a vessel or team to work on a maintenance task before it starts/resumes. Input [4] is the number of technicians on the vessel when the vessel travels to execute the maintenance task. As previously mentioned, it is assumed that every vessel is equipped with technicians of the maximum number. Input [5] is the maximum number of parallel teams and it indicates the number of teams on each vessel that can work on different maintenance tasks simultaneously.

Inputs [6-8] are weather-related limitations of each vessel and vessels cannot work if the weather condition data exceeds any limitation. Inputs [9-10] are the Jack-up/Jack-down time, which is the time for stabilizing the HLV by stationing its legs on the seabed. Inputs [8-10] are only considered for HLV because FSV and CTV are not required to lift heavy parts to the hub level of the turbine. Inputs [11-13] are related to chartering vessels. Input [11], the mobilization time, indicates the time needed by a chartered vessel to get ready before it starts maintenance tasks.

Input [12] is the length of a charter period. Input [13] indicates the length of each extended charter period, and this happens when a charter period is ended but the maintenance tasks are not finished. At the beginning of each maintenance cycle, the chartered fleet size is decided, and during the cycle, it is periodically checked whether more vessels need to be chartered, and the interval is indicated as input [14] Input [15] specifies the daily penalty factor of the exceeded days for those chartered vessels that return after the charter period has ended. Input [16] is the fuel consumption while

Table 3.5: The values of vessel inputs

No	Item	Unit
1	Travel speed	knot
2	Inter-transit time	min
3	Minimum working window	min
4	Technicians on-board	person
5	Maximum parallel teams	team
6	Limit wave height	m
7	Limit wind speed at sea	m/s
8	Limit wind speed at hub	m/s
9	Jack-up time	hour
10	Jack-down time	hour
11	Mobilisation time	day
12	Charter length	day
13	Extend charter period length	day
14	Regular charter check	day
15	Penalty factor for late return	-
16	Fuel consumption	mt/h
17	Safety margin	min

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

traveling, which is part of the total cost of the objective function. Input [17] is the required time for a team of technicians to leave the turbine and enter the vessel in terms of safety.

3.2.2.6 Additional cost inputs

Table 3.6 shows the additional cost inputs [1-12] used in two models, and all of them can be used for the total cost calculation when there is any vessel is charterd or utilized for tasks.

Input [1], the electricity price, which is mentioned in the previous chapter and assumed to be a fixed value, is used to calculate the electricity production profit. Inputs [2-4] show the fixed charter rate for each type of vessel. Inputs [5-7] are costs for the mobilization of chartered vessels before they start the maintenance tasks, Inputs [8-10] are fuel costs for each vessel type associated with the transportation. Inputs [11-13] are technician costs for each type of vessel. In this report, technician costs of

Table 3.6: The values of additional cost inputs

No	Item	Unit
1	Electricity price	€/MWh
2	HLV charter rate	€/HLV/day
3	FSV charter rate	€/FSV/day
4	CTV charter rate	€/CTV/day
5	HLV mobilisation cost	€/mobilisation
6	FSV mobilisation cost	€/mobilisation
7	CTV mobilisation cost	€/mobilisation
8	HLV fuel cost	€/mt
9	FSV fuel cost	€/mt
10	CTV fuel cost	€/mt
11	HLV technician cost	€/technician/year
12	FSV technician cost	€/technician/year
13	CTV technician cost	€/technician/year
14	Penalty cost	€/day

the entire cycle are considered for owned vessels, while for chartered vessels, only technician costs during the charter period are considered. Input [14], the daily penalty cost, is imposed when one maintenance cycle exceeds the soft time window.

3.2.2.7 Components inputs
In this research, for each turbine, four components, rotor, generator, gearbox and bearing, are considered in two simulation models, and the lifetime of each component is different and generated by using the Weibull distribution with specific shape parameters and scale parameters.

3.2.2.8 Maintenance type inputs
Maintenance type inputs include the maintenance time inputs and maintenance cost inputs. Time and cost vary when different types of maintenance tasks on the different turbine components. However, in this research, the time used for the specific maintenance of a specific component is assumed to be constant, and the cost spent on the specific maintenance of a specific component is assumed to be constant as well.

3.2.2.9 Climate inputs
Wind speed and wave height are taken into account as the climate inputs in the developed simulation model, and synthetic climate datasets can be generated by using the Weibull distribution. Referring to the idea from [21], the wind power law developed by Justus and Mikhail [31] is used to calculate the wind speed values at sea level and hub level, which is shown as the equation 3.9. In this report, the wind speed at the height of 21m can be generated and regarded from the Weibull distribution as a reference

value. Based on this, the wind speed at the hub level and the wind speed at the sea level can be calculated by using the equation.

$$\frac{v_2}{v_1} = (\frac{h_2}{h_1})^{\alpha} \tag{3.9}$$

Where, v_2 is the wind speed at height h_2, v_1 is the wind speed at height h_1, and α is the shear component, which is a constant for the wind power law equation.

For the climate inputs, all the relevant values needed in this simulation model, are shown in Table 3.7.

Table 3.7: Climate inputs

No	Item	Unit
1	Weibull shape parameter of wind speed (at 21m)	-
2	Weibull scale parameter of wind speed (at 21m)	m/s
3	Weibull shape parameter of wave height	-
4	Weibull scale parameter of wave height	m
5	Relevant height above sea	m
6	Shear component	-

Inputs [1-2] are the Weibull shape parameter and the Weibull scale parameter to generate the wind speed at the height of 21 m. Inputs [3-4] are the Weibull parameters to generate the wave height. Input [5] is the relevant height above sea level and is used to obtain the wind speed at sea level. Input [6] is the shear component used in the equation 3.9, to obtain wind speed of different altitudes.

3.2.2.10 Simulation model constraints

The features of various vessel types are different, and as a result, various constraints are set and their maintenance and operations are influenced to differing degrees, which is shown in Table 3.8. It is assumed that HLV and FSV can stay offshore for multiple days, while the CTV cannot and has to return to the base every day. In terms of shift hours, only HLV is able to work three shifts of 24 hours a day. While the FSV and CTV are constrained by shift hours. As a result of the shift hours limiting the FSV and CTV, they are only able to work during such hours. Once the shift ends, Even if a maintenance task remains unfinished after the shift ends, FSV and CTV have to stop the maintenance activity, FSV has to stay on-site and CTV has to return to base. Inputs [3-5] are weather constraints. It is assumed that all the vessel types are constrained by the wave height and the wind speed at sea level, and only HLV is constrained by the wind speed at the hub level.

Table 3.8: Constraints for transportation systems

No	Item	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	✓		

3.2.3. Simulation model agents and process

The simulation model proposed in this research contains eight different simulation agents, by using the information from the input section, each agent is responsible for a certain process and interacts with each other.

The current status of an agent is represented by its mode, for example, a turbine can have the modes ‘working’ or ‘not working’, and a vessel can have the modes ‘idle at base’, ‘travel to site’, etc. The three most important process interactions are ‘activate’, ‘passivate’, and ‘hold’. Activate is used to continue an agent’s process at the current period. Passivate is used to stop the agent’s process (the agent becomes passive). Hold is used to delay the agent’s process, and the agent becomes active at the scheduled time.

All common agents for two models, the turbine agent, turbine component agent, maintenance cycle control agent, scheduler agent, vessel agent, technician team agent, weather control agent, and shift control agent will be described as follows.

3.2.3.1 Turbine Agent

Each turbine in the offshore wind farm is represented by a turbine agent. One turbine consists of 4 turbine components: rotor, bearing, gearbox, and generator. The lifetime of each component is sampled from its Weibull distribution. The turbine has a good status in the very beginning and it starts producing electricity at the start of the simulation. The turbine stops working as soon as one or more of its components fails or when maintenance is performed on one or more of its components.

The turbine will continue running only when none of the turbine components are faulty and none turbine components are under maintenance, which is aligned with the previous assumption. The four components of the turbine only age when the turbine is working and, hence, all turbine components stop aging when the turbine is not working.

3.2.3.2 Turbine Component Agent

Each turbine component of each turbine, rotor, bearing, gearbox, and generator, is represented by a turbine component agent, and each has an individual lifetime before it fails. The component’s age is represented by the lifespan percentage that has been consumed to its total lifetime. Corresponding with the component’s age, the component is defined in zone 1, zone 2, zone 3, zone 4, or zone f (component failed), as shown in Table 3.1. A component ages over time and goes into successive zones until it may eventually fail, with each leading to a specific maintenance activity.

Based on the maintenance strategy, maintenance activities can only be performed during one maintenance cycle. A maintenance cycle is initiated when either the number of failed or the number of zone 4 reaches the defined thresholds, which is shown in Table 3.2. The turbine component agent checks if the threshold is reached, and starts a maintenance cycle by activating the maintenance cycle control agent if it happens. Turbine components in zone 2 or 3 can be repaired if a maintenance cycle is active, therefore, during this period, the only action for these two types of repair is to activate the scheduler agent, which is responsible for scheduling maintenance tasks.

When a turbine component is repaired either from zone 2 or zone 3, its age is reduced according to Table 3.1. When a turbine component is replaced either from zone 4 or zone f, a new component will be installed in the turbine. Then a new lifetime of the component is sampled from the Weibull distribution and the component's age is reset to zero.

3.2.3.3 Maintenance Cycle Control Agent

The maintenance cycle control (MCC) agent is used for the simulation environment. The MCC agent is activated if any of the maintenance cycle triggers is reached, after which a maintenance cycle is started. The MCC agent is also responsible for chartering vessels. Once the maintenance cycle has commenced, the simulation environment will be periodically checked at a fixed interval, vessels can be chartered at the start of a maintenance cycle or throughout the cycle if additional vessels are chartered.

3.2.3.4 Scheduler Agent

The scheduler agent is also used for the simulation environment. This agent is responsible for assigning maintenance tasks to specific teams of technicians as well as vessels. Each time the scheduler agent is activated, it identifies the remaining maintenance tasks of each type and sorts the tasks by maintenance priority. After that, the agent assigns the maintenance tasks to teams of technicians attached to vessels based on the maintenance priority. If all maintenance tasks are completed and all the vessels are back at base, the scheduler agent sends the signal to the MCC agent that the maintenance cycle can be completed and the MCC agent will complete the maintenance cycle.

3.2.3.5 Vessel Agent

A vessel agent is assigned to each vessel in the fleet, whether it is chartered or owned. The letter "(C)" or "(O)" is placed after the vessel name to designate a vessel that is either chartered or owned. The procedures vary depending on the type of vessel and whether it is chartered or owned. If there is not any active maintenance cycle, owned vessels are idle at the base. A vessel agent is created and the vessel is added to the fleet if the MCC agent decides to charter a new vessel. When the mobilization is complete, the chartered vessel is ready for use.

If a maintenance cycle is active, a vessel can be assigned or not assigned. If a vessel is assigned, at least one team of technicians from that vessel has been given a maintenance assignment to complete. And there are five main sub-processes as follows:

- All teams of the turbine are delivered to the destination
- Any team of the vessel completed its task
- Any team of the vessel is not at the turbine
- The vessel is interrupted by the shift end
- The vessel is interrupted by the bad weather

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 a maintenance cycle, it is checked in advance whether the charter period should be extended before the charter expires. The chartered vessel is removed from the fleet if the charter time is not extended.

The simulation of HLV logistics The majority of vessels used for heavy-lifting maintenance activities are jack-up vessels[6]. In this research, jack-up vessels are considered and an HLV is considered to be a jack-up vessel. HLVs are used for both preventive and corrective replacement tasks, where heavy parts are required to lift to the hub level of the turbine.After dropping off a team to the turbine, an HLV is operating there. Each HLV can work continuously (without being constrained by shift hours) and can remain offshore (on-site) for a number of days. Only one maintenance task can be worked on by the HLV at once.

HLVs need to be stabilized on-site before components can be lifted to the hub of the turbine. This can be done by setting up its legs on the seafloor. Then the hull can be raised above the water's surface, and a stable platform for lifting operations in inclement weather can be created. Wind speed at sea and wave height both have an impact on jacking up/down activity. Therefore, the jack-up/down activity can only be executed when the duration to satisfy both wind speed at sea and wave height is longer than the required time of jack-up/down. If the weather window is not sufficient, jack-up/down activity will not be started, and it is needed to wait until the conditions are met. Once the jacked-up is finished, it can stay jacked up under any weather condition. After jacking up, the maintenance task can be performed when the weather conditions for lifting operations are met.

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 not exceed the limit for wind speed at the hub level, within a period consisting 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 HLV's safety margin guarantees that the technicians' team will have enough time to exit the turbine and board the HLV before the weather limit is reached.

Once the current task is completed, the location of the next task will be checked. If the next task is at another turbine, the HLV will jack down when the weather window permits and it will travel to the next turbine. While the HLV will remain jacked up and begin the new repair activities if the weather window is adequate if the subsequent task is at the same turbine. If there is no new maintenance task assigned to the HLV, the HLV will travel back to the base and stay idle at the base. It will either travel to

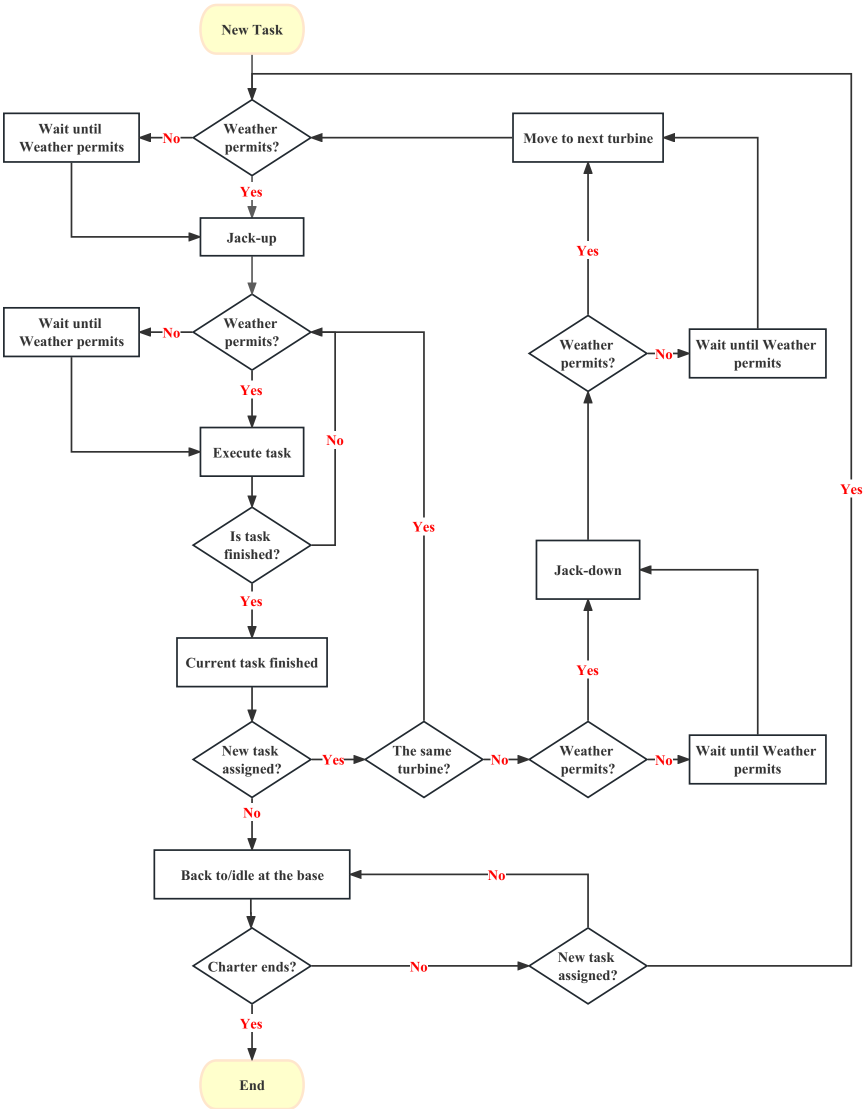


Figure 3.3: HLV logistics

the location if it is allocated to a site or remain idle at the base until the end of the maintenance cycle/charter period, whichever comes first.

The flow chart of the HLV logistics is shown in Figure 3.3.

The simulation of FSV logistics FSVs are considered for major repair maintenance tasks. For these tasks, it is assumed that medium-weighted parts are lifted to the turbine's platform. Each FSV is outfitted with a motion-compensating gangway system and dynamic positioning technologies, which enable technicians to be transported to the turbine in more erratic weather. FSVs are only permitted to work during shift hours but can stay offshore for a number of days. Each FSV can only work on one maintenance task at a time.

FSVs are constrained by weather conditions of wave height and wind speed at sea. Any maintenance operation involving FSVs cannot be completed if any of these meteorological conditions exceed the FSV restrictions. During rough weather conditions, the FSV can stay on-site at the turbine or travel. One FSV will only drop off a crew of technicians and begin operating at a turbine if the weather window is sufficient. Similar to the HLV, the FSV features a safety margin that ensures the team of technicians has enough time to leave the turbine and enter the FSV before the weather becomes too rough. Therefore, the weather window must be at least equal to the length of its minimum working window plus the safety margin before a maintenance operation is started/resumed.

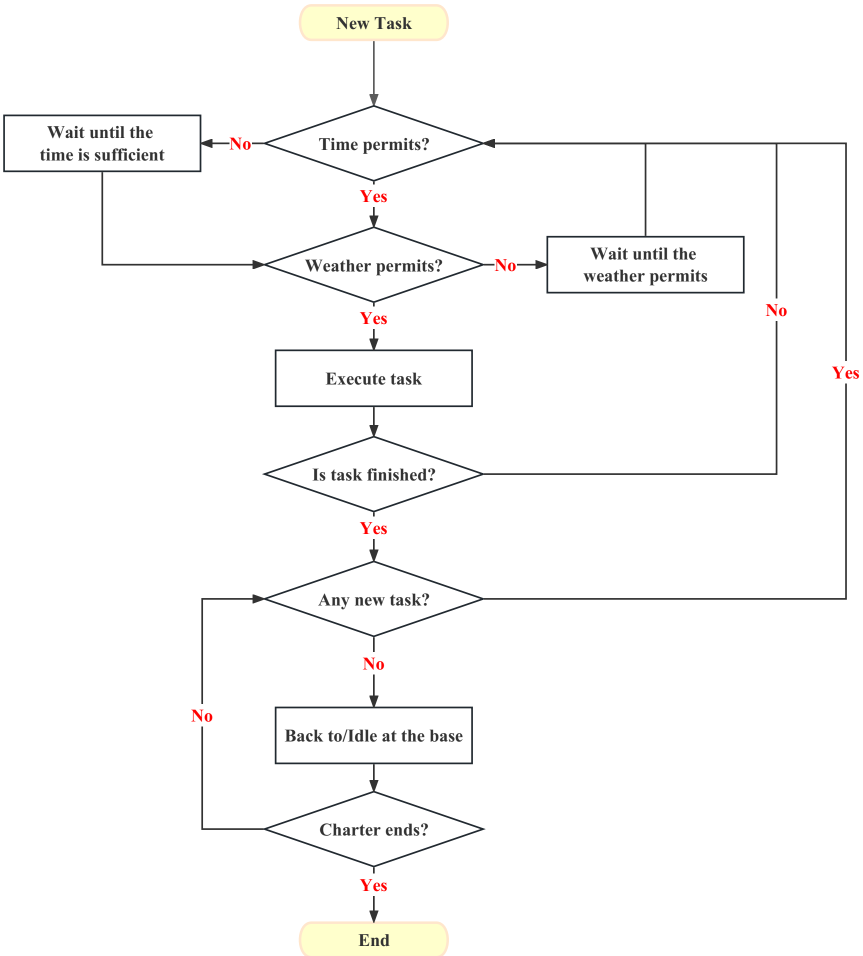


Figure 3.4: FSV logistics

The maintenance task must stop and the team of technicians will be moved to the vessel if the FSV and its crew are working on a maintenance task but the shift is about to end. The maintenance operation will be resumed at the shift start the next day if the weather permits. If a maintenance operation is halted due to rough weather and the weather window becomes sufficient for tasks again, the maintenance task will only be resumed if the remaining time of the current shift is equal to or greater than the minimum working window.

If the FSV has no more maintenance tasks to complete, it will return to base and stay there until the maintenance cycle is complete or the charter time has ended, whichever comes first, or until it is given a new maintenance task, in which case it will depart for the site.

The flow chart of the FSV logistics is shown in Figure 3.4.

The simulation of CTV logistics CTVs are used for minor repair maintenance tasks.The weather constraints for the CTV are stricter for this vessel type because it is considerably smaller than the other two vessel types. The assumption is that teams of technicians simply need to be transported and dropped off at the turbine for each maintenance task. CTVs themselves are not required to remain on-site. Four teams, each with three technicians, can fit within the CTV. The CTV can only operate within shift hours and cannot stay offshore for multiple shifts.

On the one hand, CTV activities are strictly limited by the weather condition. Any CTV can only travel to the site if the weather conditions of wave height and wind speed at sea do not go above the CTV restrictions. If not, it must be at the base. This indicates that, before rough weather comes, all minor repair activities are forced to cease, CTV must pick up all teams and travel them back to base. The maximum amount of time needed for one CTV to pick up every team and return to base is equal to the most parallel teams multiplied by the inter-transit time plus the amount of time needed to get back to base, to guarantee that CTV returns to base before the weather gets too bad,

On the other hand, CTV activities are rigidly constrained by shift hours. After the shift starts, CTVs are allowed to start their tasks. At the end of the shift, due to the shift limits, 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. The CTV will return to the location and deliver any teams that have been interrupted after the next shift begins, if the weather and time allow. Those teams not interrupted will wait for being assigned to a new maintenance task.

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 delivered. The priority of delivery is set by the repair time, and the team assigned to a repair, which needs the least repair time, will be delivered first. After every team has been delivered, the CTV returns to the first team's turbine. The CTV will stay (on-site idle at this turbine) until the first delivered team completes its work if it arrives at the team's turbine before it does. Once the team has finished its task, the team will be picked up by the CTV. If there is any new task at another turbine to be finished, the task will be assigned to this team and the CTV will travel to the corresponding turbine. In order to prevent having to send teams to the turbine and pick up the task-completed team at the same time, delivering teams is given priority over picking up finished teams. CTVs will always travel to the turbine of the team that first finishes its task if no more teams need to be delivered or picked up.

If a CTV is idle at the base and it has teams that are assigned to maintenance tasks, two conditions are checked before the CTV travels to the site. First, it should be

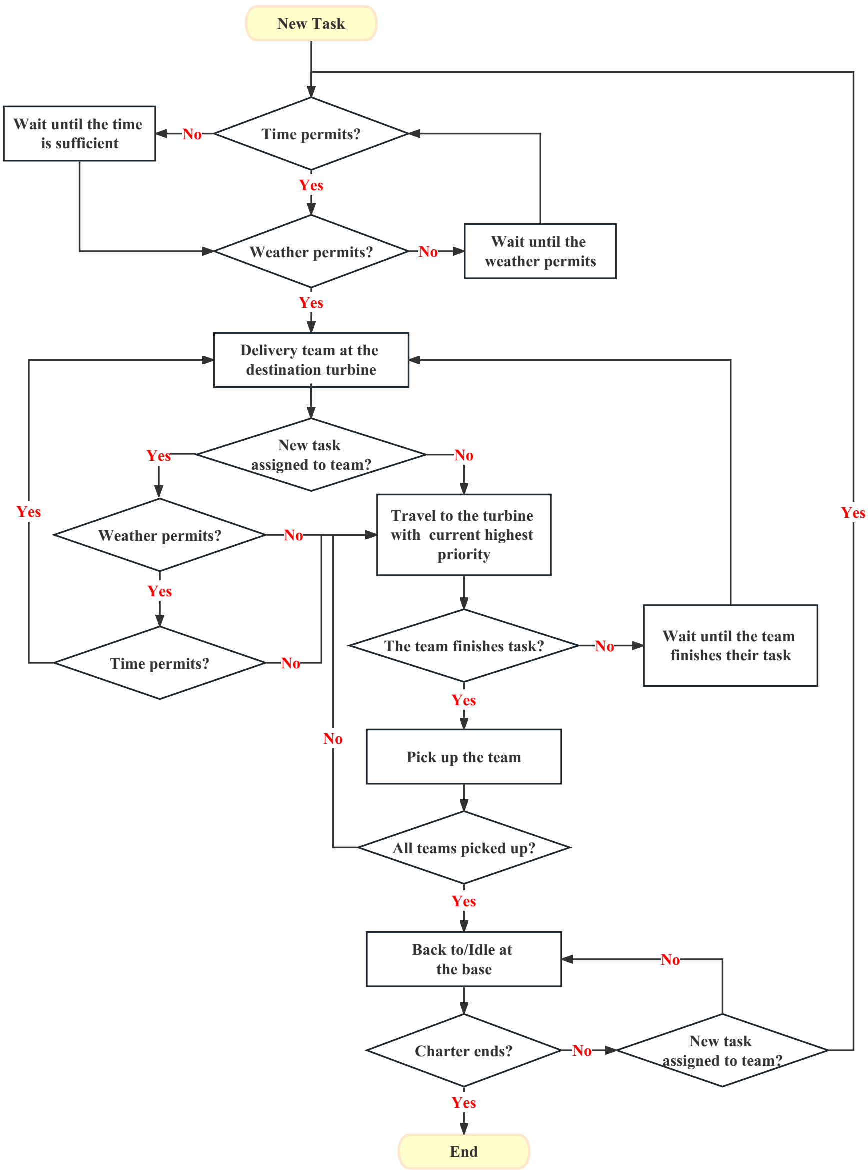


Figure 3.5: CTV logistics

confirmed that the length of the weather window that satisfies the weather conditions, is not less than the length of the required time to travel to the site plus the safety margin plus the minimum working window. If the weather window is adequate, then, it is then checked whether there is enough time left in the shift for all teams to begin or resume the maintenance activity. The CTV will only travel to the site if all assigned teams can work on the maintenance task for at least the minimum working window. This indicates that the CTV will stay at the base if the sum of the minimum working window, and the travel time to the site, plus the number of assigned teams multiplied by the inter-transit time, is greater than the remaining time in the shift. An unassigned team of the CTV will only be assigned to a new maintenance task if it can work on the task for at least the minimum working window; otherwise, the tasks to be finished will be assigned until the next time that is available.

The flow chart of the CTV logistics is shown in Figure 3.5.

3.2.3.6 Technician Team Agent

Every time a maintenance task is assigned to a team of technicians, a technician team agent is temporarily created. The generated technician team agent will terminate and be removed once the team completes its maintenance task and is picked up by the vessel.

3.2.3.7 Weather Control Agent

Each vessel in the fleet has its own weather control agent and the function of this agent is to check that the weather window is sufficient for vessels to travel to the site for maintenance activities. The weather control agent is responsible for interrupting a vessel that is in operation and must respond to terrible weather conditions, and the vessel has to stop the maintenance activity, or even travel return to the base if the vessel type is CTV.

3.2.3.8 Shift Control Agent

The shift control agent is the agent for the simulation environment that ensures the vessels constrained by shift hours are activated at the start of the shift and commence picking up teams at the end of the shift. At the end of each day (00h00) during a maintenance cycle, shift control prints the mode of each vessel to get an overview of the position and activity of each vessel in the fleet.

3.2.4. Simulation model output

In the simulation of the offshore wind farm, the process of all maintenance activities will be regularly checked and recorded in the log, through which, turbine information, cycle information, component information, vessel charter information, vessel travel information, as well as vessel time information, can be collected as simulation outputs. For each output, the contents and explanation will be given in the following sections.

3.2.4.1 Turbine information

The operating status of every turbine is monitored in two models, thus, whether the turbine is working well or under maintenance can be known and collected. Based on the information, the following output about turbine information can be calculated:

- Total electricity production of the offshore wind farm
- Time-based availability of the offshore wind farm
- Power-based availability of the offshore wind farm

To determine the wind farm's total electricity production, individual turbine's electricity production during the simulation horizon should be first calculated, and after that, sum up all electricity production. For each turbine, the relationship between the wind speed at the hub level v_t and the generated power $P_t(v_t)$ during period t is given by [32] and the power can be calculated from equation 3.10.

$$P_t(v_t) = \begin{cases} 0 & v_t < v^{\mathrm{ci}} \quad \text{or} \quad v > v^{\mathrm{co}} \\ P^{\mathrm{r}}(\mathrm{a} + \mathrm{b}v_t + \mathrm{c}v_t^2) & v^{\mathrm{ci}} \leq v_t \leq v^{\mathrm{r}} \\ P^{\mathrm{r}} & v^{\mathrm{r}} \leq v_t \leq v^{\mathrm{co}} \end{cases} \tag{3.10}$$

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 at the rated output wind speed, and parameters a, b, and c are given by:

$$\mathrm{a} = \frac{1}{(v^{\mathrm{ci}} - v^{\mathrm{r}})^2}[v^{\mathrm{ci}}(v^{\mathrm{ci}} + v^{\mathrm{r}}) - 4v^{\mathrm{r}}v^{\mathrm{ci}}(\frac{v^{\mathrm{ci}} + v^{\mathrm{r}}}{2v^{\mathrm{r}}})^3] \tag{3.11}$$

$$\mathrm{b} = \frac{1}{(v^{\mathrm{ci}} - v^{\mathrm{r}})^2}[4(v^{\mathrm{ci}} + v^{\mathrm{r}})(\frac{v^{\mathrm{ci}} + v^{\mathrm{r}}}{2v^{\mathrm{r}}})^3 - (3v^{\mathrm{ci}} + v^{\mathrm{r}})] \tag{3.12}$$

$$\mathrm{c} = \frac{1}{(v^{\mathrm{ci}} - v^{\mathrm{r}})^2}[2 - 4(\frac{v^{\mathrm{ci}} + v^{\mathrm{r}}}{2v^{\mathrm{r}}})^3] \tag{3.13}$$

The time-based availability is the percentage of time that an individual wind turbine or wind farm is available to generate electricity expressed as a percentage of the theoretical maximum[33]. In this research, it is defined as the operational time, which is equal to the total time deducted by downtime due to maintenance or failures, divided by the simulation time horizon.

Similarly, power-based availability is the operational performance and is defined as the actual power output divided by the theoretical maximum power output.

3.2.4.2 Maintenance cycle information

Once the maintenance cycle starts, it is traced by the simulation model until it ends. Together with the consideration of the soft time window for each maintenance cycle, the following things can be calculated:

- Maintenance cycle length (days)
- Penalty cost related to prolonged maintenance cycles

3.2.4.3 Maintenance tasks information

Each time when a maintenance task is completed, the information on the maintenance task is traced and collected, including the turbine and component type, the maintenance type, the costs, and the time of completion. Based on the counted information, the following things are calculated:

- The number of maintenance tasks of each type
- The costs of maintenance tasks of each type

3.2.4.4 Vessel charter cost

The developed model tracks information related to chartering vessels including the start and end time of mobilization, the maintenance cycle number when a mobilization and charter period starts, the start and end time of a charter period, 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 (together with the number of late days), and whether mobilization is stopped by the end of a cycle. Based on this information, the following items can be calculated:

- The number and cost of charters of each vessel type
- The number and cost of extended charter periods of each vessel type
- The number and cost of mobilizations of each vessel type
- The total number of days and cost of the late returned chartered vessel of each vessel type
- The cost of technicians

As previously mentioned, the technicians on chartered vessels are paid for the duration of the charter period while the technicians on an owned vessel are paid for the duration of the maintenance cycles, and this might lead to different vessel costs when two vessels of the same type are used.

3.2.4.5 Vessel travel cost

For each vessel ever in the fleet, the developed models can track traveling information, including the number of travels from base to the site, the number of travels from site to base, and the number of inter-transits. Based on the information, the following cost can be calculated as output:

- The fuel cost for traveling

3.2.4.6 Vessel time utilization

For each vessel ever in the fleet, the developed models track the time spent on several items:

- Time spent on traveling between the base and the site
- Time spent on inter-transit travels
- Time spent on repairs
- Time restricted by weather conditions
- Time restricted by shift hours
- Time of idling at the base during each maintenance cycle
- Time of idling on-site during each maintenance cycle
- Time spent on jacking up/down

Above all items listed above, the first four items are for all vessel types. The fifth item is for CTVs and FSVs because HLVs are not restricted by shift hours. The sixth item is for FSVs and HLVs because CTVs only deliver teams to the site but do not spend time on maintenance tasks. The seventh item is only for CTVs due to the fact that FSVs and HLVs return to the base if there are no more tasks and they will never idle on-site during the maintenance cycle. The last item is only for HLVs because this is the only vessel type requiring jack-up/jack-down activities.

Based on all information above, the distribution of time of each vessel type is calculated. For owned vessels, the percentage of time spent on each item is determined based on the total time of maintenance cycles. For chartered vessels, the percentage of time spent on each item is determined based on the charter length excluding mobilization time. Therefore, the distribution of time indicates the percentage of time spent on things relative to a vessel's available time in maintenance cycles.

3.2.5. Conclusion

All the details of the open-loop simulation model have been given in this section. In conclusion, this model can be seen as an evaluation tool for each decision variable combination. All that needs to do is to predetermine the decision variable combination $X_{\mathrm{T}}^{\mathrm{HLV}}$, $X_{\mathrm{T}}^{\mathrm{FSV}}$, $X_{\mathrm{T}}^{\mathrm{CTV}}$, then the model will execute the simulation process from the very beginning state S_0, and terminate the simulation when the pre-set simulation time is reached and the state is S_{SimTime}. Once the simulation is stopped, all the further calculations will be carried out, the fleet size and mix, together with other model outputs can be obtained. The concluded flowchart of this open-loop simulation model is shown in Figure 3.6.

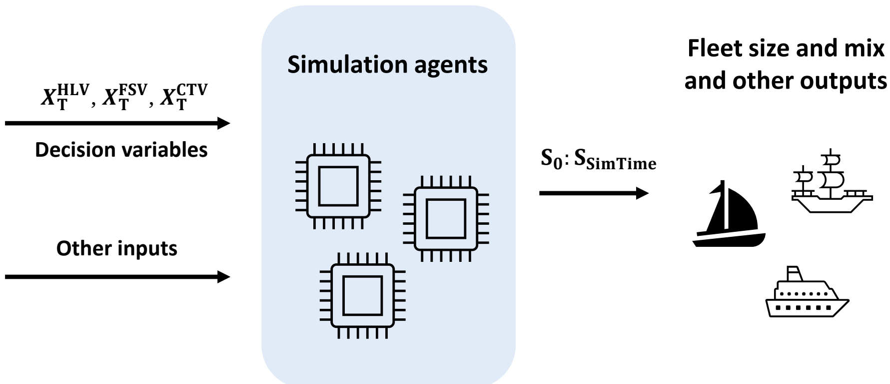


Figure 3.6: The flowchart of the open-loop simulation model

3.3. The feedforward simulation model

A feedforward simulation model, in this research, means the model can perform a simulation based on a given historical wind farm state as the feedforward signal, together with the given decision variables as power, which is the control loop seen as Fig 3.1b.

3.3.1. The development of feedforward simulation model

As an extension of the previous open-loop simulation model, very similarly, 10 simulation inputs, including maintenance strategy, decision variables, wind farm/Turbines inputs, owned vessels inputs, vessel transportation inputs, additional cost inputs, components inputs, maintenance type inputs, climate inputs as well as simulation model constraints, and 6 simulation outputs, including turbine information, maintenance cycle information, maintenance tasks information, vessel charter cost, vessel travel cost as well as vessel time utilization, are the same in the feedforward simulation model. However, among agents, some changes are made in order to realize some functions. The framework of the feedforward simulation model can be seen in Figure 3.7.

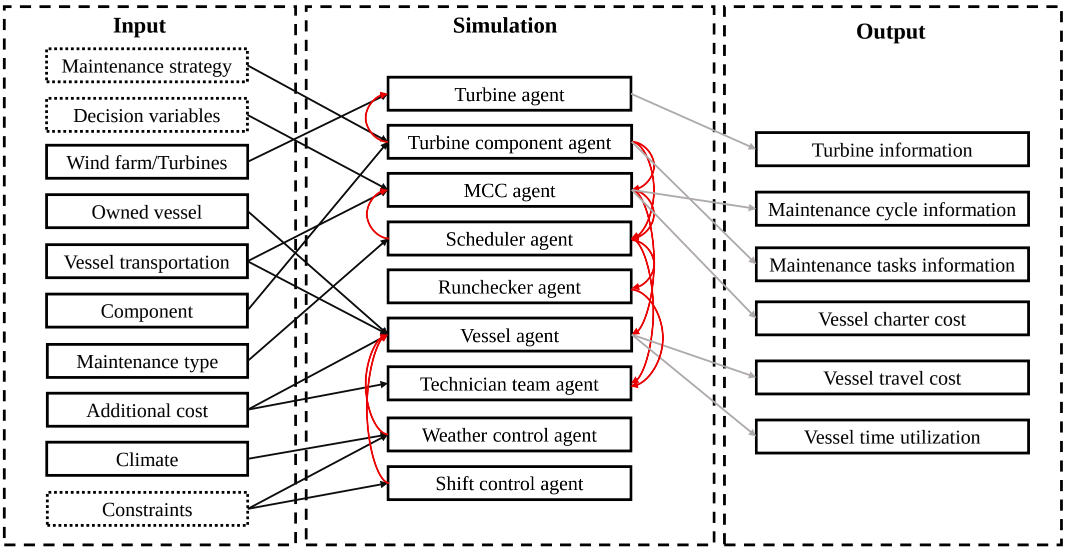


Figure 3.7: The feedforward simulation model framework

It can be seen that, among all the simulation agents, apart from the previously mentioned 8 agents, there will be another new agent in the feedforward simulation model, which is named as RunChecker agent. The function of this agent is to terminate the whole simulation under some certain condition, for example, in this research when one maintenance cycle is finished. And after this, all the further calculations are carried out and all the model outputs of this maintenance cycle can be obtained. This agent is always working in a standby status once the simulation starts, waiting for the terminate command from the Scheduler agent.

The Scheduler agent, in the open-loop simulation model, sends the signal to the MCC agent that the maintenance cycle can be completed when all maintenance tasks are completed and all the vessels are back at base and MCC agent will terminate the maintenance cycle. However, in the feedforward simulation model, the Scheduler agent not only sends the signal to the MCC agent but also sends another signal to the Runchecker agent, so that the Runchecker agent can terminate the whole simulation. Then, all the calculations will come after and the output can be acquired.

Additionally, two agents, the Turbine agent and the Turbine component agent, will have more functions in the feedforward simulation model, compared with those in the open-loop simulation model. Before the simulation starts, these two agents read the historical data about the previous wind farm states, and by using this information, the feedforward simulation model can start the simulation from a specific state but not just from the very beginning as the previous open-loop simulation model. For example, if the offshore wind farm has been used for 2 years, each component of each turbine has its own consuming age and other corresponding information, then the model will first read its data, based on which the simulation will continue until the end of the next maintenance cycle. However, if there is no historical data, then similar to the previous open-loop simulation model, a new offshore wind farm is simulated from the very beginning, the lifetime of each component of each turbine will be generated randomly by following the Weibull distribution and used for further discrete-event simulation.

3.3.2. Conclusion

The development of the feedforward simulation model has been introduced in this section. It can be seen that, compared with the previous open-loop simulation model, apart from decision variables, the historical wind farm state S_{X-1} is also an important input in the feedforward simulation model.

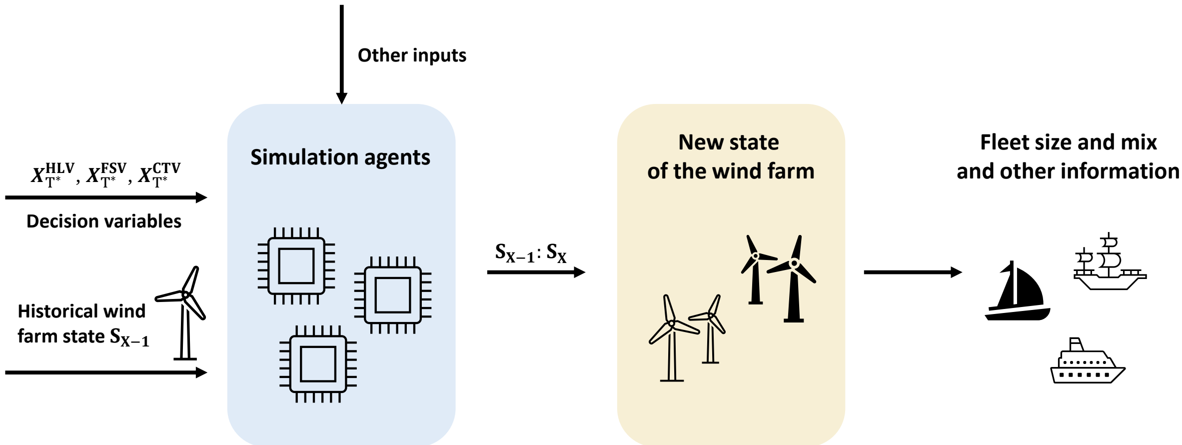


Figure 3.8: The flowchart of the feedforward simulation model

Together with other inputs, this model can perform a simulation from state S_{X-1} until the state S_X when a certain condition is met, and in this research, such a condition is when a maintenance cycle is finished. Then the information about the new state of the wind farm will be known and saved, all the further calculations will be carried out, and the fleet size and mix, together with other model outputs can be obtained. The concluded flowchart of this feedforward simulation model is shown in Figure 3.8, and this model can be seen as an evaluation tool for each decision variable combination for one maintenance cycle based on a given wind farm state.

4 Simulation-Optimisation Methodology

This project aims at the optimization of the fleet size and mix for offshore wind farms, based on the two simulation models priorly introduced in the previous chapter, in this chapter, a simulation-optimization approach will be used. Firstly, the interaction between the open-loop simulation model and the optimization tool will be given with a detailed description, secondly, the flowchart of the interaction between the feedforward simulation model and the optimizer will be shown with a detailed explanation. Lastly, the details of the optimization algorithm, including its objective function, the determination of some key parameters, the optimization method and the optimization process of this research, will be detailed explained.

4.1. The interaction between the open-loop simulation model and optimization algorithm

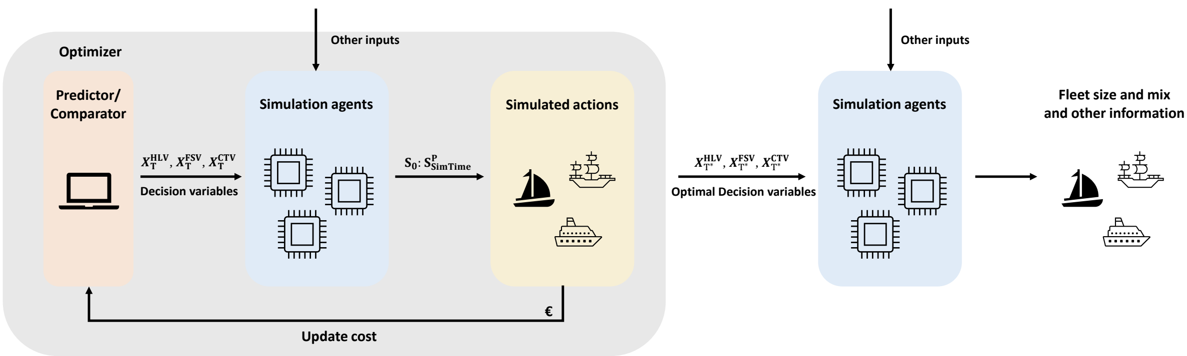


Figure 4.1: Flowchart of interaction between the open-loop simulation model and optimization algorithm

The open-loop simulation model can perform a simulation from the very beginning and last for a preset simulation time, and evaluate the performance of every decision variable combination. In this research, together with the optimization algorithm, this model can be used as a tool for a long-term optimization of the fleet size and mix for offshore wind farms, for example, a general decision for a wind farm with a 15-year lifespan. And the flowchart of the interaction between the open-loop simulation model and the optimization algorithm is shown in Figure 4.1, and the optimization method is referred to as optimizer in the flowchart.

It can be seen from the figure, within the optimizer part, the predictor will continuously try different decision variable combinations. By using each combination, the open-loop simulation model will execute a simulation from the very beginning state of the offshore farm, denoted as S_0, and terminate the simulation when the preset simulation time is reached when the state of the wind farm is donated as $S^{\mathrm{P}}_{\mathrm{SimTime}}$. This process is repeated and after the simulation of each combination is done, the cost calculated from this simulation will be updated to the comparator for a comparison. Finally, the optimal decision variable combination will be found and used for the simulation model again to obtain the corresponding fleet size and mix, as well as other outputs.

4.2. The interaction between the feedforward simulation model and optimization algorithm

As previously introduced, the feedforward simulation model can be used for the evaluation of the decision variable combination applied to one maintenance cycle based on a given historical wind farm state. In this research, together with the optimization algorithm, it can be used as a tool for a relatively short-term optimization of the fleet size and mix, in other words, a decision for a maintenance cycle. The flowchart of the interaction between the feedforward simulation model and the optimization algorithm is shown in Figure 4.2.

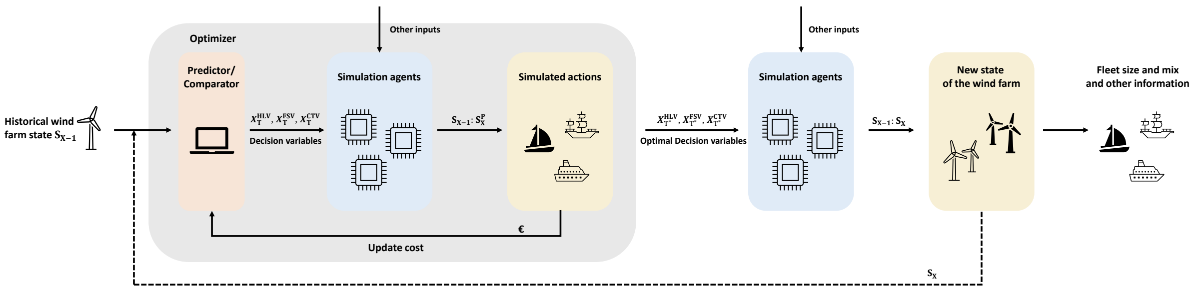


Figure 4.2: Flowchart of interaction between the feedforward simulation model and optimization algorithm

Firstly historical wind farm state is input into the model and it is marked as S_{X-1}, by using which, the predictor of the optimizer continuously tries different decision variable combinations. Each combination, together with other inputs, is fed into simulation agents, the simulation is executed and the state from initial state S_{X-1} to predicted terminal state S_X^P can be known, then the cost resulting from each simulation by each decision variable combination will be updated to comparator until the iterations are finished and the optimal decision variable combination is found. After that, the optimal one is chosen and again applied to the simulation model, then the fleet size and other outputs are obtained. Additionally, the new state of the wind farm, S_X is known and saved, and could be used as the historical wind farm state for further decision-making.

In this research, the explanation of the optimization approach of each maintenance cycle by using the feedforward simulation model is shown in Figure 4.3. Generally, for maintenance cycle X, the information about the terminal wind farm of the previous maintenance cycle $X-1$ is used as an input, which is marked as S_{X-1}. Since the previous maintenance cycle is just finished, it takes some time to trigger the next maintenance cycle, and there is a gap time with a length of t_X. When the new maintenance cycle X starts at $t = T_{X-1} + t_X$, by putting different decision variable combinations into the feedforward simulation model, the different terminal states of maintenance cycle X can be predicted, which is expressed as S_X^P, and the cost resulting from each decision variable combination will be known. Each cost is used for the performance evaluation of the corresponding decision variable combination. Among these decision variable combinations, only one optimal combination will be chosen and applied to the maintenance cycle X in the simulation model, then the specific terminal wind farm of the maintenance cycle X can be determined, which is marked as S_X. Again, for maintenance cycle $X+1$, the terminal wind farm state of maintenance cycle X is used as the next initial wind farm state of non-maintenance duration before maintenance cycle $X+1$ starts, which is also marked as previously mentioned S_X. Additionally, the cycle length of maintenance cycle X is $T_X - (T_{X-1} + t_X)$ and the length might be flexible but not a fixed time period.

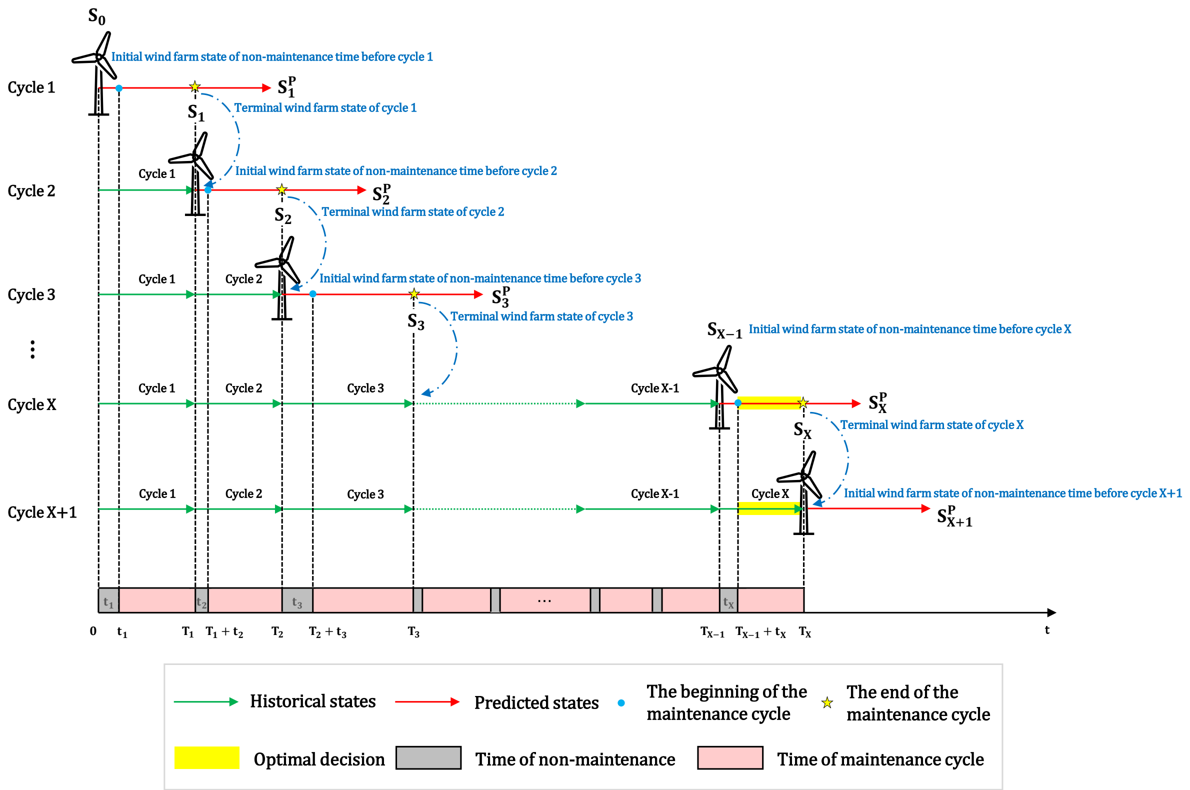


Figure 4.3: Illustration of the optimization approach of each maintenance cycle by using feedforward simulation model

For example, for the maintenance cycle 1, because this is the beginning of a wind farm, there is no historical state and a new state of an offshore wind farm will be generated, which is marked as S_0 at $t = 0$. There is no maintenance activity performed until the maintenance cycle is triggered at $t = t_1$. Thus, the time length for non-maintenance before maintenance cycle 1 is $t_1 - 0 = t_1$, which is the first grey area in Figure 4.3. At the time point t_1, different decision variable combinations are put into the simulation model, and different predicted states of maintenance cycle 1 are obtained as S_1^{P}. Among these decision variable combinations, the optimal combination is $X_{\mathrm{T}}^{\mathrm{HLV}} = 1$, $X_{\mathrm{T}}^{\mathrm{FSV}} = 2$, $X_{\mathrm{T}}^{\mathrm{CTV}} = 3$ (this combination is only an example here), then it is applied to the simulation model, and the terminal wind farm state of the maintenance cycle 1 is determined, including the lifetime, age percentage as well as the zone of each component of each turbine, can be known, which is marked as S_1. And the cycle length is $T_1 - t_1$, which is the first pink area in the time axis in Figure 4.3.

For the next maintenance cycle 2, all the previous information of maintenance cycle 1 becomes the historical state. The terminal wind farm state of maintenance cycle 1, S_1, is the initial wind farm state of non-maintenance duration before maintenance cycle 2. It takes a while when the maintenance cycle 2 is triggered and the gap time length of non-maintenance is t_2, which is the second grey area in the time axis in Figure 4.3. When the maintenance cycle 2 starts, at $T_1 + t_2$, again, the predicted states can be obtained after trying various decision variable combinations, donated as S_2^P. The optimal decision variable combination among those, for instance, $X_{\mathrm{T}}^{\mathrm{HLV}} = 2$, $X_{\mathrm{T}}^{\mathrm{FSV}} = 4$, $X_{\mathrm{T}}^{\mathrm{CTV}} = 6$, is applied to the simulation model, thus the terminal wind farm state of maintenance cycle 2 can be known after a mimic simulation, and this state is marked as S_2. The maintenance cycle 2 ends at $t = T_2$ and its maintenance cycle length is $T_2 - (T_1 + t_2)$.

Thereafter, for the next maintenance cycle 3, the previous steps are repeated in a similar way, and these also apply to any maintenance cycle X.

4.3. Optimisation Algorithm

To obtain the optimal decision variables, based on the information mentioned in the previous sections, the objective function as criteria and optimization method should be introduced for the iterations in this section.

4.3.1. Objective function

Before the simulation runs, the decision variables should be pre-defined in the model. For each decision variable combination, a set of scenarios is created with varying component lifetime and weather conditions in order to lessen the extreme results that can be produced by a single scenario. After the simulation of each scenario, all the information about the maintenance logistics of the wind farm within a planning time horizon can be known as well as the overall cost can be calculated. The objective is to minimize the expected total costs.

$$\overline{C^*} = \frac{\sum_{s \in \mathrm{S}} (C_{\mathrm{Task}}^s + C_{\mathrm{Cycle}}^s + C_{\mathrm{Vessel}}^s + C_{\mathrm{Loss}}^s)}{N_{\mathrm{S}}} \tag{4.1}$$

The average cost, which is the average value of the total costs of a certain number of scenarios, is the objective function in both two optimization models and is shown as equation 4.1. In this equation, $\mathbb{S}$ is the set of all scenarios, and in scenario s, four items are included. Where C^s_{Task} is the cost for maintenance tasks. C^s_{Cycle} is the cost for each maintenance cycle, which is for the penalty after the 60-day soft window constraint. C^s_{Vessel} is the cost for vessel-related stuff, including the cost caused by charter, charter extension, mobilization, late return, fuel and technicians. C^s_{Loss} is the cost for the turbine downtime, this is the loss when the turbine is not operating because of component failure or being repaired. N_{S} is the number of a set of scenarios.

4.3.2. The determination of scenario number

The more scenarios are considered for the average cost calculation, the more accurate the result of the decision variable combination is. However, more scenarios lead to more computation time, and the performance of computers is required to be higher. Considering the limited computation time and computer capacity in this project, a balance between fast computation and accurate results is needed to be found in this project.

Before applying the optimization method into two simulation models, the sensitivity of the scenario quantity is executed, where three combinations of the decision variables are chosen randomly. For each decision variable combination, 20, 30, 40 and 50 scenarios have separately been generated for a 15-year simulation and the annual costs are calculated accordingly. The results and gaps are shown in Table 4.1, Table 4.2 and Table 4.3.

Table 4.1: The result of scenario quantity of the first random combination

Decision variables combination	Scenario quantity	Annual cost (K€)	Gap (%)
$X^{\text{HLV}}_{\text{T}}$ = 5, $X^{\text{FSV}}_{\text{T}}$ = 10, $X^{\text{CTV}}_{\text{T}}$ = 20	20	7361.46	/
	30	7420.88	0.81%
	40	7524.34	2.21%
	50	7492.71	1.78%

Table 4.2: The result of scenario quantity of the second random combination

Decision variables combination	Scenario quantity	Annual cost (K€)	Gap (%)
$X^{\text{HLV}}_{\text{T}}$ = 8, $X^{\text{FSV}}_{\text{T}}$ = 18, $X^{\text{CTV}}_{\text{T}}$ = 60	20	6562.07	/
	30	6651.30	1.36%
	40	6784.69	3.39%
	50	6716.34	2.35%

Gap is expressed as a percentage of the annual cost difference based on when the number of scenarios is 20. It can be seen that the gaps in the scenario quantities from 20 to 50 are lower than 5% and acceptable, thus in this research, 20 scenarios are used for the average cost calculation considering the faster computation time and less result gaps.

Table 4.3: The result of scenario quantity of the third random combination

Decision variables combination	Scenario quantity	Annual cost (K€)	Gap (%)
X_T^{HLV} = 50, X_T^{FSV} = 100, X_T^{CTV} = 200	20	6435.55	/
	30	6549.79	1.78%
	40	6647.89	3.30%
	50	6592.00	2.43%

4.3.3. Simulated annealing

Because the references to the Salabim package are limited, the optimization method of the Salabim simulation model is rare to find in previous research. Inspired by [34], Simulated annealing is used to find the optimal result in the simulation model built with Salabim. Simulated annealing (SA) is a heuristic solution method applicable to a wide variety of optimization problems, and yields a workable solution in a fair amount of time for typical issues. First, a randomly generated initial solution is created, and the simulation model assesses the performance. The performance of the new random solutions that are created subsequently can be assessed. The Metropolis criterion can be applied in this situation because in the SA process, either one better or worse solution to the problem can be accepted with a specific probability[35].

The acceptance probability can be calculated as follows:

$$P = \begin{cases} 1 & E(n+1) < E(n) \\ e^{-\frac{E(n+1)-E(n)}{T(n)}} & E(n+1) \geq E(n) \end{cases} \tag{4.2}$$

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 model. While $T(n)$ is the current temperature. New solution is accepted when its energy value is lower than that of the old solution. Otherwise, a random variable U from distributed uniform over (0,1) will be used to compare with the acceptance probability from the equation 4.2. If the value of U is smaller, the new solution is accepted[36].

The temperature decreases according to a cooling schedule. The most common cooling schedule follows an exponential decay curve. The shape of this curve is determined by the starting temperature T_0, the cooling factor α and the cooling step n, which can be expressed as:

$$T(n) = T_0 \alpha^n \tag{4.3}$$

For each temperature T, inner loops are performed, and a series of accepted solution points need to be judged by the criterion expressed as equation 4.2, to reach a state of equilibrium. After reaching equilibrium, the temperature is reduced to a new temperature determined by the cooling schedule. The iterations of the algorithm keep running until the stopping criterion is met, and the system is considered to have frozen[36]. The final iteration ends when the final temperature is lower than the stopping temperature T_f, which can serve as the stopping criterion[37]. And the maximum number of cooling steps N can be calculated through:

$$N = \left\lceil \frac{lnT_f - lnT_0}{ln\alpha} \right\rceil \tag{4.4}$$

4.3.4. The optimization process of this research

Initially, as well as the first move of the optimization algorithm, an initial solution is generated randomly based on each decision variable's search domain. For each decision variable, it has its own search domain, the minimum value is the lower limit and the maximum value is the upper limit. A number is randomly chosen in this range and all three random numbers compose the initial solution. By applying this decision variable combination to the open-loop simulation model or feedforward simulation model, the simulation of the discrete events of an offshore wind farm under 20 scenarios will be executed, all the total costs of each scenario can be obtained, and the average cost of 20 scenarios will be calculated as the energy of the current move.

Next, a new solution will be generated. This can be realized by choosing one of the three decision variables randomly and generating a new random number based on its search domain and valuing it. Then the new number of the chosen decision variable and another two numbers of another two decision variables form the new solution. Again, by applying this new decision variable combination to the simulation model for the new costs under 20 scenarios, all total costs and the average cost, which is the energy of the new move, can be obtained.

Then a comparison between the initial solution and the new solution is performed by comparing their average costs obtained from the simulation model, 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, and 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) will be generated and compared with the current acceptance probability. If the value of the current 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.

Before jumping to the next move, the current temperature and the number of iterations at the current temperature should be always checked. There are a certain number of iterations at each planned temperature, only when all the iterations are done, can the temperature decreases. And the new temperature should be compared with the stopping temperature before starting the iterations at the new temperature. 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 will be 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 temperature is decreasing based on the cooling schedule, which is expressed as 4.3. In the very beginning, when the temperature is high, the acceptance for the new solution with higher energy is relatively and the as the temperature drops, the acceptance probability is lower and lower, and the cooling process is close to stable. All these steps iterate until the temperature is lower than the stopping temperature. All these procedures of the simulated annealing in this research is expressed as the flow chart shown in Figure 4.4.

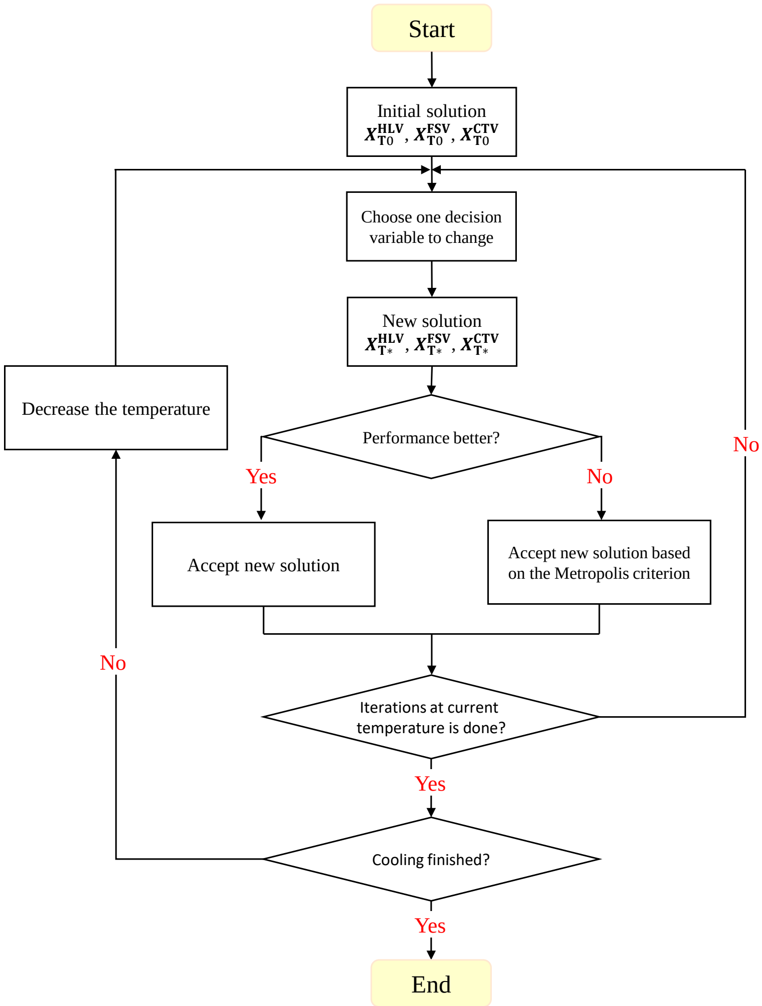


Figure 4.4: The flow chart of the simulated annealing process

For example, the search domain of $X_{\mathrm{T}}^{\mathrm{HLV}}$ is [1, 10], the search domain of $X_{\mathrm{T}}^{\mathrm{FSV}}$ is [1, 20] and the search domain of $X_{\mathrm{T}}^{\mathrm{CTV}}$ is [1, 30]. The initial decision variable combination is $X_{\mathrm{T}}^{\mathrm{HLV}} = 5$, $X_{\mathrm{T}}^{\mathrm{FSV}} = 15$, $X_{\mathrm{T}}^{\mathrm{CTV}} = 25$, and after applying this combination into the simulation model, the cost of the predicted period is 4000 EUR, which is the energy of this step and it is the performance evaluation of this decision variable combination. Then, one decision variable is randomly chosen, here take $X_{\mathrm{T}}^{\mathrm{CTV}}$ for an instance, and the new value of it randomly generated as 8, based on its search domain. Then the new combination, $X_{\mathrm{T}}^{\mathrm{HLV}} = 5$, $X_{\mathrm{T}}^{\mathrm{FSV}} = 15$, $X_{\mathrm{T}}^{\mathrm{CTV}} = 8$ is the new solution, the new predicted cost can be obtained and it is the energy of this new step and it is the performance evaluation of this new decision variable combination. If the cost is 3500 EUR, then the new solution is directly accepted, while if the cost is 4500 EUR, it is accepted based on the Metropolis criterion as previously mentioned. For example, if the current temperature is 50 degree, according to the equation 4.2, the acceptance probability is

$$e^{-\frac{E(n+1)-E(n)}{T(n)}} = e^{-\frac{4500-4000}{500}} = e^{-1} = 0.368 \tag{4.5}$$

If a random variable U from distributed uniform over (0,1) is 0.2, then it is smaller than the acceptance probability at the current temperature, then the new solution is accepted, and if the annealing is not finished, the next new solution will be generated based on $X_{\mathrm{T}}^{\mathrm{HLV}} = 5$, $X_{\mathrm{T}}^{\mathrm{FSV}} = 15$, $X_{\mathrm{T}}^{\mathrm{CTV}} = 8$ by changing one of these three decision variables. However, if U is randomly generated as 0.4, then the new solution is rejected, and if the annealing is not finished, the next new solution will be generated based on $X_{\mathrm{T}}^{\mathrm{HLV}} = 5$, $X_{\mathrm{T}}^{\mathrm{FSV}} = 15$, $X_{\mathrm{T}}^{\mathrm{CTV}} = 25$ by changing one of these three decision variables. After this, the simulated annealing will stop until the stopping criterion is met.

5
Case Study and Results

In this chapter, one case study will be performed based on the models and optimization methods introduced in the previous chapter. By referring to previous research and using the corresponding data in the models, the logistics discrete event at an offshore wind farm can be simulated and the result can be evaluated. All simulations are realized by using Salabim, a discrete event simulation package in Python, the open-loop simulation-optimization model runs on an Intel Xeon 40-core-80-threads processor with 192G ddr4 memory and the feedforward open-loop simulation-optimization model runs on an Intel Xeon 14-core-28-threads processor with 128G ddr4 memory.

5.1. Case study

5.1.1. Wind farm and turbines inputs

For the wind farm-specific inputs, all the values are defined in Table 5.1. All these values are referred and estimated from Dalgic et al.[21].

5.1.2. Vessel transportation inputs

For the vessel-related inputs of 3 vessel types, all the values are listed in Table 5.2. All these values are referred and estimated from Dalgic et al. [21].

Table 5.1: The values of wind farm and turbine inputs

No	Item	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	Soft time window	60	day

Table 5.2: The values of vessel inputs

No	Item	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	α	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	–	–	hour
10	Jack-down time	3	–	–	hour
11	Mobilisation 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	Penalty factor for late return	2	2	2	-
16	Fuel consumption	0.55	0.2	0.24	mt/h
17	Safety margin	20	20	β	min

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

5.1.3. Owned vessels inputs

In this research, for the owned vessel inputs, it is considered that there is only one owned CTV, and neither FSV nor HLV is owned. Therefore, if there is any major repair, preventive replacement or corrective replacement, the corresponding FSV or HLV has to be chartered into the fleet. Also, for each scenario in the case study, the number of owned vessels of each vessel type is the same.

Table 5.3: The values of owned vessels inputs

No	Item	Value	Unit
1	Number of owned HLVs	0	vessel
2	Number of owned FSVs	0	vessel
3	Number of owned CTVs	1	vessel

5.1.4. Components inputs

In this report, all the values of the Weibull shape parameters and Weibull scale parameters referred from Sarker et al.[38] are shown in Table 5.4.

Table 5.4: The values of component lifetime inputs

Component	Weibull shape parameter (Unit: −)	Weibull scale parameter (Unit: day)
Rotor	3	3,000
Bearing	2	3,750
Gearbox	3	2,400
Generator	2	3,300

5.1.5. Maintenance type inputs

Maintenance type inputs include the maintenance time inputs and maintenance cost inputs. Time and cost vary when different types of maintenance tasks on the different turbine components, and all these data are estimated and collected from Carroll et al.[39], and Andrews et al.[40]. All the time values are provided in Table 5.5.

While for different types of maintenance tasks on the different turbine components, different costs are shown in Table 5.6.

5.1.6. Additional cost inputs

Table 5.7 shows the additional cost inputs [1-12] used for the total cost calculation, and the values of inputs [1-13] are referred from Dalgic et al. [21].

Table 5.5: The values of maintenance time inputs

Maintenance type	Time value (Unit: h)			
	Rotor	Bearing	Gearbox	Generator
Minor repair	9	6	8	7
Major repair	18	12	16	14
Preventive replacement	70	50	70	60
Corrective replacement	100	70	100	81

Table 5.6: The values of maintenance cost inputs

Maintenance type	Cost value (Unit: €)			
	Rotor	Bearing	Gearbox	Generator
Minor repair	4,000	1,000	5,000	1,500
Major repair	15,000	3,750	18,750	5,000
Preventive replacement	60,000	15,000	75,000	20,000
Corrective replacement	185,000	45,000	230,000	60,000

Table 5.7: The values of additional cost inputs

No	Item	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	2,500	€/CTV/day
5	HLV mobilisation cost	800,000	€/mobilisation
6	FSV mobilisation cost	200,000	€/mobilisation
7	CTV mobilisation cost	50,000	€/mobilisation
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

5.1.7. Climate inputs

For the climate inputs, the values of inputs [1-4] are from Barth and Eecen[41] and the value of input[6] is from Yalcin at al.[21]. All the relevant values are shown in Table 5.8.

Table 5.8: Climate inputs

No	Item	Value	Unit
1	Weibull shape parameter of wind speed (at 21m)	2.43	-
2	Weibull scale parameter of wind speed (at 21m)	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	Shear component	0.1	-

5.1.8. Parameters for simulated annealing

Referred to [34], the values of some SA parameters are defined. In practice, some values are assumed and tweaked to find the most feasible ones that are feasible to work with. Considering each time-horizon simulation costs around 8 minutes and each feedforward simulation model uses around 2 minutes, the number of each model's iterations is set to 200. In this research, all these parameters, listed in Table 5.9, are defined by taking into account the limitations of the computation power of the computer and can be changed by different situations and needs, and the tuning of the SA parameters can be the future work:

Table 5.9: Parameters for simulated annealing

Item	Value
Initial temperature	100°C
Stopping temperature	4°C
Cooling factor	0.5
Cooling step	5
Inner loops at each temperature	40

The number of cooling steps is calculated through formula 4.4:

$$N = \left\lceil \frac{ln(4) - ln(100)}{ln(0.5)} \right\rceil = \left\lceil 4.64 \right\rceil = 5 \tag{5.1}$$

And the number of iterations is calculated as:

$$5 * 40 = 200 \quad (5.2)$$

While for the search domain of each decision variable, considering the assumption that every component can only be repaired once in every maintenance cycle, the worst case is that all the components get repaired, so the upper limit of the search domain is 50 (the number of turbines in the wind farm) × 4 (the number of components for each turbine) = 200 (the number of components). Also, considering that the number of tasks for corrective replacement and preventive replacement and the number of tasks for major repair are lower than the number of tasks for minor repairs. Altogether, the search domains are estimated as shown in Table 5.10.

Table 5.10: Search domain for each decision variable

Item	Lower limit	Upper limit
$X_{\mathrm{T}}^{\mathrm{HLV}}$	1	25
$X_{\mathrm{T}}^{\mathrm{FSV}}$	1	75
$X_{\mathrm{T}}^{\mathrm{CTV}}$	1	200

5.2. The result of long-term optimization

Long-term horizon, in this research, is The open-loop simulation-optimization model is applied for long-term optimization of a 15-year offshore wind farm, and this section presents all the results of simulation outputs including turbine information, cycle information, component information, vessel charter information, vessel travel information, and vessel utilization information. All their corresponding analysis follows the result in every section. Each scenario is referred to as Set in the following figures and tables in this section.

5.2.1. Decision variables and fleet configurations

All values are presented in Table 5.11 for the number of chartered vessels for each maintenance cycle, based on the optimal decision variable result of $X_{\mathrm{T}}^{\mathrm{HLV}}$ = 6, $X_{\mathrm{T}}^{\mathrm{FSV}}$ = 24, $X_{\mathrm{T}}^{\mathrm{CTV}}$ = 150.

5.2.2. Turbine information result

Turbine information results consist of three parts, the result of the total electricity production of the offshore wind farm, the result of the time-based availability of the offshore wind farm, and the result of the power-based availability of the offshore wind farm.

For the result of the total electricity production of the offshore wind farm, all 20-scenario values and average values are shown in Figure 5.1. Therefore, weather conditions, including wave height and wind speed, vary between the various scenarios, and electricity production, which is derived from equation 3.10, is different, respectively. When turbines are operating well and wind speeds are appropriate for

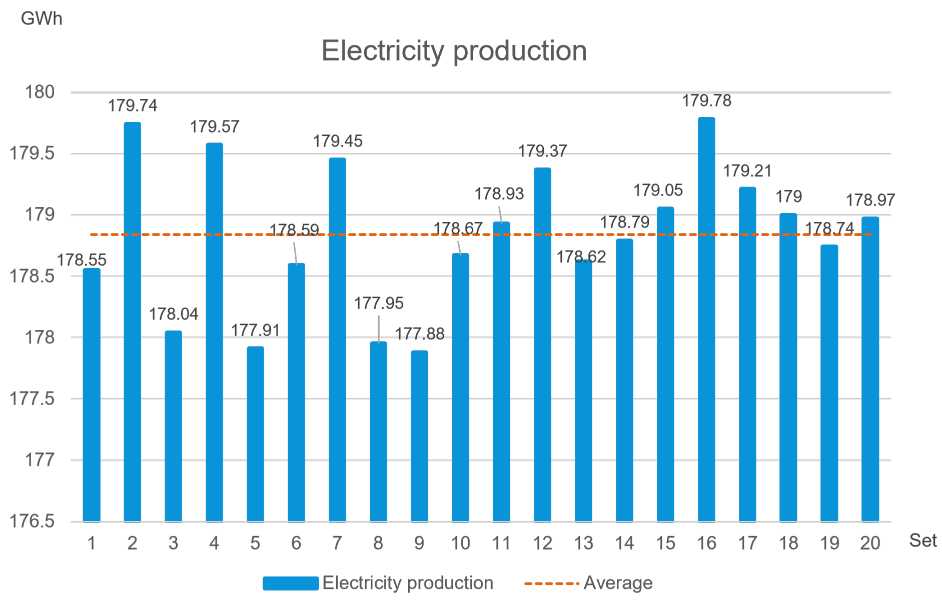


Figure 5.1: The result of wind farm electricity production

producing energy, the value of electricity produced can be higher than in more adverse circumstances.

Based on the actual power produced by the turbines, the value for electricity production for each scenario is determined. The power generated by turbines operating over a planned period of time can be used to calculate theoretical power output. The cost loss is the difference between these two values multiplied by the electricity cost.

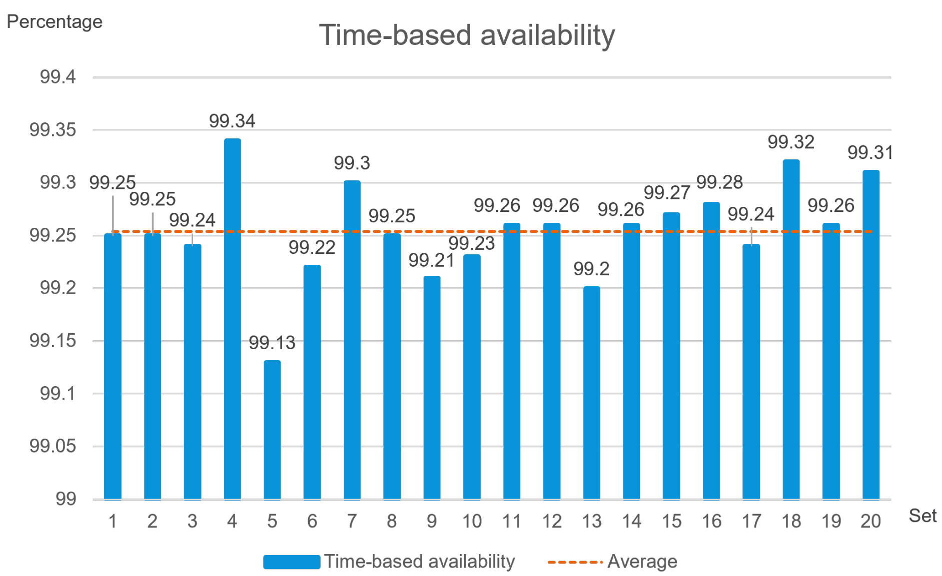


Figure 5.2: The result of time-based availability

Table 5.11: The values of chartered vessels

	SET1	SET2	SET3	SET4	SET5	SET6	SET7	SET8	SET9	SET10	SET11	SET12	SET13	SET14	SET15	SET16	SET17	SET18	SET19	SET20
Cycle 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
Cycle 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
Cycle 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
Cycle 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
Cycle 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
Cycle 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
Cycle 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
Cycle 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
Cycle 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
Cycle 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
Cycle 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
Cycle 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
Cycle 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
Cycle 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	-
Cycle 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	-
Cycle 16	-	-	1, 2, 0	-	1, 1, 0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cycle 17	-	-	-	-	1, 1, 0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

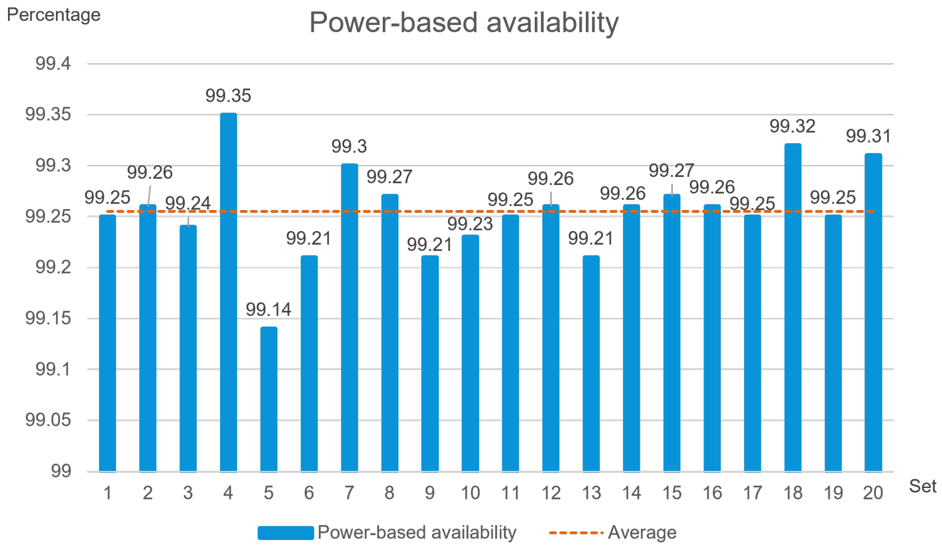


Figure 5.3: The result of power-based availability

The outcome of the offshore wind farm's power-based availability is depicted similarly in Figure 5.3. During a planning time period, all turbine information reflects the overall state of the offshore wind farm.

5.2.3. Maintenance cycle information

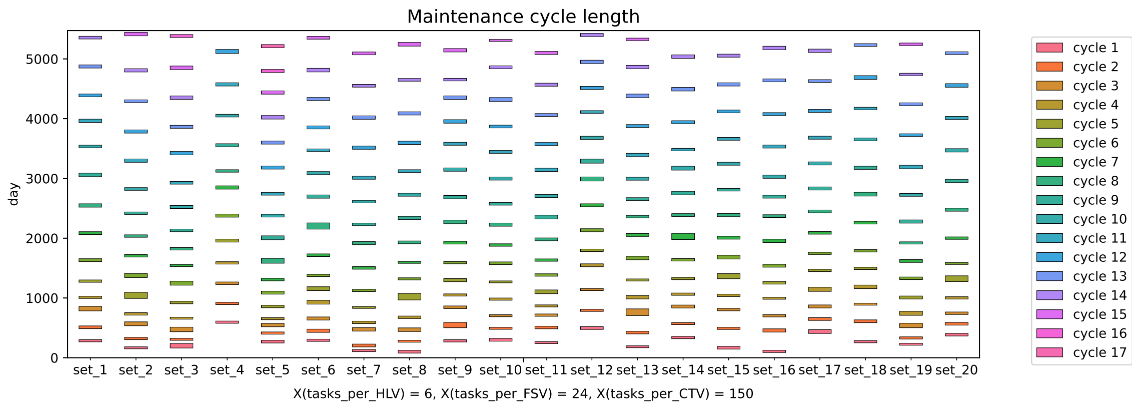
The results of the turbine information are divided into two categories: the maintenance cycle length (days), and the cost of extended maintenance cycles

Figure 5.4 displays all the data for the maintenance cycle length result. The relative location of each maintenance cycle of each scenario to the entire time horizon is shown in the top portion of Figure 5.4, from a down-to-up perspective to the Y-axis. And the width of each bar depicts the relative length of each maintenance cycle. As can be seen, all of the bars are complete, which means that under any circumstance, the wind farm's 15-year time horizon will not cause any maintenance cycles to be disrupted.

The bottom portion of Figure 5.4 shows the specifics for the number of maintenance cycle days. It is clear that the number of maintenance cycles may 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 not easy to initiate the maintenance cycle, thus the amount of maintenance cycles will be less.

The length also changes for each maintenance cycle. The workload during this time period and the weather conditions may have an impact on this. All maintenance jobs can be completed more quickly when the weather is conducive for task performance as opposed to when it is not. Also, each maintenance cycle requires less time if there are fewer maintenance activities, therefore its duration falls in direct proportion.

The majority of each maintenance cycle often lasts fewer than 60 days. The daily penalty cost and any vessel-related expenses will be assessed once the soft time limit has been exceeded. Figure 5.5 depicts all of the numbers for the former cost, which was the result of the penalty cost associated with extended maintenance cycles outside of the soft time range. As can be seen, the cost of the penalty is 0 for every



Unit: day	X(tasks_per_HLV) = 6, X(tasks_per_FSV) = 24, X(tasks_per_CTV) = 150																			
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10	set_11	set_12	set_13	set_14	set_15	set_16	set_17	set_18	set_19	set_20
cycle 1 length	37	34	75	38	45	38	37	45	38	46	34	48	33	39	45	39	64	37	33	43
cycle 2 length	47	39	33	38	38	55	48	33	89	34	43	35	44	35	37	54	48	48	37	45
cycle 3 length	75	66	77	43	55	52	60	61	44	34	40	36	112	50	41	41	51	34	75	42
cycle 4 length	37	41	33	40	37	64	42	42	37	38	35	49	58	39	40	34	70	60	68	39
cycle 5 length	40	103	42	50	42	65	33	109	52	33	64	42	35	39	85	45	39	39	50	96
cycle 6 length	49	68	67	52	50	39	39	36	38	46	41	51	59	42	63	49	37	39	44	34
cycle 7 length	48	42	37	55	42	45	45	33	47	42	40	50	49	104	49	56	44	46	48	41
cycle 8 length	57	42	42	42	82	104	51	47	61	54	48	68	43	47	52	47	48	64	38	52
cycle 9 length	60	41	44	52	66	55	44	52	56	46	64	69	49	60	44	50	52	53	54	56
cycle 10 length	44	45	51	45	47	51	44	51	56	52	53	52	51	66	50	54	52	48	48	56
cycle 11 length	55	56	46	55	47	45	52	48	50	47	56	44	56	42	47	51	51	43	59	51
cycle 12 length	47	54	56	67	52	51	54	55	59	47	50	51	49	50	48	49	51	62	46	60
cycle 13 length	52	46	50	-	52	50	57	54	60	66	47	56	60	60	54	49	46	45	47	46
cycle 14 length	46	55	56	-	59	61	47	45	43	48	51	53	57	59	51	59	56	-	42	-
cycle 15 length	-	60	59	-	55	47	48	62	57	33	50	-	43	-	-	-	-	-	44	-
cycle 16 length	-	-	49	-	51	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 17 length	-	-	-	-	53	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
total	694	792	817	577	873	822	701	773	787	666	716	704	798	732	706	677	709	618	733	661

Figure 5.4: The result of the maintenance cycle length

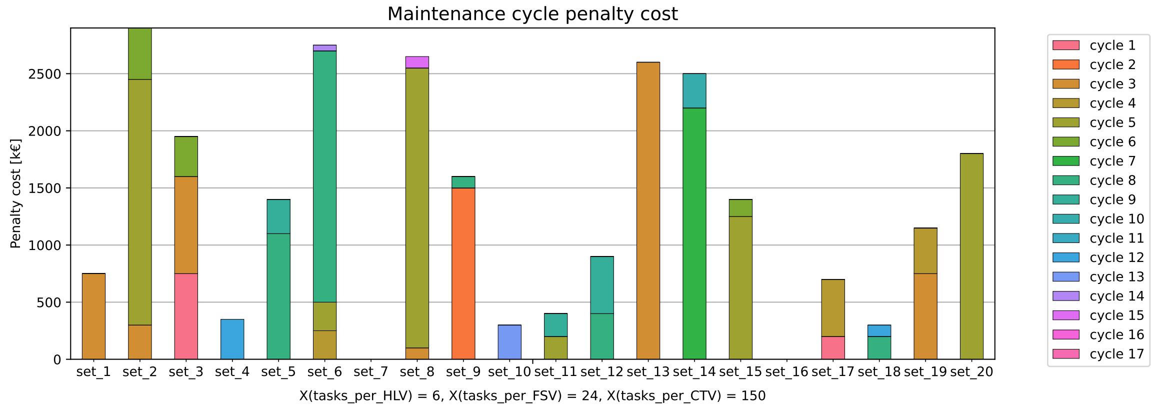
maintenance cycle with a duration of fewer than 60 days, and for cycles of more than 60 days, the cost of the penalty is calculated by multiplying the number of days above 60 days by the daily penalty.

5.2.4. Maintenance tasks information

The results of the maintenance tasks information include two parts, the number of maintenance activities of each type, and the costs of maintenance activities of each type.

Figure 5.6 displays all values for the quantity of each type of maintenance activity.

The figure shows that, of all the maintenance tasks, the number of minor repairs dominates, followed by the number of major repairs and preventative replacements, and the number of corrective replacements has the lowest number. The maintenance strategy, where the component age and the related zone and age reduction are determined, have an impact on this result. The proportion of each task type will fluctuate as the range of each zone changes. The component's lifetime can also have an impact on how many tasks are performed. Because for components with longer lifetime, it takes longer days to enter their repair zones, and less maintenance is needed after each repair due to the absolute days of reduced lifespan being more.



Unit: k€	X(tasks_per_HLV) = 6, X(tasks_per_FSV) = 24, X(tasks_per_CTV) = 150																			
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10	set_11	set_12	set_13	set_14	set_15	set_16	set_17	set_18	set_19	set_20
cycle 1	0	0	750	0	0	0	0	0	0	0	0	0	0	0	0	0	200	0	0	0
cycle 2	0	0	0	0	0	0	0	0	1500	0	0	0	0	0	0	0	0	0	0	0
cycle 3	750	300	850	0	0	0	0	100	0	0	0	0	2600	0	0	0	0	0	750	0
cycle 4	0	0	0	0	0	250	0	0	0	0	0	0	0	0	0	0	500	0	400	0
cycle 5	0	2150	0	0	0	250	0	2450	0	0	200	0	0	0	1250	0	0	0	0	1800
cycle 6	0	450	350	0	0	0	0	0	0	0	0	0	0	0	150	0	0	0	0	0
cycle 7	0	0	0	0	0	0	0	0	0	0	0	0	0	2200	0	0	0	0	0	0
cycle 8	0	0	0	0	1100	2200	0	0	100	0	0	400	0	0	0	0	0	200	0	0
cycle 9	0	0	0	0	300	0	0	0	0	0	200	500	0	0	0	0	0	0	0	0
cycle 10	0	0	0	0	0	0	0	0	0	0	0	0	0	300	0	0	0	0	0	0
cycle 11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
cycle 12	0	0	0	350	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0
cycle 13	0	0	0	-	0	0	0	0	0	300	0	0	0	0	0	0	0	0	0	0
cycle 14	0	0	0	-	0	50	0	0	0	0	0	0	0	0	0	0	0	-	0	-
cycle 15	-	0	0	-	0	0	0	100	0	0	0	-	0	-	-	-	-	-	0	-
cycle 16	-	-	0	-	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 17	-	-	-	-	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
total	750	2900	1950	350	1400	2750	0	2650	1600	300	400	900	2600	2500	1400	0	700	300	1150	1800

Figure 5.5: The result of the cost related to prolonged maintenance cycles

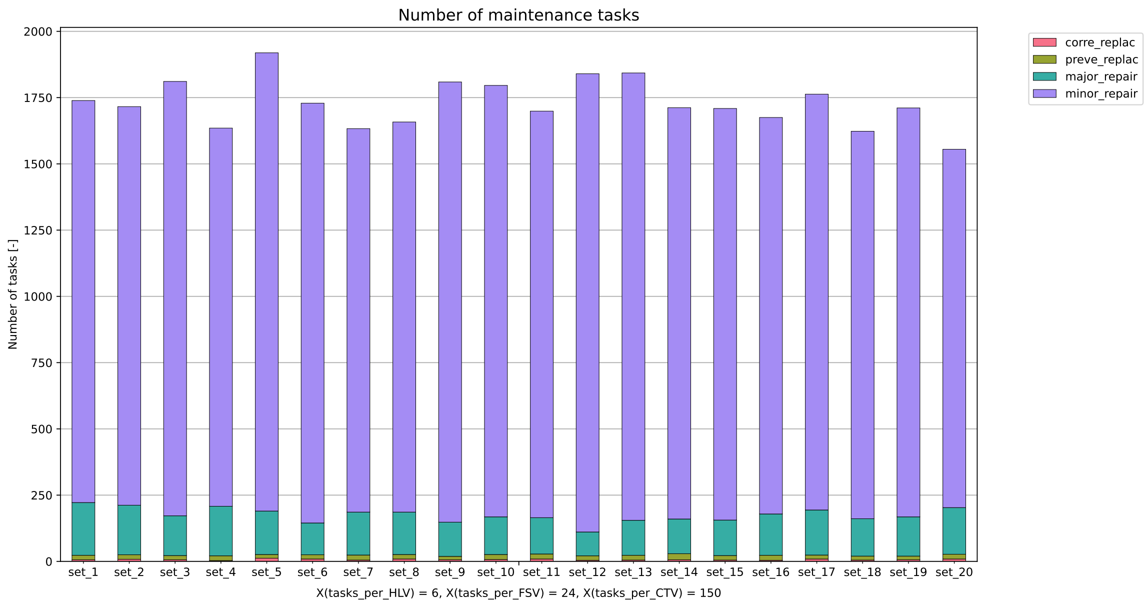
While for the cost of maintenance activities of each type, all the values are shown in Figure 5.7.

In contrast to the preceding figure 5.6, the proportion of each task type in each scenario is varied. This occurs because different maintenance types on different components have different costs. For instance, the cost of the corrective replacement of each component is far more than the cost of each component's minor repairs. The cost of corrective replacements continues to rise despite the fact that there are relatively few of them, which causes an increase in their proportion on cost bars.

5.2.5. Vessel charter cost

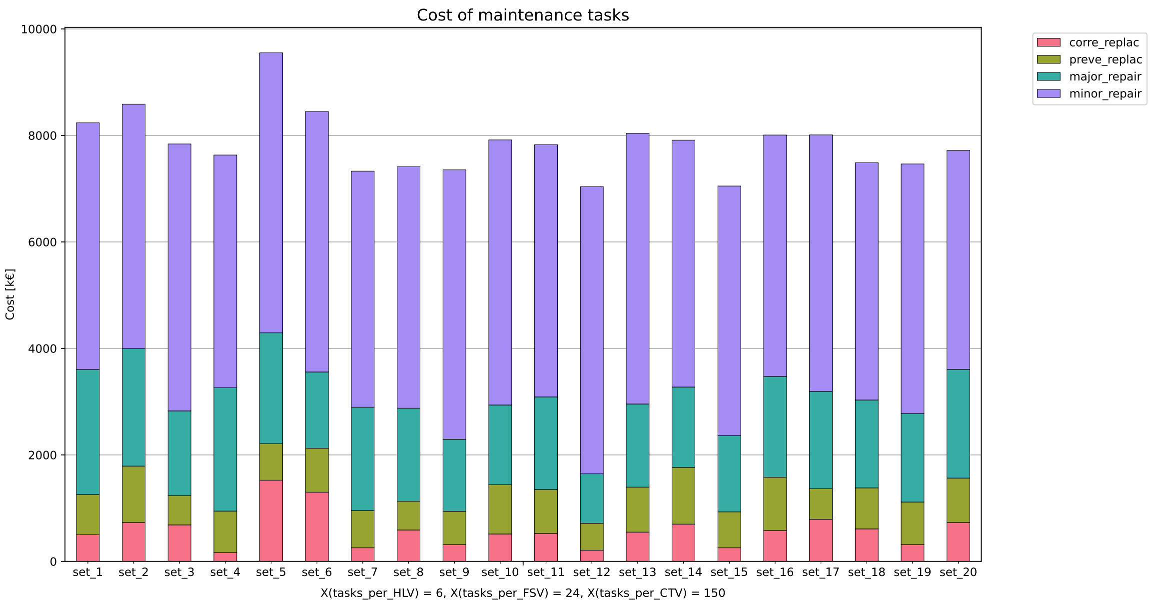
The results of the vessel charter information consist of five parts: the number and cost of charters of each vessel type, the number and cost of extended charter periods of each vessel type, the number and cost of mobilizations of each vessel type, the total number of days and cost of the late-returned chartered vessel of each vessel type, and the cost of technicians.

Each combination of three numbers reveals the chartered number of each vessel type in each maintenance cycle in each scenario. The first number represents the number of HLV type, the second number represents the number of FSV type, and the third number represents the number of CTV type, respectively. The results indicate



Unit: -	X(tasks_per_HLV) = 6, X(tasks_per_FSV) = 24, X(tasks_per_CTV) = 150																			
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10	set_11	set_12	set_13	set_14	set_15	set_16	set_17	set_18	set_19	set_20
corre_replac	6	8	6	3	12	9	5	9	6	7	9	4	5	6	5	4	9	5	6	9
preve_replac	17	17	16	18	14	16	19	17	13	19	19	17	18	23	17	19	15	15	14	18
major_repair	199	187	150	187	164	120	162	160	129	142	137	90	132	131	134	156	170	141	148	176
minor_repair	1517	1504	1639	1427	1729	1584	1447	1472	1661	1628	1534	1729	1688	1552	1553	1496	1569	1462	1543	1352
total	1739	1716	1811	1635	1919	1729	1633	1658	1809	1796	1699	1840	1843	1712	1709	1675	1763	1623	1711	1555

Figure 5.6: The result of the number of maintenance tasks



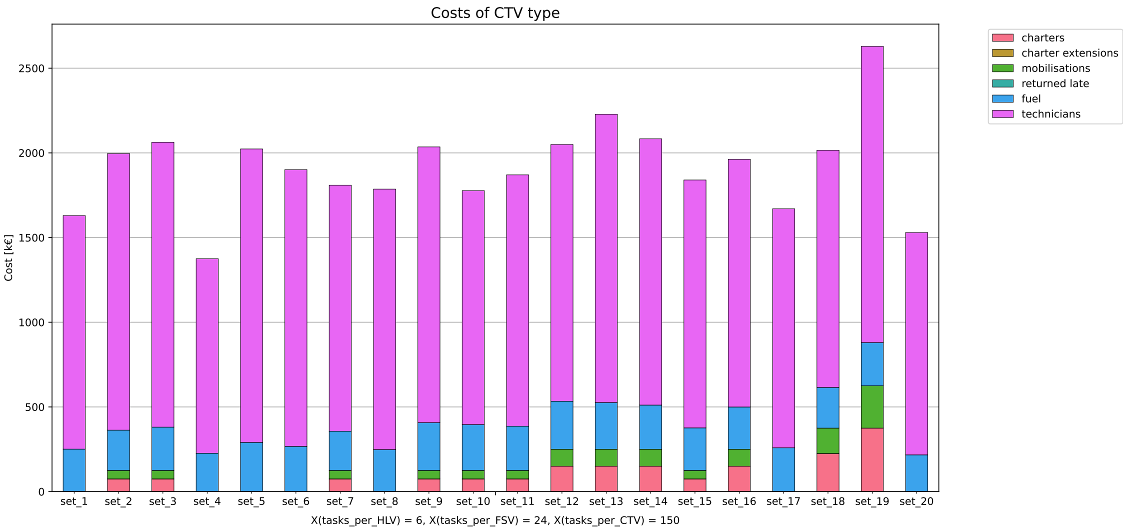
Unit: k€	X(tasks_per_HLV) = 6, X(tasks_per_FSV) = 24, X(tasks_per_CTV) = 150																			
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10	set_11	set_12	set_13	set_14	set_15	set_16	set_17	set_18	set_19	set_20
corre_replac	500.0	730.0	685.0	165.0	1525.0	1300.0	255.0	590.0	315.0	515.0	525.0	210.0	550.0	700.0	255.0	580.0	790.0	610.0	315.0	730.0
preve_replac	755.0	1060.0	550.0	780.0	685.0	825.0	700.0	540.0	625.0	925.0	825.0	505.0	845.0	1065.0	675.0	1000.0	575.0	770.0	800.0	835.0
major_repair	2348.75	2206.25	1591.25	2316.25	2082.5	1432.5	1941.25	1747.5	1352.5	1497.5	1738.75	930.0	1561.25	1510.0	1432.5	1892.5	1827.5	1651.25	1661.25	2041.25
minor_repair	4632.5	4590.5	5013.0	4370.5	5258.5	4891.0	4433.0	4534.0	5061.0	4978.0	4737.0	5393.0	5082.0	4636.0	4687.0	4534.5	4817.0	4455.5	4687.5	4115.5
total	8236.25	8586.75	7839.25	7631.75	9551.0	8448.5	7329.25	7411.5	7353.5	7915.5	7825.75	7038.0	8038.25	7911.0	7049.5	8007.0	8009.5	7486.75	7463.75	7721.75

Figure 5.7: The result of the cost of maintenance tasks

that HLV is necessary in every maintenance cycle since both preventative replacement and corrective replacement, which are the two triggers that initiate maintenance, require HLV type. All the chartered values for HLV are 1 because the number of such task types is always small. What is more, most of the time, one FSV and one CTV are sufficient, and because there is only one owned vessel, the chartered CTV is zero.

More FSV and CTV are still necessary in a few situations, and these take place in the middle or at the end of the planning time horizon. This is because the maintenance can keep up with the rate of aging of the components during the earlier part of the planning horizon. As components get older, their overall condition deteriorates and more maintenance operations are needed, demanding the need for more vessels.

The distribution of different costs can be calculated after the simulation is finished. For all the costs of CTV type, all the values are shown in Figure 5.8 while the cost distribution of FSV and HLV can be seen in the appendix.



Unit: k€	X(tasks_per_HLV) = 6, X(tasks_per_FSV) = 24, X(tasks_per_CTV) = 150																			
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10	set_11	set_12	set_13	set_14	set_15	set_16	set_17	set_18	set_19	set_20
charters	0	75.0	75.0	0	0	0	75.0	0	75.0	75.0	75.0	150.0	150.0	150.0	75.0	150.0	0	225.0	375.0	0
charter extensions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
mobilisations	0	50.0	50.0	0	0	0	50.0	0	50.0	50.0	50.0	100.0	100.0	100.0	50.0	100.0	0	150.0	250.0	0
returned late	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
fuel	250.9	238.0	255.8	226.3	290.4	266.8	231.5	248.5	282.5	270.9	261.2	283.4	276.0	261.1	251.3	249.7	258.7	239.9	255.1	216.9
technicians	1379.1	1632.9	1682.1	1148.9	1732.8	1634.4	1452.8	1537.7	1627.8	1381.3	1484.0	1516.2	1702.3	1572.0	1463.8	1462.2	1411.2	1400.8	1748.8	1312.8
total	1629.9	1995.9	2062.9	1375.2	2023.2	1901.2	1809.3	1786.2	2035.3	1777.2	1870.2	2049.6	2228.3	2083.1	1840.0	1961.9	1669.8	2015.8	2628.9	1529.7

Figure 5.8: The cost of CTV

The cost of technicians and petrol cannot be disregarded and is evident in every scenario, as this figure demonstrates. In some cases, the owned CTV is sufficient for all maintenance duties, eliminating the need for a charter cost and the associated mobilization cost. Also, in cases when the charter cost and the mobilization cost are needed, these two costs are positively associated. Moreover, there are no decisions on charter extension, and all CTV vessels return to the base before their charter expires, thus there are no charter extension costs or return-late costs for any of the scenarios.

Because the charter cost is comparatively greater for HLV and FSV types, especially for the HLV type, the charter cost is the most important cost among all the costs. The data are included in the appendix and provide more information on the costs of

HLV and FSV.

5.2.6. Vessel travel cost

The results of the vessel travel information only have one part: the fuel cost for traveling, which is included as one part of the vessel cost. For the fuel cost of CTV, all details are illustrated in Figure 5.8. It can be seen that, in any case, fuel cost cannot be ignored and in most cases, it is the second most significant cost, following behind technician costs.

5.2.7. Vessel utilization

The results of the vessel utilization information are divided into nine categories: the time spent on traveling to the base, the time spent on traveling to the site, the time spent on inter-transit travel, the time restricted by weather conditions, the time of idling at the base during each maintenance cycle, the time restricted by shift hours, the time spent on maintenance tasks, the time of idling on-site during each maintenance cycle, and the time spent on jacking up/down.

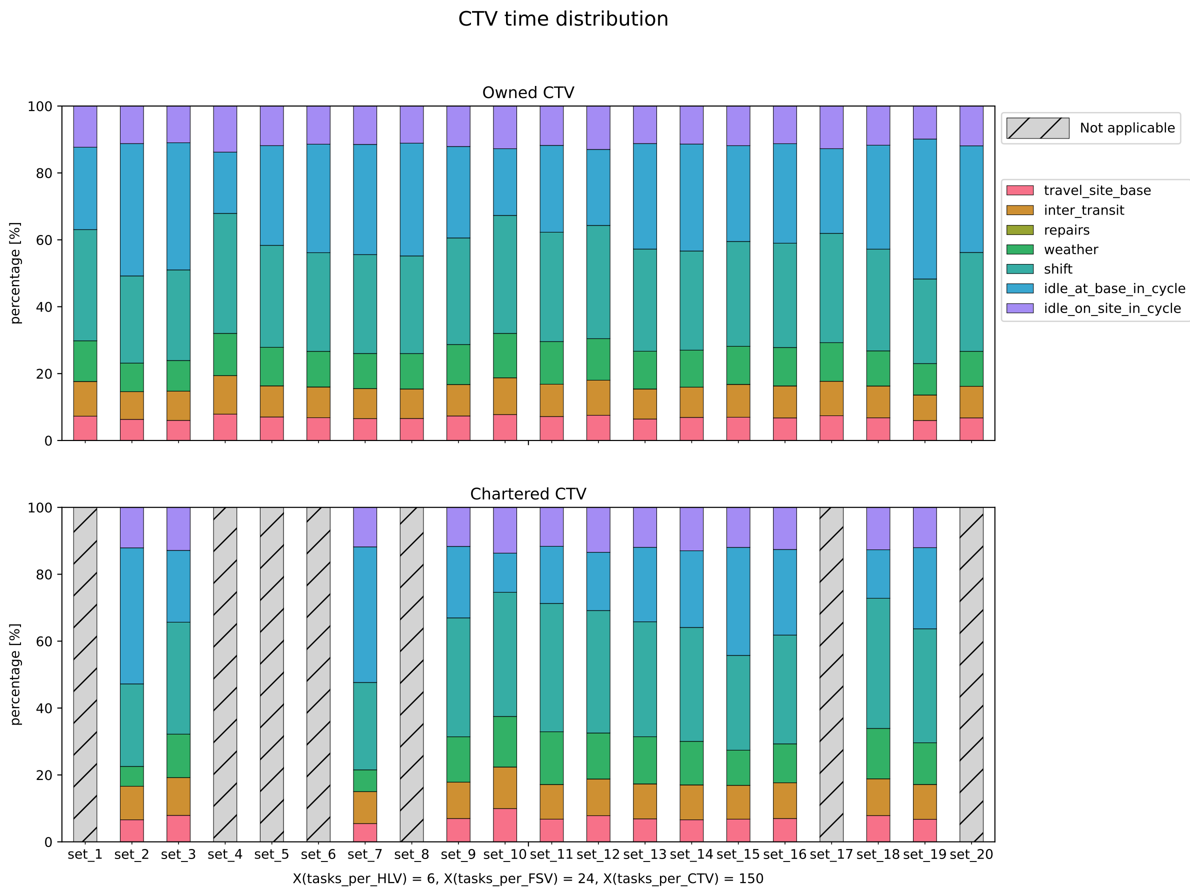


Figure 5.9: The result of CTV time distribution

Figure 5.9 displays all the data for the CTV type's time distribution. The picture's histograms at the top and bottom display the time distribution for owned CTV and chartered CTV, respectively.

The majority of the time is idle for owned CTV, either at the base or on-site. Due to the limitations of the weather and shift, the time spent on traveling due to inclement weather and shift end up taking a significant amount of time, with the weather conditions contributing even more. Because the CTV's primary purpose is to transport teams to the turbines, there is no time utilized for repairs. The time spent traveling between the site and the base and the time spent in transit only make up a small portion, but wind farm operators and developers should take this into consideration.

The time distribution of each scenario for chartered CTV is substantially similar to that of owned CTV. While it is preferable to use owned CTV when performing maintenance tasks, it is possible that in some circumstances no additional CTV will need to be chartered, which will result in the statement "Not applicable" Figure 5.9 and the absence of time distribution data.

While the data for the HLV and FSV time distribution can be found in the appendix.

5.3. The sensitivity analysis of the open-loop simulation-optimization model

Due to the fact that the simulation model's outputs depend on a wide range of inputs, this section performs a sensitivity analysis on a few of these inputs in order to test various values for verification and assess how these inputs affect the outcomes, which wind farm developers and researchers may use as a reference. Below is a list of all the modifications made to some input parameters:

- Weibull scale parameter of climate input times 1.5
- Weibull scale parameter of climate input times 0.5
- Maximum parallel teams number on CTV changed to 6
- Maximum parallel teams number on CTV changed to 2
- Penalty cost times 1.5
- Penalty cost times 0.5
- Charter length times 1.5
- Charter length times 0.5
- The range of each component zone times 1.5
- The range of each component zone times 0.5

The average values of 20 scenario results are then obtained after running additional 10 simulations in a similar manner. The results of total charters, which are the sum of the charter cost and charter extension cost for all vessel types, and the cost of maintenance tasks from 10 sensitivity simulations are presented in Table 5.12 result and will be analyzed along with the previous results.

All of the annual cost results for the various categories are presented and sorted by total O&M cost in descending order, along with the results obtained using the original input parameters in the preceding sections. The sensitivity study's findings show that, adjustments in the penalty have little impact on the costs other than the annual penalty cost. As a result, the overall O&M costs are quite similar. This is because, in the developed simulation model, the balance between the number of chartering vessels and the lengths of maintenance cycles is significant to the overall costs under certain weather conditions. The number of chartered vessels affects how quickly maintenance tasks are completed and how long maintenance cycles last. In this instance, higher charter costs are caused by more vessels. If the vessel size is insufficient for the maintenance activities, on the other hand, the maintenance cycle must be extended; as a result, the penalty cost will be paid when the soft window is exceeded. As the magnitudes of the two penalty costs in the sensitivity study and the original penalty cost are equal, the adjustments have no effect on any of the costs other than the annual penalty cost.

Regarding the changes in the climate Weibull scale parameter, there are minor variations in other costs with a general drop in every cost, and the annual cost of production loss decreases notably when the parameter decreases as No. 10 in the table. Nonetheless, the influence cannot be disregarded as the scale parameter increases and the weather conditions become worse. The annual costs of the vessel's traveling, the total amount of the charter, the penalty, and the production loss significantly diverge from the previous results. Under extreme weather conditions as No.1 in the table, the minimum operating window of HLV is never satisfied, and it must always wait for appropriate weather. As a result, once the maintenance cycle begins, it doesn't terminate until the end of the wind farm's time horizon. In this case, preventative replacement and corrective replacement have little effect on maintenance costs, minor repairs account for the majority of them.

The differences in result cost provide significant signals in the aspect of charter length sensitivity. The cost of maintenance tasks from the longer charter period is not significantly different from the original cost results. However, the longer charter length means that in the first few maintenance cycles with a low number of tasks, vessels can quickly finish the tasks and have to wait until the end of the charter length with doing anything, during which the charter cost is still charged. The longer charter period will waste vessel utilization when accomplishing the same amount of tasks, which will inevitably increase the overall cost of the charter. The shorter charter period, however, moves the charter in a different direction where it is more flexible. With a shorter starting charter length, the charter duration can be increased as necessary and each charter can be utilized effectively, resulting in a remarkable reduction in the overall charter cost.

Furthermore, the changes in the component zone range lead to various costs. One component needs to be repaired after its age reaches 20%, therefore when the length of each component zone increases by 1.5 times, more components are identified to be performed for maintenance duties. As a result of the early repair, components are less likely to fail, which significantly reduces the need for corrective replacement, the most costly maintenance task.

Table 5.12: The results of sensitivity study

No	Sensitivity operation	Annual cost (K€/year)					
		Vessel traveling	Total charter	Maintenance tasks	Penalty	Production loss	Total O&M
1	1.5 * Climate Weibull scale parameter	6.8	15908.8	110.1	17205.2	89655.1	122886.0
2	0.5 * Each component zone range	15.8	6543.8	517.4	429.0	712.1	8218.1
3	1.5 * Charter length	19.2	6653.4	522.9	87.5	672.4	7955.4
4	0.5 * CTV Maximum parallel teams	24.9	5290.8	515.1	1020.0	682.6	7533.4
5	1.5 * CTV Maximum parallel teams	17.5	5094.0	520.9	93.7	699.0	6425.1
6	1.5 * Penalty cost	19.2	5052.8	522.8	132.0	671.6	6398.5
7	1.5 * Each component zone range	27.0	4755.9	666.4	63.5	867.6	6380.4
8	Original input parameters	19.2	5052.8	522.8	88.0	671.6	6354.5
9	0.5 * Penalty cost	19.2	5052.8	522.8	44.0	671.6	6310.5
10	0.5 * Climate Weibull scale parameter	15.4	4670.8	513.4	40.8	49.2	5289.7
11	0.5 * Charter length	19.6	3879.1	525.0	106.0	673.9	5203.6

As a result, significant cost savings can be made. However, as more minor and major repairs are made, the cost of maintenance tasks is sharply increasing. Moreover, more turbines must be shut down for maintenance, increasing the cost of production losses. On the other hand, because each component could only be repaired or replaced when its condition was really bad, the component zone shortening leads to an accumulation of maintenance tasks. To solve this condition, more vessels must be employed, and longer maintenance cycles are required. The growth of the overall charter cost as well as the penalty is represented as No.2 in Table 5.12.

Additionally, the changes in the maximum parallel team result in fluctuations in the output results differently. The drop in team size results in a lack of resources for maintenance jobs, which necessitates more time and longer maintenance cycles, and the need for more frequent activities necessitates higher travel costs. On the other hand, the increase in the maximum parallel team does not equate to a reduction in the overall O&M cost. When maintenance tasks are accomplished more quickly, more triggers for starting a maintenance cycle can be achieved, and the number of maintenance cycles may rise. Besides that, because each component may only be repaired once during each maintenance cycle, the quicker the maintenance operation is completed, the more time components spend on aging, which leads to the accumulation of preventative and corrective replacement.

5.4. The result of the short-term optimization

Compared with a whole lifespan of an offshore wind farm, the length of one maintenance cycle which usually only takes around a few months is relatively short, and in this research, the term short-term horizon is used to describe a duration of a maintenance cycle. The feedforward open-loop simulation-optimization model is used for relatively short-term optimization, the optimal decision variable of each maintenance cycle can be obtained as well as the corresponding model outputs. All these results are cycle-oriented, and in this section, some significant results from the short-term optimization by using the feedforward simulation model will be given, together with comparisons with results from the previous long-term optimization.

In order to make a good comparison, the same weather condition data of 20 scenarios generated in the open-loop simulation-optimization model and the same wind farm situation at the beginning of each maintenance cycle, including the detailed turbine information and turbine component information, will be applied for the feedforward open-loop simulation-optimization model. Thus two discrete event simulations are performed under 20 pairs of scenarios and each pair is exactly the same, and results from two models can be compared and analyzed.

5.4.1. Simulation model output

Similarly, as the framework in Figure 3.7 shows, the simulation model outputs, including the turbine information, maintenance cycle information, maintenance tasks information, vessel charter cost, vessel travel cost and vessel utilization, can all be obtained after the simulation is performed. All outputs focus on one maintenance cycle, and more details of one maintenance cycle can be known. Compared with the results obtained from the open-loop simulation-optimization model, the optimal decision variables obtained from the feedforward open-loop simulation-optimization model for each maintenance cycle may be different, resulting in the same or lower-cost situations. In other words, judged by the total cost of each maintenance cycle, the optimal decision variables of fleet configuration obtained from the determined open-loop simulation-optimization model may not be the optimal ones for each maintenance cycle.

From maintenance cycle No. 1 to maintenance cycle No. 6, even though the optimal decision variables are different, the corresponding fleet configuration and other outputs are all the same from two models. When it comes to maintenance cycle No. 7, different optimal decision variables lead to different fleet configurations and other different outputs, and these decision variables are summarized in Table 5.13.

Table 5.13: Optimal decision variables from two models

Cycle No.	Optimal decision variables from long-term optimization	Optimal decision variables from short-term optimization
Cycle 1	$X_{\mathrm{T}}^{\mathrm{HLV}}=6, X_{\mathrm{T}}^{\mathrm{FSV}}=24, X_{\mathrm{T}}^{\mathrm{CTV}}=150$	$X_{\mathrm{T}}^{\mathrm{HLV}}=19, X_{\mathrm{T}}^{\mathrm{FSV}}=18, X_{\mathrm{T}}^{\mathrm{CTV}}=35$
Cycle 2		$X_{\mathrm{T}}^{\mathrm{HLV}}=22, X_{\mathrm{T}}^{\mathrm{FSV}}=26, X_{\mathrm{T}}^{\mathrm{CTV}}=61$
Cycle 3		$X_{\mathrm{T}}^{\mathrm{HLV}}=3, X_{\mathrm{T}}^{\mathrm{FSV}}=26, X_{\mathrm{T}}^{\mathrm{CTV}}=92$
Cycle 4		$X_{\mathrm{T}}^{\mathrm{HLV}}=23, X_{\mathrm{T}}^{\mathrm{FSV}}=27, X_{\mathrm{T}}^{\mathrm{CTV}}=128$
Cycle 5		$X_{\mathrm{T}}^{\mathrm{HLV}}=5, X_{\mathrm{T}}^{\mathrm{FSV}}=27, X_{\mathrm{T}}^{\mathrm{CTV}}=136$
Cycle 6		$X_{\mathrm{T}}^{\mathrm{HLV}}=5, X_{\mathrm{T}}^{\mathrm{FSV}}=24, X_{\mathrm{T}}^{\mathrm{CTV}}=154$
Cycle 7		$X_{\mathrm{T}}^{\mathrm{HLV}}=5, X_{\mathrm{T}}^{\mathrm{FSV}}=22, X_{\mathrm{T}}^{\mathrm{CTV}}=116$

In the later content, as representatives in both situations, maintenance cycle No.1 and cycle No.7 are taken as examples, most important results will be displayed and detailed analyzed. While more details of the outputs of maintenance cycle 7 can be checked in Appendix.

5.4.2. The comparison of results of the maintenance cycle No.1 from two models

By using the same weather condition data for both the open-loop simulation-optimization model and the feedforward open-loop simulation-optimization model, all the optimal results from the heuristic algorithm are listed in Table 5.14. The second column is the results of the short-term optimization and the last column is the results of the long-term optimization.

As previously mentioned, the optimal decision variables of the open-loop simulation-optimization model for each maintenance cycle within 15 years are [6, 24, 150]. While in the feedforward open-loop simulation-optimization model, the optimal decision variables for the first maintenance cycle are [19, 18, 35].

The details of calculating the fleet configuration from the decision variables will be given as followed, taking scenario 1 as an example.

Given input: Owned vessel fleet configuration:

- The number of owned HLVs: 0

Table 5.14: The comparison of the fleet configuration of maintenance cycle 1

Scenario No.	The fleet configuration from long-term optimization	The fleet configuration from short-term optimization
Scenario 1	1, 0, 0	1, 0, 0
Scenario 2	1, 0, 0	1, 0, 0
Scenario 3	1, 0, 0	1, 0, 0
Scenario 4	1, 1, 0	1, 1, 0
Scenario 5	1, 1, 0	1, 1, 0
Scenario 6	1, 1, 0	1, 1, 0
Scenario 7	1, 0, 0	1, 0, 0
Scenario 8	1, 0, 0	1, 0, 0
Scenario 9	1, 0, 0	1, 0, 0
Scenario 10	1, 1, 0	1, 1, 0
Scenario 11	1, 0, 0	1, 0, 0
Scenario 12	1, 0, 0	1, 0, 0
Scenario 13	1, 0, 0	1, 0, 0
Scenario 14	1, 0, 0	1, 0, 0
Scenario 15	1, 0, 0	1, 0, 0
Scenario 16	1, 0, 0	1, 0, 0
Scenario 17	1, 1, 0	1, 1, 0
Scenario 18	1, 0, 0	1, 0, 0
Scenario 19	1, 0, 0	1, 0, 0
Scenario 20	1, 1, 0	1, 1, 0

- The number of owned FSVs: 0
- The number of owned CTVs: 1

Decision variables of the open-loop simulation-optimization model:

- $X_{\mathrm{T}}^{\mathrm{HLV}}$: 6
- $X_{\mathrm{T}}^{\mathrm{FSV}}$: 24
- $X_{\mathrm{T}}^{\mathrm{CTV}}$: 150

Decision variables of the feedforward open-loop simulation-optimization model:

- $X_{\mathrm{T}}^{\mathrm{HLV}}$: 19
- $X_{\mathrm{T}}^{\mathrm{FSV}}$: 18
- $X_{\mathrm{T}}^{\mathrm{CTV}}$: 35

Model check: The number of maintenance tasks per vessel type to be performed

- The number of tasks for HLV: 1
- The number of tasks for FSV: 0
- The number of tasks for CTV: 2

Decisions to charter for the open-loop simulation-optimization model:

- The number of HLVs to charter = $\left\lceil \frac{1}{6} \right\rceil - 0 = 1 - 0 = 1$
- The number of FSVs to charter = $\left\lceil \frac{0}{24} \right\rceil - 0 = 0 - 0 = 0$
- The number of CTVs to charter = $\left\lceil \frac{2}{150} \right\rceil - 1 = 1 - 1 = 0$

Decisions to charter for the feedforward open-loop simulation-optimization model:

- The number of HLVs to charter = $\left\lceil \frac{1}{19} \right\rceil - 0 = 1 - 0 = 1$
- The number of FSVs to charter = $\left\lceil \frac{0}{18} \right\rceil - 0 = 0 - 0 = 0$
- The number of CTVs to charter = $\left\lceil \frac{2}{35} \right\rceil - 1 = 1 - 1 = 0$

All other 19 scenarios of maintenance cycle No.1 have similar calculation steps for the fleet configuration decisions. Based on the calculations and the results, it can be seen that even the decision variables are different. The fleet configurations of all scenarios could be the same.

What is more, as the total cost is the objective function, apart from the fleet configuration, all costs from 20 scenarios are also significant results and the cost of 20 scenarios of the maintenance cycle No.1 from two models are shown in Table 5.15.

It can be seen that, in maintenance cycle No.1, for each scenario, the costs from two models are the same, as well as the average cost from two models. Combined with previous results of the fleet configuration, it is clear that for maintenance cycle No.1, the different decision variables obtained from two models lead to the same fleet configuration and finally lead to the same costs.

This information reveals that, the optimal fleet configuration obtained from the open-loop simulation-optimization model can be applicable for this maintenance cycle for the minimum average cost, while in this case, the feedforward open-loop simulation-optimization model has no influence on this maintenance cycle, in another word, it cannot improve the decisions better.

This usually happens when the dynamics in the offshore wind farm are not that drastic, for example, at the very beginning of the operation of a wind farm. Under this situation, all maintenance tasks can be fixed fast and orderly, tasks are not piled up and no more productivity loss shows up. Also with no more extension of the charter or no penalty because of exceeding the soft time window.

Table 5.15: The comparison of cost results of maintenance cycle 1

Scenario No.	The cost of long-term optimization (€)	The cost of short-term optimization (€)
Scenario 1	4396891.79	4396891.79
Scenario 2	4411375.31	4411375.31
Scenario 3	9403774.88	9403774.88
Scenario 4	5040613.53	5040613.53
Scenario 5	5397289.24	5397289.24
Scenario 6	5013036.97	5013036.97
Scenario 7	4434399.63	4434399.63
Scenario 8	4562000.18	4562000.18
Scenario 9	4417705.21	4417705.21
Scenario 10	5192341.40	5192341.40
Scenario 11	4388206.96	4388206.96
Scenario 12	4604420.68	4604420.68
Scenario 13	4364126.66	4364126.66
Scenario 14	4638477.66	4638477.66
Scenario 15	4527178.00	4527178.00
Scenario 16	4476406.35	4476406.35
Scenario 17	6891685.62	6891685.62
Scenario 18	4419319.65	4419319.65
Scenario 19	4358279.06	4358279.06
Scenario 20	5073151.05	5073151.05
Average cost	5000533.99	5000533.99

5.4.3. The comparison of results of the maintenance cycle No.7 from two models

The optimal fleet configurations of one maintenance cycle obtained from the open-loop simulation-optimization model may be the same as those from the feedforward open-loop simulation-optimization model. However, in some cases, the optimal fleet configurations given by the open-loop simulation-optimization model may not be optimal for each maintenance cycle, and the feedforward open-loop simulation-optimization model can improve it and give an optimal decision for a certain maintenance cycle.

In Table 5.16, different fleet configurations of 20 scenarios for maintenance cycle No.7 from two models are shown. In the column of the fleet configuration results from the feedforward open-loop simulation-optimization model, all those cells with a symbol $*$ mean, in the corresponding scenarios, the fleet configurations from two models are different.

As previously mentioned, the optimal decision variables of the open-loop simulation-optimization model for each maintenance cycle within 15 years are [6, 24, 150]. While

Table 5.16: The comparison of the fleet configuration of maintenance cycle 7

Scenario No.	The fleet configuration from long-term optimization	The fleet configuration from short-term optimization
Scenario 1	1, 1, 0	1, 1, 1*
Scenario 2	1, 1, 0	1, 1, 0
Scenario 3	1, 1, 0	1, 1, 0
Scenario 4	1, 2, 0	1, 2, 1*
Scenario 5	1, 1, 0	1, 1, 0
Scenario 6	1, 1, 0	1, 1, 0
Scenario 7	1, 1, 0	1, 1, 0
Scenario 8	1, 1, 0	1, 1, 0
Scenario 9	1, 1, 0	1, 1, 1*
Scenario 10	1, 1, 0	1, 1, 0
Scenario 11	1, 1, 0	1, 1, 0
Scenario 12	1, 1, 0	1, 1, 1*
Scenario 13	1, 1, 0	1, 1, 1*
Scenario 14	1, 1, 0	1, 1, 1*
Scenario 15	1, 1, 0	1, 1, 0
Scenario 16	1, 1, 0	1, 1, 1*
Scenario 17	1, 1, 0	1, 1, 1*
Scenario 18	1, 1, 1	1, 1, 1
Scenario 19	1, 1, 0	1, 1, 0
Scenario 20	1, 1, 0	1, 1, 1*

in the feedforward open-loop simulation-optimization model, the optimal decision variables for maintenance cycle No.7 are [5, 22, 116].

The details of calculating the fleet configuration from the decision variables will be given as followed, taking Scenario 1 as an example. Given input: Owned vessel fleet configuration:

- The number of owned HLVs: 0
- The number of owned FSVs: 0
- The number of owned CTVs: 1

Decision variables of the open-loop simulation-optimization model:

- $X_{\mathrm{T}}^{\mathrm{CTV}}$: 6
- $X_{\mathrm{T}}^{\mathrm{FSVV}}$: 24
- $X_{\mathrm{T}}^{\mathrm{HLV}}$: 150

Decision variables of the feedforward open-loop simulation-optimization model:

- $X_{\mathrm{T}}^{\mathrm{CTV}}$: 5
- $X_{\mathrm{T}}^{\mathrm{FSV}}$: 22
- $X_{\mathrm{T}}^{\mathrm{HLV}}$: 116

Model check: The number of maintenance tasks per vessel type to be performed

- The number of tasks for HLV: 1
- The number of tasks for FSV: 21
- The number of tasks for CTV: 130

Decisions to charter for the open-loop simulation-optimization model:

- The number of HLVs to charter = $\left\lceil \frac{1}{6} \right\rceil - 0 = 1 - 0 = 1$
- The number of FSVs to charter = $\left\lceil \frac{21}{24} \right\rceil - 0 = 1 - 0 = 1$
- The number of CTVs to charter = $\left\lceil \frac{130}{150} \right\rceil - 1 = 1 - 1 = 0$

Decisions to charter for the feedforward open-loop simulation-optimization model:

- The number of HLVs to charter = $\left\lceil \frac{1}{5} \right\rceil - 0 = 1 - 0 = 1$
- The number of FSVs to charter = $\left\lceil \frac{21}{22} \right\rceil - 0 = 1 - 0 = 1$
- The number of CTVs to charter = $\left\lceil \frac{130}{116} \right\rceil - 1 = 2 - 1 = 1$

Based on the calculation, it can be known that, for Scenario 1 of the maintenance cycle No.7, the decision variable of $X_{\mathrm{T}}^{\mathrm{HLV}}$ of the feedforward open-loop simulation-optimization model is much lower than that of the open-loop simulation-optimization model, which leads to one more vessel to charter. While another two decision variables do not lead to different vessel charters of HLV and FSV.

Similarly, the other 19 scenarios of maintenance cycle No.7 have these calculation steps for the fleet configuration decisions, and according to the results, the fleet configuration of Scenario 4, Scenario 9, Scenario 12, Scenario 13, Scenario 14, Scenario 16, Scenario 17 and Scenario 20 from two models are different from each other.

Again, apart from the fleet configuration results, as the objective function of the optimization method, all the costs of 20 scenarios of two models should be focused and those results are shown in Table 5.17.

Table 5.17: The comparison of cost results of maintenance cycle 7

Scenario No.	The cost of long-term optimization (€)	The cost of short-term optimization (€)
Scenario 1	6577189.08	6765999.86*
Scenario 2	5995901.54	5995901.54
Scenario 3	5850322.76	5850322.76
Scenario 4	7408707.57	7498570.16*
Scenario 5	5757230.95	5757230.95
Scenario 6	6301044.66	6301044.66
Scenario 7	6284698.99	6284698.99
Scenario 8	5710159.48	5710159.48
Scenario 9	6279967.34	6156518.62*
Scenario 10	6106325.71	6106325.71
Scenario 11	5993455.48	5993455.48
Scenario 12	6366115.08	6451259.61*
Scenario 13	6390971.76	6508824.62*
Scenario 14	14868310.08	7617911.33*
Scenario 15	6105300.86	6105300.86
Scenario 16	6679004.89	6689015.71*
Scenario 17	6227309.01	6347917.61*
Scenario 18	6924475.09	6924475.09
Scenario 19	6175207.24	6175207.24
Scenario 20	6278026.66	6434574.82*
Average cost	6713986.21	6383735.76

As seen from the results, accordingly, each scenario previously with different fleet configuration results has different costs. In all these scenarios, the costs of 7 scenarios: Scenario 1, Scenario 4, Scenario 12, Scenario 13, Scenario 16, Scenario 17 and Scenario 20 from the feedforward open-loop simulation-optimization model, are even higher than the costs from the long-term optimization. While only the costs of Scenario 9 and Scenario 14 are the opposite. However, the average cost, the most objective function of the simulated annealing, has a lower value from the feedforward open-loop simulation-optimization model and a higher one is obtained by the open-loop simulation-optimization model. This is because the decrease in Scenario 14 is much higher than the sum of the increment of any other scenario.

The most influential reason behind the cost decrease in Scenario 14 can be told from the maintenance cycle length. From Figure 5.4, it can be seen that, in the open-loop simulation-optimization model, Scenario 14 of maintenance cycle No.7 has a length of 104 days, which is extremely high, while the cycle length of any other scenario of maintenance cycle No.7 is lower than 60 days, which is the soft time window set in this research. This overlong maintenance cycle length leads to extra costs including costs caused by the extension of the charter, more maintenance tasks and the penalty of exceeding the soft time window. By choosing different decision variables and the fleet configurations are changed accordingly, and the cost of this extreme scenario can be spread across other scenarios. From Figure 5.10, it can be seen that, the cycle length of Scenario 14 dramatically decreases to 62 days, together with a little cycle length decrease in Scenario 4, Scenario 9, Scenario 12, Scenario 13, Scenario 16 and Scenario 20.

Unit: day	X(tasks_per_HLV) = 5, X(tasks_per_FSV) = 22, X(tasks_per_CTV) = 116																			
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10	set_11	set_12	set_13	set_14	set_15	set_16	set_17	set_18	set_19	set_20
cycle 1 length	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 2 length	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 3 length	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 4 length	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 5 length	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 6 length	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 7 length	48	42	37	47	42	45	45	33	33	42	40	41	36	62	49	55	44	46	48	39
total	48	42	37	47	42	45	45	33	33	42	40	41	36	62	49	55	44	46	48	39

Figure 5.10: The cycle lengths of maintenance cycle 7 of the short-term optimization

Even though more vessels are chartered in some scenarios, which leads to an increment of the cost correspondingly, the decrease in other scenarios also takes a dominant influence and the average cost will be affected. Thus, the balance between the fluctuation of many factors is found and shown as the new decision variables and fleet configuration. Also, the result of maintenance cycle No.7 shows that, the optimal decision variables and fleet configuration of the open-loop simulation-optimization model may not be the optimal ones for every maintenance cycle, while the feedforward open-loop simulation-optimization model could strongly fill this gap.

6
Conclusions and Recommendations

6.1. Conclusion

Compared with state-of-the-art research, this thesis contributes a decision-making tool for fleet size and mix problems for offshore wind farms on a simulation-optimization method, so that optimal decision-making can be obtained after a number of iterations.

By answering sub-research questions one by one, the main research question, how to obtain the optimal fleet size and mix for an offshore wind farm based on a simulation model, can be answered. Firstly, in Chapter 2, a detailed literature review is performed, and all the research papers for fleet size and mix problems for offshore wind farms are scanned, thus all the state-of-the-art modeling methods, as well as the considered factors in the papers, are reviewed and summarized, through which the research gaps are clearly known. Especially, all papers used the Monte–Carlo approach to find the optimal result among all the scenarios they created and no paper combines the optimization method with a simulation model. Therefore, sub-question 1 is answered at the same time.

As this is an extension work of the collaboration work with Mingxin and Bas, the presented model improves the previous work. In Chapter 3, thorough introductions to both the open-loop simulation model and the developed feedforward simulation model are given. The frameworks of two models, together with the flowcharts, are shown where the connections between various inputs of the model, all functional agents and different outputs are displayed, and a detailed explanation of each part is executed. And by the end of this chapter, sub-question 2 and sub-question 3 are both answered.

Afterward, in Chapter 4, the simulation-optimization methodology is introduced, the interaction between the optimization algorithm and the open-loop simulation model, as well as the interaction between the optimization algorithm and feedforward simulation model was illustrated. In order to obtain optimal results, the objective function is also defined accordingly. Also, the optimization method simulated annealing and its process of this research are in detail explained, Therefore, sub-question 4 is answered in this chapter.

After answering all the research questions, one case study is executed, by using the open-loop simulation model with an optimization method for a long-term decision focusing on the whole lifespan of a 15-year offshore wind farm, and using the feedforward simulation model with an optimization method for a short-term optimization focusing on each maintenance cycle of an offshore wind farm. A sensitivity analysis is performed and all the results are shown and analyzed in Chapter 5, thus sub-question 5 is answered.

6.2. Discussion

The result shows that, together with the optimization method, the presented feedforward simulation model for fleet size and mix problems of an offshore wind farm gives a different perspective for the optimal fleet configuration in comparison with the previous papers and previous work. There are many advantages to the proposed feedforward simulation model together with the optimization algorithm. Firstly, this model starts simulation from a given state including the state of each turbine component. What is more, this model focuses on each maintenance cycle, thus the decision-making is more suitable for relatively short-term optimization and is more flexible. Especially, the optimal decision variables are regarded as the estimation of the maintenance tasks for each vessel type in one maintenance cycle, one optimal result of the long-term optimization may not be always accurate for a short-term optimization, while at this point, the optimal results for each maintenance cycle obtained from the proposed feedforward simulation model can be more accurate and be given as a reference for wind farm operators and researchers when they perform a prediction or analysis.

At the same time, there are some limits to the proposed model and the optimization algorithm. For example, the search domain of each decision variable in this research is connected to the size of the wind farm with some estimation, it should be adjusted accordingly if the size of the wind farm is changed. Also, due to the time limit of this project, the iteration of the decision variables is chosen as only 200 and it is very small compared with the massive search area, which is 375000. Thus the obtained optimal result is relatively optimal. With more computation time, the result can be more decent. Also, the case study is based on previous research, and the weather data is generated by the Weibull distribution but not the historical weather data in reality. If more available real data can be applied to this model and compared the result from this model to the decision made in the past, the results can be more persuasive and the model can be improved more specifically. Additionally, some assumptions are made in the simulation model, some of them are not realistic and could be improved.

In the future, some directions can be still improved based on this study. For example, the mothership and daughter ship can be considered in the model as different vessel types with more realistic functions. Also, introducing the fluctuating electricity price into the model is another direction, which has been done by some papers using mathematical models. Similarly, the technician numbers can be considered in a dynamic way in the model, so that maximum technicians are not always equipped in the very vessel when performing the maintenance tasks. Plus, considering some task type crossing, so that one task type can be performed by different vessels and the priority should be re-arranged accordingly. What is more, the optimization from a one-year or two-year perspective can be tried and made a comparison with the cycle-oriented optimization. Lastly, converting the simulation model to practice use in the industry area is the most vital long-term direction of future work.

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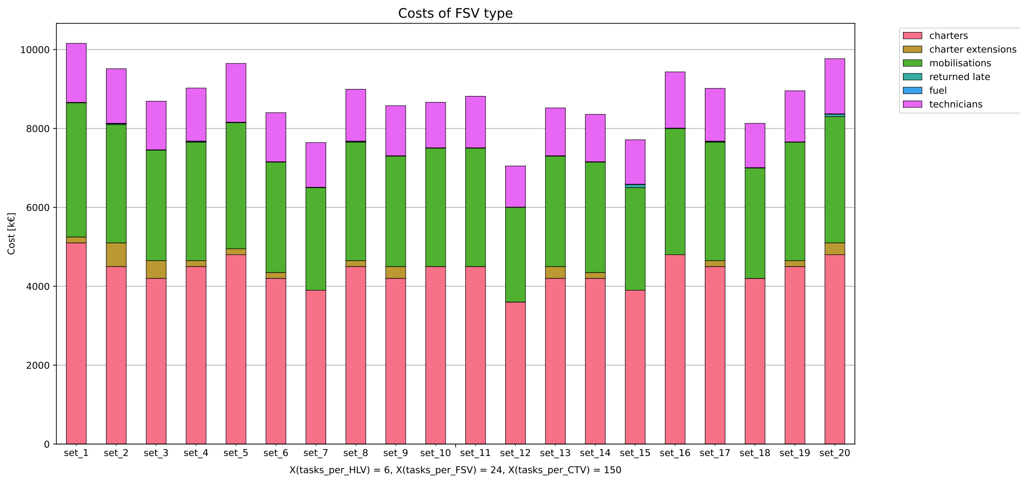
A
Appendix

A.1. Simulation results

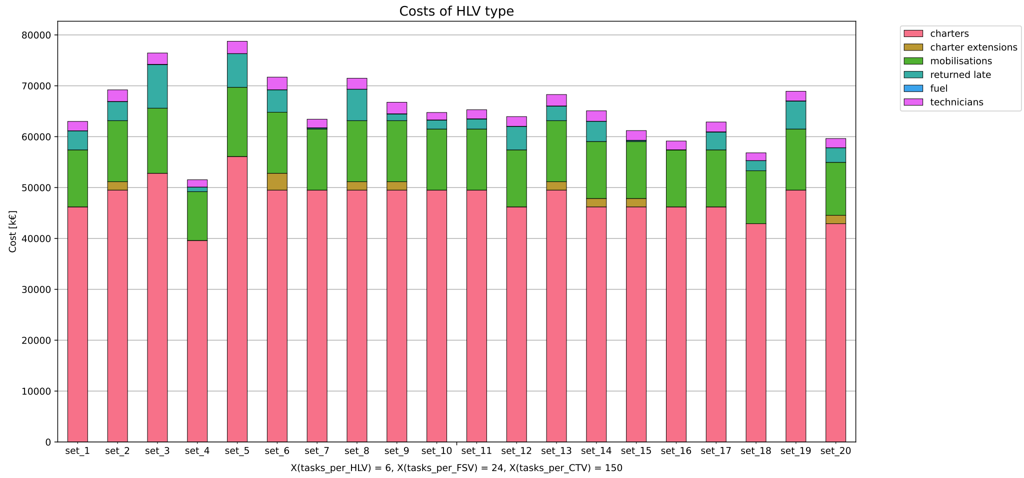
A.1.1. 15-year FSV cost distribution from the long-term optimization



Unit: k€	X(tasks_per_HLV) = 6, X(tasks_per_FSV) = 24, X(tasks_per_CTV) = 150																			
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10	set_11	set_12	set_13	set_14	set_15	set_16	set_17	set_18	set_19	set_20
charters	5100.0	4500.0	4200.0	4500.0	4800.0	4200.0	3900.0	4500.0	4200.0	4500.0	4500.0	3600.0	4200.0	4200.0	3900.0	4800.0	4500.0	4200.0	4500.0	4800.0
charter extensions	150.0	600.0	450.0	150.0	150.0	150.0	0	150.0	300.0	0	0	0	300.0	150.0	0	0	150.0	0	150.0	300.0
mobilisations	3400.0	3000.0	2800.0	3000.0	3200.0	2800.0	2600.0	3000.0	2800.0	3000.0	3000.0	2400.0	2800.0	2800.0	2600.0	3200.0	3000.0	2800.0	3000.0	3200.0
returned late	0	20.0	0	20.0	0	0	0	20.0	0	0	0	0	0	0	80.0	0	20.0	0	0	60.0
fuel	10.7	10.8	9.3	10.0	9.1	7.6	8.8	9.0	8.2	8.2	8.2	6.1	8.1	8.0	7.6	9.2	8.9	8.0	8.9	10.0
technicians	1495.8	1382.6	1231.6	1344.2	1488.6	1242.2	1134.4	1314.6	1267.1	1154.4	1308.1	1042.4	1211.4	1199.3	1125.2	1423.4	1336.6	1120.3	1295.3	1398.0
total	10156.5	9513.3	8690.9	9024.2	9647.7	8399.8	7643.1	8993.6	8575.3	8662.6	8816.3	7048.5	8519.5	8357.3	7712.9	9432.6	9015.5	8128.3	8954.1	9768.1

Figure A.1: 15-year FSV cost distribution from the long-term optimization

A.1.2. 15-year HLV cost distribution from the long-term optimization



Unit: k€	X(tasks_per_HLV) = 6, X(tasks_per_FSV) = 24, X(tasks_per_CTV) = 150									
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10
charters	46200.0	49500.0	52800.0	39600.0	56100.0	49500.0	49500.0	49500.0	49500.0	49500.0
charter extensions	0	1650.0	0	0	0	3300.0	0	1650.0	1650.0	0
mobilisations	11200.0	12000.0	12800.0	9600.0	13600.0	12000.0	12000.0	12000.0	12000.0	12000.0
returned late	3740.0	3740.0	8580.0	880.0	6600.0	4400.0	220.0	6160.0	1320.0	1760.0
fuel	22.3	25.1	24.8	19.3	26.7	26.6	23.8	25.4	24.3	24.1
technicians	1835.3	2283.1	2237.9	1432.6	2421.0	2476.1	1689.8	2149.3	2268.3	1468.9
total	62997.5	69198.2	76442.6	51531.9	78747.7	71702.6	63433.5	71484.7	66762.6	64753.0

Unit: k€	set_11	set_12	set_13	set_14	set_15	set_16	set_17	set_18	set_19	set_20
charters	49500.0	46200.0	49500.0	46200.0	46200.0	46200.0	46200.0	42900.0	49500.0	42900.0
charter extensions	0	0	1650.0	1650.0	1650.0	0	0	0	0	1650.0
mobilisations	12000.0	11200.0	12000.0	11200.0	11200.0	11200.0	11200.0	10400.0	12000.0	10400.0
returned late	1980.0	4620.0	2860.0	3960.0	220.0	0	3520.0	1980.0	5500.0	2860.0
fuel	24.4	21.9	24.9	24.6	23.4	22.3	22.3	20.5	23.1	22.9
technicians	1787.9	1904.3	2247.5	2046.5	1903.7	1724.5	1942.2	1519.5	1898.1	1806.2
total	65292.3	63946.2	68282.4	65081.1	61197.2	59146.8	62884.5	56820.0	68921.2	59639.2

Figure A.2: 15-year HLV cost distribution from the long-term optimization

A.1.3. 15-year FSV time distribution from the long-term optimization

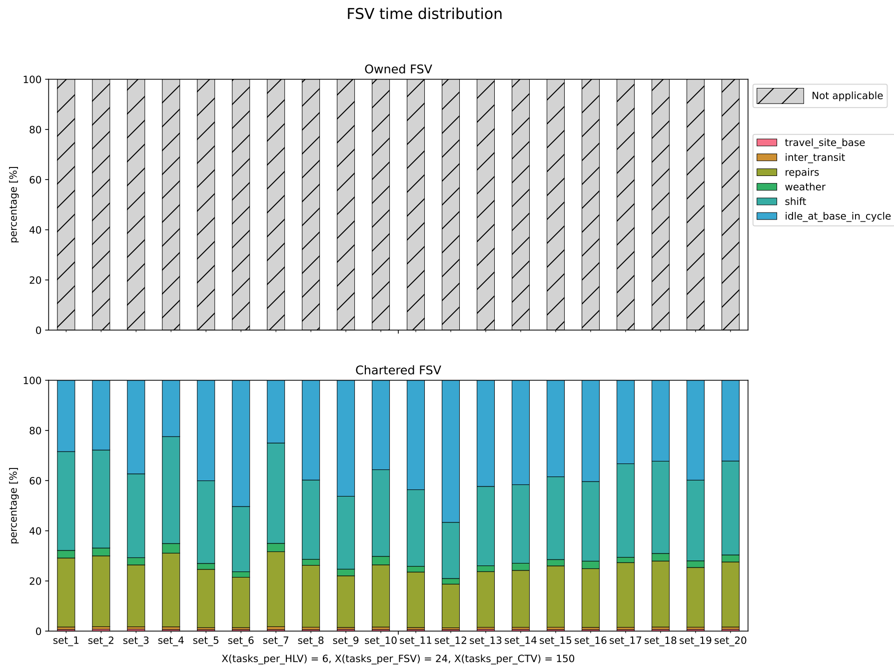


Figure A.3: 15-year FSV time distribution of long-term optimization

A.1.4. 15-year HLV time distribution from the long-term optimization

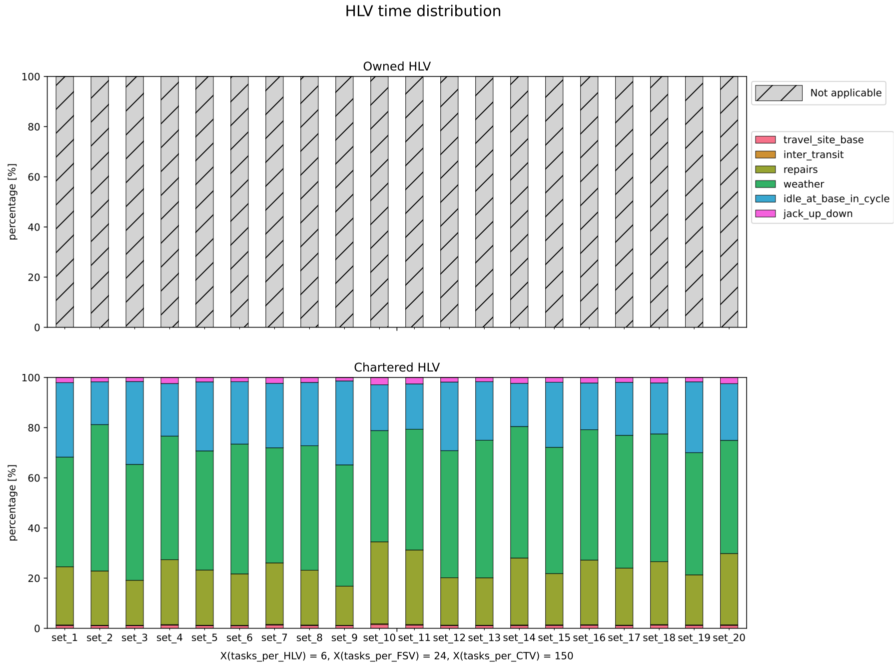


Figure A.4: 15-year HLV time distribution from the long-term optimizationl

A.1.5. CTV time distribution of maintenance cycle 7 from the short-term optimization

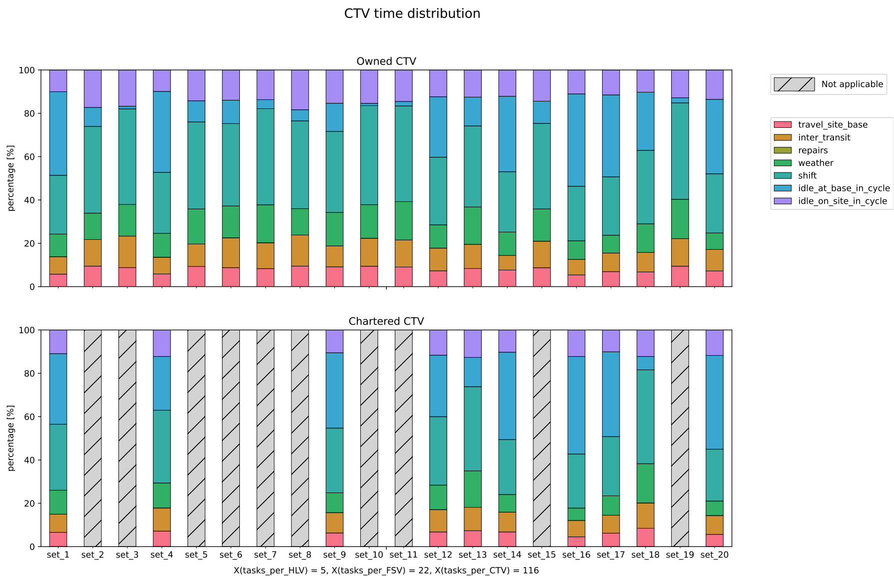


Figure A.5: CTV time distribution of maintenance cycle 7 from the long-term optimization

A.1.6. FSV time distribution of maintenance cycle 7 from the short-term optimization

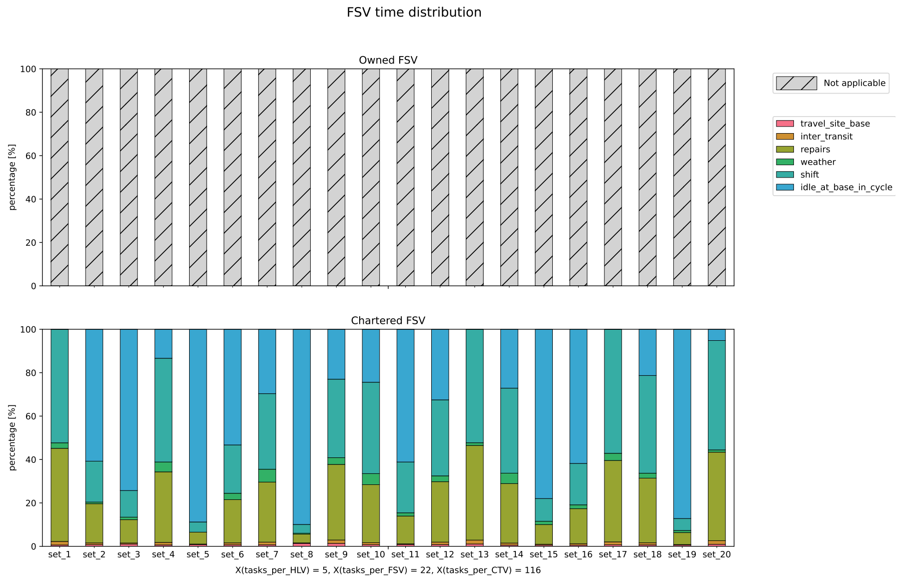


Figure A.6: FSV time distribution of maintenance cycle 7 from the short-term optimization

A.1.7. HLV time distribution of maintenance cycle 7 from the short-term optimization

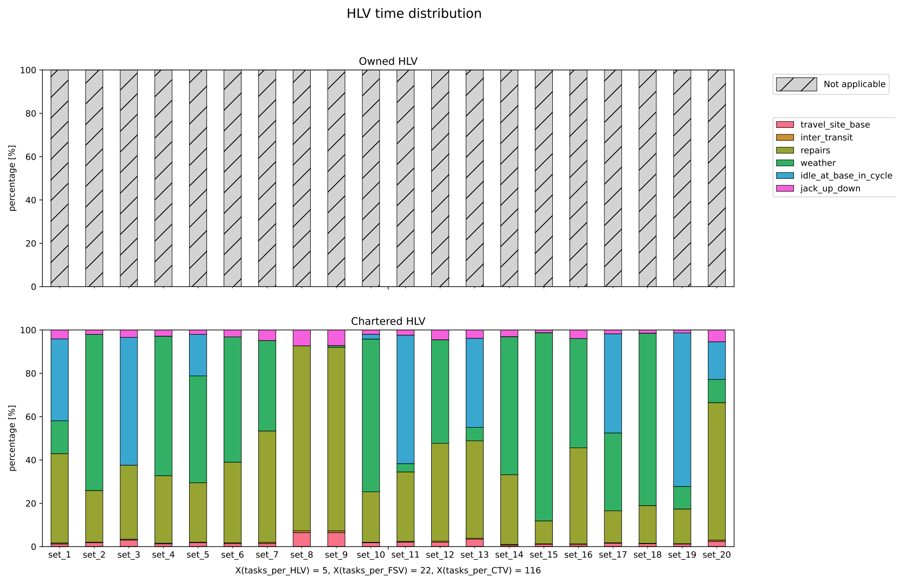
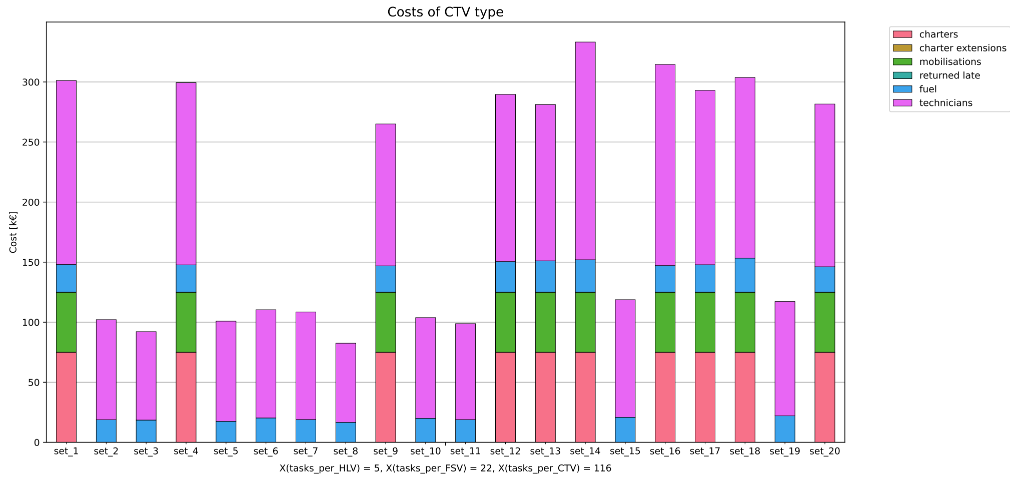


Figure A.7: HLV time distribution of maintenance cycle 7 from the short-term optimization

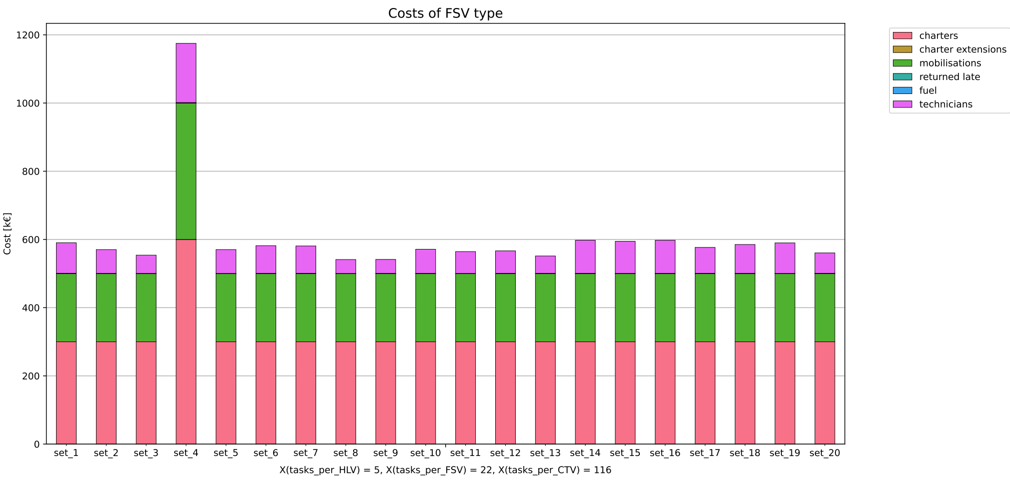
A.1.8. CTV cost distribution of maintenance cycle 7 from the short-term optimization



Unit: k€	X(tasks_per_HLV) = 5, X(tasks_per_FSV) = 22, X(tasks_per_CTV) = 116																			
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10	set_11	set_12	set_13	set_14	set_15	set_16	set_17	set_18	set_19	set_20
charters	75.0	0	0	75.0	0	0	0	0	75.0	0	0	75.0	75.0	75.0	0	75.0	75.0	75.0	0	75.0
charter extensions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
mobilisations	50.0	0	0	50.0	0	0	0	0	50.0	0	0	50.0	50.0	50.0	0	50.0	50.0	50.0	0	50.0
returned late	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
fuel	23.0	18.8	18.5	22.7	17.4	20.3	18.9	16.6	21.9	19.9	18.9	25.4	26.1	27.0	20.8	22.1	22.8	28.4	22.1	21.1
technicians	153.3	83.3	73.6	151.7	83.5	90.1	89.6	65.9	118.1	83.9	79.9	139.2	130.1	181.3	97.9	167.5	145.2	150.4	95.2	135.5
total	301.2	102.1	92.1	299.4	100.9	110.4	108.5	82.5	265.1	103.8	98.8	289.6	281.2	333.3	118.8	314.6	293.0	303.8	117.2	281.6

Figure A.8: CTV cost distribution of maintenance cycle 7 from the short-term optimization

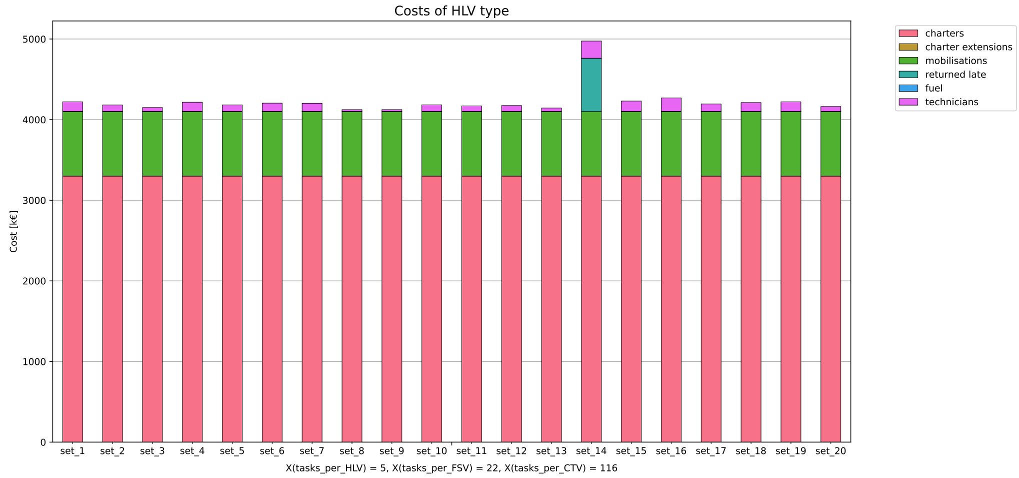
A.1.9. FSV cost distribution of maintenance cycle 7 from the short-term optimization



Unit: k€	X(tasks_per_HLV) = 5, X(tasks_per_FSV) = 22, X(tasks_per_CTV) = 116																			
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10	set_11	set_12	set_13	set_14	set_15	set_16	set_17	set_18	set_19	set_20
charters	300.0	300.0	300.0	600.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0
charter extensions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
mobilisations	200.0	200.0	200.0	400.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
returned late	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
fuel	0.9	0.5	0.4	1.4	0.3	0.6	0.7	0.3	0.5	0.5	0.3	0.6	0.6	0.6	0.4	0.5	0.7	0.6	0.3	0.7
technicians	89.4	69.8	53.7	173.6	70.0	81.1	80.2	40.8	40.9	70.7	64.2	66.0	50.9	97.0	94.2	97.0	76.0	84.6	89.5	59.8
total	590.3	570.3	554.0	1175.0	570.4	581.7	580.9	541.1	541.4	571.2	564.5	566.5	551.5	597.6	594.6	597.5	576.7	585.2	589.9	560.5

Figure A.9: FSV cost distribution of maintenance cycle 7 from the short-term optimization

A.1.10. HLV cost distribution of maintenance cycle 7 from the short-term optimization



Unit: k€	X(tasks_per_HLV) = 5, X(tasks_per_FSV) = 22, X(tasks_per_CTV) = 116																			
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10	set_11	set_12	set_13	set_14	set_15	set_16	set_17	set_18	set_19	set_20
charters	3300.0	3300.0	3300.0	3300.0	3300.0	3300.0	3300.0	3300.0	3300.0	3300.0	3300.0	3300.0	3300.0	3300.0	3300.0	3300.0	3300.0	3300.0	3300.0	3300.0
charter extensions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
mobilisations	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0
returned late	0	0	0	0	0	0	0	0	0	0	0	0	0	660.0	0	0	0	0	0	0
fuel	1.8	1.5	1.5	1.6	1.5	1.6	1.8	1.5	1.5	1.5	1.5	1.6	1.5	2.0	1.5	2.0	1.5	1.5	1.5	1.6
technicians	119.6	80.5	48.1	114.4	80.9	103.1	101.3	22.5	22.6	82.3	69.1	72.8	42.6	213.1	129.2	167.0	92.8	110.0	119.9	60.5
total	4221.4	4181.9	4149.6	4216.1	4182.4	4204.8	4203.1	4123.9	4124.1	4183.8	4170.6	4174.4	4144.1	4975.0	4230.7	4269.0	4194.3	4211.5	4221.4	4162.1

Figure A.10: HLV cost distribution of maintenance cycle 7 from the short-term optimization

A.1.11. The penalty costs of maintenance cycle 7 from the short-term optimization

Unit: k€	X(tasks_per_HLV) = 5, X(tasks_per_FSV) = 22, X(tasks_per_CTV) = 116																			
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10	set_11	set_12	set_13	set_14	set_15	set_16	set_17	set_18	set_19	set_20
cycle 1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 7	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0
total	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0

Figure A.11: The penalty costs of maintenance cycle 7 from the short-term optimization

A.2. Scientific Paper

TU Delft, 2023 , 00, 01-15
Published Online May 2023 in (http://repository.tudelft.nl/)
Doi:2023.MME.8803

Optimization of vessel fleet size and mix for offshore wind farm maintenance based on a simulation method

Kangjie Wu, Mingxin Li, Xiaoli Jiang and Bas Bijvoet
Department of Maritime and Transport Technology, Delft University of Technology, 2628CD, the Netherlands.
Email: k.wu-2@student.tudelft.nl, m.li-6@tudelft.nl, x.jiang@tudelft.nl, b.j.bijvoet@student.tudelft.nl

Abstract—This research work tries to combine the optimization method with the simulation model used for the fleet size and mix problem of offshore wind farm maintenance. Firstly, the open-loop simulation model is developed into a feedforward simulation model, which can start the simulation from a given wind farm state. Furthermore, the optimization method is combined with two models and used for a long-term optimization and a short-term optimization separately and the results will be given. This simulation-optimization approach is expected to be a decision support tool for fleet size and mix problems and the outputs can be a reference for wind farm operators.

Index Terms—Offshore wind farm, Operation and maintenance, Simulation model, Optimization, Fleet size and mix problem

I Introduction

Wind energy is renewable and inexhaustible energy that will be investigated more in the next decades potentially. The share of wind power in the EU's electricity supply was 10.4% in 2016, while it is predicted to achieve 20% by 2030[1][2]. What is more, it is expected that Europe will install 116 GW of new wind farms over the period from 2022-2026, during which EU-27 is expected to build on average 18 GW of new wind farms[3].

Compared with onshore wind energy, offshore wind energy has better offshore wind resources which are usually stronger and softer. Also, compared with the limited land onshore, more space in the sea and wind farms can be installed with less environmental noise emission and less visual impacts[4]. However, the cost of offshore wind farms is much higher than onshore wind farms[4]. Where, operation and maintenance (O&M) cost contributes about one-third of the life cycle cost of an offshore wind farm[5][6][7], which is even triple higher than that of an onshore wind farm[6][8]. What is more, 50% of O&M costs result from acquiring and operating a vessel fleet[9]. Therefore, it is significant to reduce the O&M cost and fleet management should be paid more attention.

In order to solve the fleet size and mix problem, three methods, deterministic optimization modeling, stochastic programming modeling and simulation modeling have been used in past research. In the first two modeling methods, a mathematical model with an objective function and some corresponding constraints is built and solved. While for the simulation modeling, the results can be obtained after the maintenance activities are simulated dynamically.

In deterministic optimization modeling, all the parameters are assumed to be known and used in mathematical expressions. Two papers [10][11] used this method and considered different determined parameters and constraints in their models.

However, the important uncertainty aspect of the real-life problem is ignored in the deterministic optimization models, stochastic programming (SP) has been introduced to improve it, and the uncertainty is considered in many equivalent scenarios from a node-based scenario tree. Gundegjerde et al.[12] first introduce stochastic programming for fleet size and mix problems and considered vessel spot rates, weather conditions, electricity prices and failures in the system while Stalhane et al. [13] ignore the uncertainty in the electricity price and vessels' charter rates because this can be acceptable according to the paper [14] by Sperstad. Elin E. Halvorsen et al.[15] introduce a metaheuristic solution method based on the stochastic mathematical model formulation of [13] and Kamilla et al. design the reactive GRASP heuristic for the stochastic programming model based on [16].

Very different from the previous two methods, without many mathematical expressions, the simulation modeling method is achieved by reconstructing the detailed development of discrete events, and the processes are simulated in a dynamic way. Simulation modeling has some incomparable advantages. Firstly, the simulation model is more realistic and dynamic, the details of the discrete events are revealed and all the information and process can be traced back. Secondly, when using the simulation method, different fleet configurations can be simulated and different results can be a useful reference for the operators to make an analysis. Nevertheless, the mathematical method can only give one and only optimal result based on its objective function, and more potential analysis between different fleet configurations is not possible. Lastly, the detailed modeling of the simulation modeling is not publicly available but the other two models are publicly available and described in detail in their papers. Thus, the model's uniqueness can be protected and have more potential commercial value in the future.

Yalcin Dalgic et al. [17] propose a simulation model considering climate parameters, failure characteristics of different failure modes and different transportation systems conditions, and finally the best 10 offshore wind farm O&M planning configurations and worst 10 configuration are obtained. In the paper [18], they introduce the mothership concept into a simulation model, the result of different cost distributions shows that mothership can greatly improve performance, thus a mothership is suggested to be considered in the far offshore wind farm. In the paper [9], they introduce an extensive methodology in the simulation for CTV fleet selection, and the result shows that in the future, new generation CTVs with higher operational capabilities need to be considered, instead of simply increasing the size of the CTV fleet. And in the paper [6], they execute the investigation of optimum chartering strategy for jack-up vessels, and they suggest that jack-up mobilization time might be the main cause of the significant delays. Therefore, it might be considered that chartering the vessel for the entire project life cycle for the non-small wind farms. Dinwoodie et al. compare four different operation and maintenance simulation models in the paper [19], and the result shows that different modeling approaches and assumptions have a great influence on differences on the simulation results. Michiel A.J. et al. present a simulation model take resource sharing into account in the paper [20] and analyze two types of resource sharing between offshore wind farm service providers.

In order to obtain the decision on fleet size and mix, all papers used Monte–Carlo approach, with which the optimal result is found among all the scenarios they created. But such a method can only find the optimal solution among the given limited simulations. However, in this research, one optimization method will be introduced and used to find the optimal result of the simulation model in a wide range of possible decisions.

The structure of this research paper is as follows. At first, the open-loop simulation model and the developed feedforward simulation model will be introduced. Next, the simulation-optimization methodology including the interaction between the optimization method and simulation model as well as the optimization method will be given. After that, a case study will be executed and the results will be shown. Finally, a conclusion and some recommendations regarding this research will be given.

II The open-loop simulation model

The open-loop simulation model consists of Inputs, Simulation, and Outputs. In the inputs section, in order to build the simulation environment, all the information about the simulation is defined and the information is delivered to the specific simulations section where different agents work. Afterward, agents will use the given information and interact with each other, in this way the development of the discrete event process is simulated based on the specific information and the behaviors are counted. And finally, in the output section, the average results of the operational simulations are obtained. The framework of the open-loop simulation model can be seen in Fig.1.

A Framework

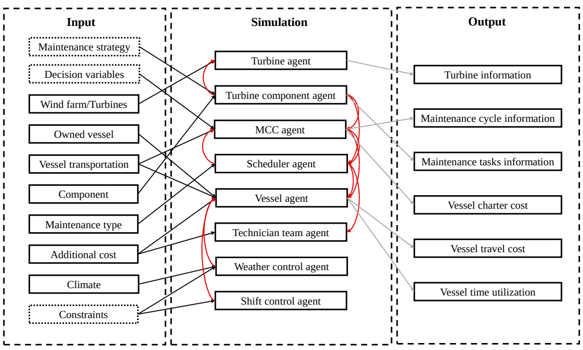


Fig. 1: The open-loop simulation model framework

B Assumption

Because of the complexity of the maintenance system and due to many reality factors being considered into the system, it is necessary to make some assumptions for a better understanding of the system. Thus, the following assumptions are made when building the simulation model in this paper:

1. *Maintenance cycle* Maintenance activities can be performed within a certain period, which is referred to as the maintenance cycle in this research. A maintenance cycle is started when one of the maintenance task thresholds is reached. And a maintenance cycle is ended if all maintenance tasks are completed.
2. *Weather condition* The weather conditions, wave height and wind speed, are independent. While wind speed at sea level/hub level can be obtained from the calculation, where wind speed of 21m level is a reference. Also, the current weather condition is not dependent on the previous weather condition. The weather conditions are assumed to be constant for 2 hours (equal to 6 periods).
3. *Maintenance time* All the maintenance times are considered constant and they are independent of weather conditions.
4. *Traveling time* The travel speed of a vessel is assumed to be constant. And the travel time between the base and the wind farm back and forth is considered constant and independent of weather conditions. While the inter-transit time between two turbines is assumed to be constant, where the detailed layout of the wind farm is ignored.
5. *Maintenance tasks* Maintenance tasks for different components of a turbine can be performed simultaneously. Once a maintenance task is started by a vessel, it must be finished before this vessel can be assigned to a new task. And once the maintenance task starts, the chartered vessel should always finish it even though its charter period has ended, and its late return will lead to the extra cost based on late-return days. After the end of a charter period, a vessel will never be assigned to a new maintenance task.
6. *Component* The lifetime of one component is independent of any other component. A turbine can only work when none of its components is being maintained and none of its components is defective. Either a minor repair or a major repair cannot be performed twice on one component within the same maintenance cycle. While a component that has been replaced can be again repaired in the same maintenance cycle since it is considered a new component.
7. *Technicians* Each vessel is equipped with technicians of the maximum number. And the technicians are assumed to be always sufficient when any vessel is chartered. 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 a charter period until the day when the vessel is returned.
8. *Spare parts* It is assumed that spare parts are always available and every vessel is equipped with sufficient spare parts for its maintenance tasks.
9. *Vessel charter* It is assumed that the charter rates are fixed for the simulation time horizon. And the charter period can be extended unlimitedly. Once the charter period starts, the complete charter period will be charged. The costs of non-maintenance personnel are assumed to be included in the charter rate.
10. *Vessel mobilization* When mobilization is initiated, if one maintenance cycle is ended before the mobilization of any vessel is finished, the mobilization activity needs to be stopped and the full mobilization cost is charged.
11. *Charter extension* Once a charter period is ended, the vessel always returns to base, regardless of whether the charter period will be extended. Through 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, after it arrived at the base, it will return back to the site after the shift start of the next day if weather permits.
12. *Maintenance priority* For maintenance tasks that need the same vessel for maintenance, the component with a higher age is prioritized. For vessels, the on-site vessels are prioritized over the vessels staying at the base. And if there are multiple available vessels on site, the vessels with more assigned teams are prioritized.

C Simulation input

Maintenance strategy For every component of the turbine in the offshore wind farm, it ages over time, and eventually, it fails when its lifetime is entirely used. When the age of one component reaches a certain percentage, which is the fraction of the consumed age relative to the components' lifetime, a component is categorized in a pre-defined zone and the corresponding type of maintenance is required to execute on this component. Four types of maintenance, minor repair, major repair, preventive replacement, as well as corrective replacement, need different maintenance resources, including different vessels and different amounts of technicians. After the maintenance activity is finished, the minor repair and the major repair result in different age reductions of the component, the preventive replacement and corrective replacement will lead to the replacement of a new component, and its lifetime is generated from the Weibull distribution of the components. All this maintenance strategy information is summarized in Table 1.

As mentioned in the assumption, one maintenance cycle can be initiated by any one of two triggers, one is when the number of components in zone 4 equals or exceeds a defined threshold, and another one is when the number of failed components equals or exceeds a defined threshold. The threshold values for starting a maintenance cycle are listed in Table 2.

Decision variables The simulation model aims to optimize the fleet size and mix, comprising of HLVs, FSVs, and CTVs, for O&M activities of an offshore wind farm, based on the given owned vessel in the fleet. In this model, instead of directly setting the number of vessels to be chartered, the decision logic is used to determine the number of vessels and these dynamic decisions are made based on the number of maintenance tasks per vessel type to be completed. The decision variables whose values must be defined before performing a simulation are:

- $X_{\mathrm{T}}^{\mathrm{HLV}}$
- $X_{\mathrm{T}}^{\mathrm{FSV}}$
- $X_{\mathrm{T}}^{\mathrm{CTV}}$

For each decision variable, it indicates the estimation of how many tasks one vessel is expected to execute during the maintenance cycle. Based on the number of tasks of each vessel type, $N_{\mathrm{T}}^{V}(V = \mathrm{HLV/FSV/CTV})$, which can be known from the model, and the given number of owned vessels of each type, $N_{\mathrm{O}}^{V}(V = \mathrm{HLV/FSV/CTV})$, which is given before simulation, the general equations used to decide how many vessels of each type to charter can be expressed as:

$$N_{\mathrm{C}}^{\mathrm{HLV}} = \left\lceil \frac{N_{\mathrm{T}}^{\mathrm{HLV}}}{X_{\mathrm{T}}^{\mathrm{HLV}}} \right\rceil - N_{\mathrm{O}}^{\mathrm{HLV}} \tag{1}$$

$$N_{\mathrm{C}}^{\mathrm{FSV}} = \left\lceil \frac{N_{\mathrm{T}}^{\mathrm{FSV}}}{X_{\mathrm{T}}^{\mathrm{FSV}}} \right\rceil - N_{\mathrm{O}}^{\mathrm{FSV}} \tag{2}$$

$$N_{\mathrm{C}}^{\mathrm{CTV}} = \left\lceil \frac{N_{\mathrm{T}}^{\mathrm{CTV}}}{X_{\mathrm{T}}^{\mathrm{CTV}}} \right\rceil - N_{\mathrm{O}}^{\mathrm{CTV}} \tag{3}$$

Where $\left\lceil * \right\rceil$ denotes the ceiling operation in equation 1-3.

Charting extension decision

All three decision variables are set before the simulation starts. During each maintenance cycle, the charter period of each vessel type may need to be extended due to a large number of remaining tasks. Then, the decision logic to decide whether a charter period should be extended or not is given as:

$$\text{Charter extension} = \begin{cases} \text{Yes} & N_{\mathrm{C}}^{V} + N_{\mathrm{O}}^{V} \geq N_{\mathrm{F}}^{V} \\ \text{No} & N_{\mathrm{C}}^{V} + N_{\mathrm{O}}^{V} < N_{\mathrm{F}}^{V} \end{cases} \tag{4}$$

Where, $N_{\mathrm{C}}^{V}(V = \mathrm{HLV/FSV/CTV})$ is the number of the chartered vessel of each type, N_{O}^{V} is the number of the owned vessel of each type, $N_{\mathrm{F}}^{V}(V = \mathrm{HLV/FSV/CTV})$ is the number of each vessel type in the current fleet, including the vessel that must be determined if the charter period will be extended.

Wind farm and turbines inputs Table 3 shows the wind farm-specific inputs. The input [1] shows the number of turbines in the offshore wind farm. Input [2] displays the distance between the based onshore and the offshore wind farm. Input [3] indicates the simulation time horizon. Inputs [4-5] are the shift start and shift end of the wind farm, and all the maintenance tasks can only be executed within this period. The inputs [6-10] are the specification of every turbine. Input [11] is the soft time window for each maintenance cycle, once the number is exceeded, the daily penalty cost will be taken into account. All these values are referred and estimated from Dalgic et al. [17].

Owned vessels inputs The number of owned vessels of each type in Table 4 should be pre-defined as inputs in the simulation model. The number of owned vessels per type for all the scenarios in this research.

Vessel transportation inputs For 3 vessels, different transportation inputs are shown in Table 5. Input [1] is different travel speeds. Input [2] is the inter-transit time for different vessels to move between two turbines, where the time of a team entering the turbine is included. Inputs [1-2] are independent of the weather condition and assumed to be constant according to the prior assumption section. Input [3] is the minimum working window, which means that, the time window that at least must be available for a vessel or team to work on a maintenance task before it starts/resumes. Input [4] is the number of technicians on the vessel when the vessel travels to execute the maintenance task. As previously mentioned, it is assumed that every vessel is equipped with technicians of the maximum number. Input [5] is the maximum number of parallel teams and it indicates the number of teams on each vessel that can work on different maintenance tasks simultaneously. Inputs [6-8] are weather-related limitations of each vessel and vessels cannot work if the weather condition data exceeds any limitation. Inputs [9-10] are the Jack-up/Jack-down time, which is the time for stabilizing the HLV by stationing its legs on the seabed. Inputs [8-10] are only considered for HLV because FSV and CTV are not required to lift heavy parts to the hub level of the turbine. Inputs [11-13] are related to chartering vessels. Input [11], the mobilization time, indicates the time needed by a chartered vessel to get ready before it starts maintenance tasks. Input [12] is the length of a charter period. Input [13] indicates the length of each extended charter period, and this happens when a charter period is ended but the maintenance tasks are not finished. At the beginning of each maintenance cycle, the chartered fleet size is decided, and during the cycle, it is periodically checked whether more vessels need to be chartered, and the interval is indicated as input [14] Input [15] specifies the daily penalty factor of the exceeded days for those chartered vessels that return after the charter period has ended. Input [16] is the fuel consumption while traveling, which is part of the total cost of the objective function. Input [17] is the required time for a team of technicians to leave the turbine and enter the vessel in terms of safety. All these values are referred and estimated from Dalgic et al. [17].

Components inputs Four components, rotor, generator, gearbox and bearing, are considered in the simulation model, and the lifetime of each component is generated by using the Weibull distribution with specific shape parameters and scale parameters.

For the components' lifetime inputs, all the values of the Weibull shape parameters and Weilbull scale parameters referred from Sarker et al.[21] are shown in Table 6.

Maintenance type inputs Maintenance type inputs contain the time and cost of different types of maintenance tasks on the different turbine components.

For the maintenance type inputs, time and cost vary when different types of maintenance tasks on the different turbine components. All these data are estimated and collected from Carroll et al.[22], and Andrews et al.[23]. All the time values are provided in Table 7.

TABLE 1: MAINTENANCE STRATEGY

Maintenance type	Component age (%)	Zone	Age reduction	Vessel type	The number of technicians
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	Replace a new component	HLV	8
Corrective replacement	≥ 100	Failed	Replace a new component	HLV	8

TABLE 2: THRESHOLD FOR STARTING A MAINTENANCE CYCLE

The trigger of starting a maintenance cycle	Threshold value
The number of zone 4 components	1
The number of failed components	1

TABLE 3: WIND FARM AND TURBINE INPUTS

No	Name	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	Soft time window	60	day

TABLE 4: OWNED VESSELS INPUTS

No	Name	Value	Unit
1	Number of owned HLVs	0	vessel
2	Number of owned FSVs	0	vessel
3	Number of owned CTVs	1	vessel

While for different types of maintenance tasks on the different turbine components, costs are different and they are shown in Table 8.

Additional cost inputs Table 9 shows the additional cost inputs [1-12] used for the total cost calculation. Input [1], the electricity price, which is previously mentioned and assumed to be fixed, is used to calculate the electricity production profit. Inputs [2-4] show the fixed charter rate for each type of vessel. Inputs [5-7] are costs for the mobilization of chartered vessels before they start the maintenance tasks, Inputs [8-10] are fuel costs for each vessel type associated with the transportation. Inputs [11-13] are technician costs for each type of vessel. For owned vessels, technician costs of the entire cycle are considered, while for chartered vessels, only technician costs during the charter period are considered. Input [14], the daily penalty cost, is imposed when one maintenance cycle exceeds the soft time window. The values of inputs [1-13] are referred from Dalgic et al. [17].

Climate inputs Wind speed and wave height are considered the climate inputs in the simulation model, and synthetic climate datasets can be generated by using the Weibull distribution. Referring to the idea from [17], the wind power law developed by Justus and Mikhail [24], shown as the equation 5, is used to calculate the wind speed values at sea level and hub level, based on the wind speed value at the reference level 21m.

TABLE 5: TRANSPORTATION INPUTS OF VESSELS

No	Name	Value HLV	Value FSV	Value CTV	Unit
1	Travel speed	11	13.5	24	knot
2	Inter-transit time	40	40	20	min
3	Minimum working window	α	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	–	–	hour
10	Jack-down time	3	–	–	hour
11	Mobilisation 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	Penalty factor for late return	2	2	2	-
16	Fuel consumption	0.55	0.2	0.24	mt/h
17	Safety margin	20	20	β	min

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

TABLE 6: THE VALUES OF COMPONENT LIFETIME INPUTS

Component	Weibull shape parameter (Unit: −)	Weibull scale parameter (Unit: day)
Rotor	3	3,000
Bearing	2	3,750
Gearbox	3	2,400
Generator	2	3,300

TABLE 7: THE VALUES OF MAINTENANCE TIME INPUTS

Maintenance type	Time value (Unit: h) Rotor	Bearing	Gearbox	Generator
Minor repair	9	6	8	7
Major repair	18	12	16	14
Preventive replacement	70	50	70	60
Corrective replacement	100	70	100	81

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \tag{5}$$

where v_2 is the wind speed at height h_2, v_1 is the wind speed at height h_1, and α is the shear component, which is a constant for the wind power law equation.

Inputs [1-2] are the Weibull shape parameter and the Weibull scale pa-

TABLE 8: THE VALUES OF MAINTENANCE COST INPUTS

Maintenance type	Cost value (Unit: €)			
	Rotor	Bearing	Gearbox	Generator
Minor repair	4,000	1,000	5,000	1,500
Major repair	15,000	3,750	18,750	5,000
Preventive replacement	60,000	15,000	75,000	20,000
Corrective replacement	185,000	45,000	230,000	60,000

TABLE 9: ADDITIONAL COST INPUTS

No	Name	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	2,500	€/CTV/day
5	HLV mobilisation cost	800,000	€/mobilisation
6	FSV mobilisation cost	200,000	€/mobilisation
7	CTV mobilisation cost	50,000	€/mobilisation
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: CLIMATE INPUTS

No	Name	Value	Unit
1	Weibull shape parameter of wind speed (at 21m)	2.43	-
2	Weibull scale parameter of wind speed (at 21m)	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	Shear component	0.1	-

rameter to generate the wind speed at the height of 21 m. Inputs [3-4] are the Weibull parameters to generate the wave height. Input [5] is the relevant height above sea level and is used to obtain the wind speed at sea level. Input [6] is the shear component used in the equation 5, to obtain wind speed of different altitudes. The values of inputs [1-4] are from Barth and Eecen[25]. The value of the input [6] is referred and estimated from Justus and Mikhail [24].

D Simulation process

The simulation model proposed in this paper contains eight different simulation agents, and each agent is responsible for a certain process.

The current status of an agent is represented by its mode, for example, a turbine can have the modes ‘working’ or ‘not working’, and a vessel can have the modes ‘idle at base’, ‘travel to site’, etc. The three most important process interactions are ‘activate’, ‘passivate’, and ‘hold’. Activate is used to continue an agent’s process at the current period. Passivate is used to stop the agent’s process (the agent becomes passive). Hold is used to delay the agent’s process, and the agent becomes active at the scheduled time.

All agents, the turbine agent, turbine component agent, maintenance cycle control agent, scheduler agent, vessel agent, technician team agent, weather control agent, and shift control agent will be described as follows.

Turbine Agent Each turbine in the offshore wind farm is represented by a turbine agent. One turbine consists of 4 turbine components: rotor, bearing, gearbox, and generator. The lifetime of each component is sampled from its Weibull distribution. The turbine starts producing electricity at the start of the simulation. The turbine stops working as soon as one or more of its components fails or when maintenance is performed on one or more of its components.

The turbine will continue running only when none of the turbine components are faulty and none turbine components are under maintenance. The four components of the turbine only age when the turbine is working and, hence, all turbine components stop aging when the turbine is not working.

Turbine Component Agent Each turbine component of each turbine is represented by a turbine component agent, and each has an individual lifetime before it fails. The component’s age is represented by the lifespan percentage that has been consumed. Corresponding with the components’ age, the components are categorized in zone 1, zone 2, zone 3, zone 4, or zone f (component failed), as shown in Table 1. A component ages over time and enters consecutive zones until it may eventually fail.

Based on the maintenance strategy, maintenance activities can only be performed within a maintenance cycle. A maintenance cycle is started when either the number of failed or the number of zone 4 reaches the defined thresholds, which is shown in Table 2. The turbine component agent checks whether any threshold is reached, and initiates a maintenance cycle by activating the maintenance cycle control agent if it happens. Turbine components in zone 2 or 3 can be repaired if a maintenance cycle is active, therefore, during this period, the only action for these two types of repair is to activate the scheduler agent, which is responsible for scheduling maintenance tasks.

When a turbine component is repaired either from zone 2 or zone 3, its age is reduced according to Table 1. When a turbine component is replaced either from zone 4 or zone f, a new component will be installed in the turbine. Then a new lifetime of the component is sampled from the Weibull distribution and the component’s age is reset to zero.

Maintenance Cycle Control Agent The maintenance cycle control (MCC) agent is used for the simulation environment. The MCC agent is activated if any of the maintenance cycle triggers is reached, after which a maintenance cycle is started. The MCC agent is also responsible for chartering vessels. Once the maintenance cycle starts, the simulation environment will be periodically checked with a fixed interval, vessels can be chartered at the start of a maintenance cycle or during the cycle if additional vessels should be chartered.

Scheduler Agent The scheduler agent is also used for the simulation environment. This agent is responsible for assigning maintenance tasks to teams of technicians as well as vessels. Every time the scheduler agent is activated, it determines the remaining maintenance tasks of each type and sorts the tasks according to the maintenance priority. Then, the agent assigns the maintenance tasks to teams of technicians tied to vessels based on the maintenance priority. If all maintenance tasks are completed and all the vessels are back at base, the scheduler agent will send the signal to the MCC agent that the maintenance cycle can be ended and the MCC agent will end the maintenance cycle.

Vessel Agent Each vessel in the fleet, either chartered or owned, is represented by a vessel agent. A vessel either chartered vessels or owned is respectively denoted by ‘(C)’ or ‘(O)’ after the vessel’s name. The processes vary for the different vessel types, and vary for chartered and owned vessels. Owned vessels idle at the base if no maintenance cycle is active. If it is decided to charter a new vessel by the MCC agent, a vessel agent is created and the vessel is added to the fleet. The chartered vessel is available after the mobilization is done.

If a maintenance cycle is active, a vessel can be assigned or not assigned. If the vessel is assigned, it means that at least one team of technicians of the vessels is assigned to a maintenance task. And there are five main subprocesses as follows:

- All teams of the turbine are delivered to the destination
- Any team of the vessel completed its task
- Any team of the vessel is not at the turbine
- The vessel is interrupted by the shift end
- The vessel is interrupted by the bad weather

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 a 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.

Technician Team Agent Every time a maintenance task is assigned to a team of technicians, a technician team agent is temporarily created. The created technician team agent will terminate and be removed once the team has finished the maintenance task and is picked up by the vessel.

Weather Control Agent Each vessel in the fleet has its own weather control agent and the agent has the function to check whether the weather window is sufficient for vessels to travel to the site for maintenance activities. The weather control agent is responsible for interrupting a vessel that is in operation and must respond to rough future weather conditions, and the vessel has to stop the maintenance activity, or even travel back to the base if the vessel type is CTV.

Shift Control Agent The shift control agent is the agent for the simulation environment that ensures the vessels constrained by shift hours are activated at shift start and start picking up teams at shift end. At the end of each day (00h00) during a maintenance cycle, Shift Control prints the mode of each vessel to get an overview of the location and activity of each vessel in the fleet.

E Simulation outputs

During the simulation, the process of all maintenance activities in the wind farm will be checked and recorded every 20 minutes in the log, through which, turbine information, cycle information, component information, vessel charter information, vessel travel information, as well as vessel time information can be collected as simulation outputs. Based on the above-mentioned information, the total cost can be obtained and used for the objective function.

Turbine information The operating status of every turbine is monitored in the model, based on this information, the following output about turbine information can be calculated:

- Total electricity production of the offshore wind farm
- Time-based availability of the offshore wind farm
- Power-based availability of the offshore wind farm

To determine the wind farm's total electricity production, individual turbines' electricity production during the simulation horizon should be first calculated. The relationship between the wind speed at the hub level v_t and the generated power $P_t(v_t)$ during period t is given by [26] and the power can be calculated from equation 6.

$$P_t(v_t) = \begin{cases} 0 & v_t < v^{\mathrm{ci}} \text{ or } v > v^{\mathrm{co}} \\ P^{\mathrm{r}}(\mathrm{a}+\mathrm{b}v_t+\mathrm{c}v_t^2) & v^{\mathrm{ci}} \le v_t \le v^{\mathrm{r}} \\ P^{\mathrm{r}} & v^{\mathrm{r}} \le v_t \le v^{\mathrm{co}} \end{cases} \tag{6}$$

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 at the rated output wind speed, and parameters a, b, and c are given by:

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

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

$$\mathrm{c} = \frac{1}{(v^{\mathrm{ci}}-v^{\mathrm{r}})^2}[2-4(\frac{v^{\mathrm{ci}}+v^{\mathrm{r}}}{2v^{\mathrm{r}}})^3] \tag{9}$$

The time-based availability is the percentage of time that an individual wind turbine or wind farm is available to generate electricity expressed as a percentage of the theoretical maximum[27]. In this research, it is defined as the operational time, which is equal to total time minus downtime due to maintenance or failures, divided by the simulation time horizon.

The power-based availability is the operational performance and is defined as the actual power output divided by the theoretical maximum power output.

Maintenance cycle information The model tracks when maintenance cycles start and end, based on which the following things can be calculated:

- Maintenance cycle length (days)
- Penalty cost related to prolonged maintenance cycles

Maintenance tasks information Each time when a maintenance task is completed, the information on the maintenance task is traced, including the turbine and component type, the maintenance type, the costs, and the time of completion. Based on this information, the following things are calculated:

- The number of maintenance tasks of each type
- The costs of maintenance tasks of each type

Vessel charter cost The developed model tracks information related to chartering vessels including the start and end time of mobilization, the maintenance cycle number when a mobilization and charter period starts, the start and end time of a charter period, 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 (together with the number of late days), and whether mobilization is stopped by the end of a cycle. Based on this information, the following items can be calculated:

- The number and cost of charters of each vessel type
- The number and cost of extended charter periods of each vessel type
- The number and cost of mobilizations of each vessel type
- The total number of days and cost of late returned chartered vessel of each vessel type
- The cost of technicians

As previously mentioned, the technicians on chartered vessels are paid for the duration of the charter period while the technicians on an owned vessel are paid for the duration of the maintenance cycles.

Vessel travel cost For each vessel ever in the fleet, the developed model tracks traveling information, including the number of travels from base to the site, the number of travels from site to base, and the number of inter-transits. Based on this information, the following cost can be calculated:

- The fuel cost for traveling

Vessel time utilization For each vessel ever in the fleet, the developed model tracks the time spent on several items:

- Time spent on traveling between the base and the site
- Time spent on inter-transit travels
- Time spent on repairs
- Time restricted by weather conditions
- Time restricted by shift hours
- Time of idling at the base during each maintenance cycle
- Time of idling on-site during each maintenance cycle
- Time spent on jacking up/down

Above all items listed above, the first four items are for all vessel types. The fifth item is for CTVs and FSVs because HLVs are not restricted by shift hours. The sixth item is for FSVs and HLVs because CTVs only deliver teams to the site but do not spend time on maintenance tasks. The seventh item is only for CTVs due to the fact that FSVs and HLVs return to the base if there are no more tasks and they will never idle on-site during the maintenance cycle. The last item is only for HLVs because this is the only vessel type requiring jack-up/jack-down activities.

Based on this information, the distribution of time of each vessel type is calculated. For owned vessels, the percentage of time spent on each item is determined based on the total time of maintenance cycles. For chartered vessels, the percentage of time spent on each item is determined based on the charter length excluding mobilization time. Therefore, the distribution of time indicates the percentage of time spent on things relative to a vessel's available time in maintenance cycles.

F Constraints for transportation systems

Different types of vessels have different characteristics, thus, different constraints are applied and their maintenance and operations will be affected to varying degrees, and all these characteristics are shown in Table 11. It is assumed that HLV and FSV can stay offshore for multiple days, while the CTV cannot and has to return to the base every day. In terms of shift hours. only HLV can work 24 hours a day on a three-shift basis. While the FSV and CTV are constrained by shift hours, resulting that, FSV and CTV can only work within the shift hours. Once the shift ends, even if there is any maintenance task not finished, FSV and CTV has to stop the maintenance activity, FSV has to stay on-site and CTV has to return to base. Inputs [3-5] are weather constraints. It is assumed that all the vessel types are constrained by the wave height and the wind speed at sea level, and only HLV is constrained by the wind speed at the hub level.

TABLE 11: CONSTRAINTS FOR TRANSPORTATION SYSTEMS

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	✓		

G The concluded open-loop simulation model flowchart

This model can be seen as an evaluation tool for each decision variable combination. All that needs to do is to predetermine the decision variable combination $X_{\mathrm{T}}^{\mathrm{HLV}}$, $X_{\mathrm{T}}^{\mathrm{FSV}}$, $X_{\mathrm{T}}^{\mathrm{CTV}}$, then the model will execute the simulation process from the very beginning state S_0, and terminate the simulation when the pre-set simulation time is reached and the state is S_{SimTime}. The concluded flowchart of this open-loop simulation model is shown in Figure 2.

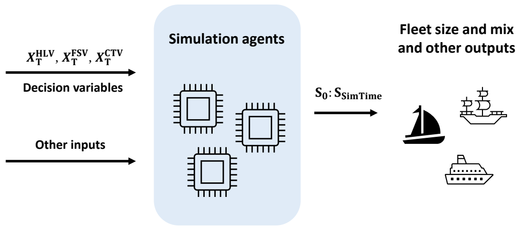


Fig. 2: The open-loop simulation model flowchart

III THE FEEDFORWARD SIMULATION MODEL

A Framework

As an extension of the previous open-loop simulation model, very similarly, 10 simulation inputs and 6 simulation outputs, are the same in the feedforward simulation model. However, among agents, some changes are made in order to realize some functions. The framework of the feedforward simulation model can be seen in Figure 3.

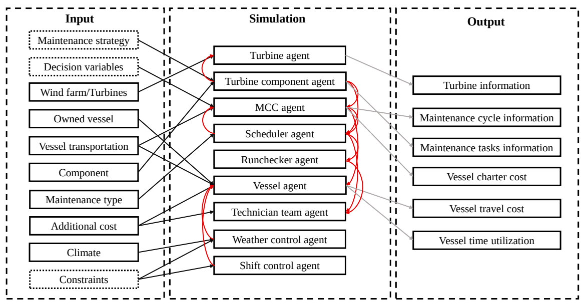


Fig. 3: The feedforward simulation model framework

One new agent named RunChecker agent is added into the feedforward simulation model. The function of this agent is to terminate the whole simulation under some certain condition, for example, in this research when one maintenance cycle is finished. And after this, all the further calculations are carried out and all the model outputs of this maintenance cycle can be obtained. This agent is always working in a standby status once the simulation starts, waiting for the terminate command from the Scheduler agent.

The Scheduler agent, in the feedforward simulation model, the Scheduler agent not only sends the signal to the MCC agent but also sends another signal to the Runchecker agent, so that the Runchecker agent can terminate the whole simulation. Then, all the calculations will come after and the output can be acquired.

Additionally, two agents, the Turbine agent and the Turbine component agent, will have more functions in the feedforward simulation model. Before the simulation starts, these two agents read the historical data about the previous wind farm states, and by using this information, the feedforward simulation model can start the simulation from a specific state but not just from the very beginning as the previous open-loop simulation model.

B The concluded feedforward simulation model flowchart

Together with other inputs, this model can perform a simulation from state S_{X-1} until the state S_X when a certain condition is met, and in this research, such a condition is when a maintenance cycle is finished. Then the information about the new state of the wind farm will be known and saved, all the further calculations will be carried out, and the fleet size and mix, together with other model outputs can be obtained. The concluded flowchart of this feedforward simulation model is shown in Figure 4.

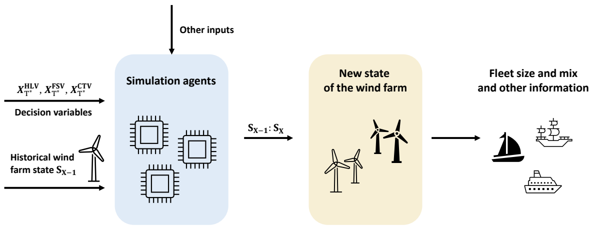


Fig. 4: The flowchart of the feedforward simulation model

IV SIMULATION-OPTIMISATION METHODOLOGY

A The interaction between the open-loop simulation model and optimization algorithm

Combined with the optimization algorithm, the open-loop simulation model can be a tool for long-term optimization of the fleet size and mix for an offshore wind farm, e.g. a general decision for a wind farm of a 15-year lifespan. And the flowchart of the interaction between the open-loop simulation model and the optimization algorithm is shown in Figure 5, where the optimization method is referred to as optimizer.

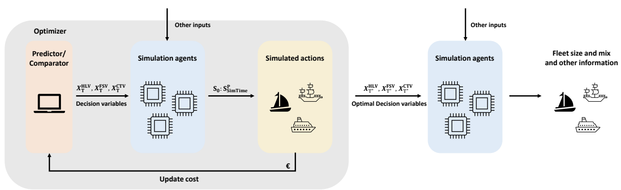


Fig. 5: Flowchart of interaction between the open-loop simulation model and optimization algorithm

B The interaction between the feedforward simulation model and optimization algorithm

In this research, together with the optimization algorithm, the feedforward simulation model can be used as a tool for a relatively short-term optimization of the fleet size and mix, in other words, a decision for a maintenance cycle. The flowchart of the interaction between the feedforward simulation model and the optimization algorithm is shown in Figure 6.

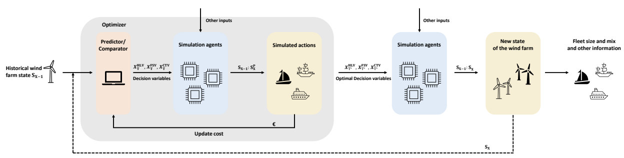


Fig. 6: Flowchart of interaction between the feedforward simulation model and optimization algorithm

The explanation of the optimization approach of each maintenance cycle by using the feedforward simulation model is shown in Figure 7. Generally, for maintenance cycle X, the information about the terminal wind farm of the previous maintenance cycle $X-1$ is used as an input, marked as S_{X-1}. Since the previous maintenance cycle is just finished, it takes some time to trigger the next maintenance cycle, and there is a gap time with a length of t_X. When the new maintenance cycle X starts at $t = T_{X-1} + t_X$, by putting different decision variable combinations into the feedforward simulation model, the different terminal states of maintenance cycle X can be predicted, which is expressed as S_X^p, and the cost resulting from each decision variable combination will be known. Each cost is used for the performance evaluation of the corresponding decision variable combination. Among these decision variable combinations, only one optimal combination will be chosen and applied to the maintenance cycle X in the simulation model, then the specific terminal wind farm of the maintenance cycle X can be determined, which is marked as S_X. Again, for maintenance cycle $X+1$, the terminal wind farm state of maintenance cycle X is used as the next initial wind farm state of non-maintenance duration before maintenance cycle $X+1$ starts, which is also marked as previously mentioned S_X. Additionally, the cycle length of maintenance cycle X is $T_X - (T_{X-1} + t_X)$ and the length might be flexible but not a fixed time period.

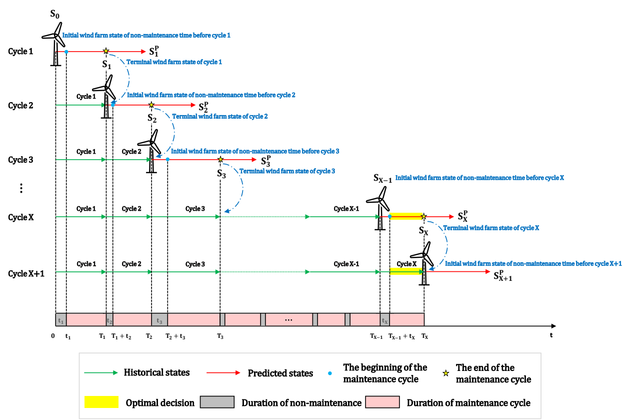


Fig. 7: Illustration of the optimization approach of each maintenance cycle by using feedforward simulation model

C Optimisation Algorithm

Objective function Before the simulation runs, the decision variables should be defined in the model. In order to reduce the extreme result brought by a single scenario, for each decision variable combination, a set of 20 scenarios is made, where the data of both component lifetime and weather conditions differ. After the simulation of each scenario, all the information about the maintenance logistics of the wind farm within a planning time horizon can be known as well as the total cost can be known. The objective is to minimize the expected total costs.

$$\overline{C^*} = \frac{\sum_{s \in S} (C^s_{\text{Task}} + C^s_{\text{Cycle}} + C^s_{\text{Vessel}} + C^s_{\text{Loss}})}{N_S} \tag{10}$$

The average cost, which is the average value of the total costs of 20 scenarios, is the objective function in this model and is shown as equation 10. In this equation, S is the set of all scenarios, and in scenario s, four items are included. Where C^s_{Task} is the cost for maintenance tasks. C^s_{Cycle} is the cost for each maintenance cycle, which is for the penalty after the 60-day soft window constraint. C^s_{Vessel} is the cost for vessel-related stuff, including the cost caused by charter, charter extension, mobilization, late return, fuel and technicians. C^s_{Loss} is the cost for the turbine downtime, this is the loss when the turbine is not operating because of component failure or being repaired. N_S is the number of a set of scenarios.

Simulated annealing Simulated annealing (SA) is a heuristic solution strategy applicable to a wide variety of optimization problems, and an acceptable answer for typical problems can be obtained in a reasonable time. Firstly, an initial solution is generated randomly and the simulation model evaluates the performance. After that, new random solutions are generated and their corresponding performances can be evaluated. In the SA process, either one better or worse solution to the problem is accepted with a certain probability, and the Metropolis criterion, can be employed in this case [28].

The acceptance probability can be calculated as follows:

$$P = \begin{cases} 1 & E(n+1) < E(n) \\ e^{-\frac{E(n+1)-E(n)}{T(n)}} & E(n+1) \geq E(n) \end{cases} \tag{11}$$

Where, $\mathrm{E}(\mathrm{n}+1)$ is the energy of the next move and $\mathrm{E}(\mathrm{n})$ is the energy of the current status, both of them are the evaluation results from the simulation model. While $\mathrm{T}(\mathrm{n})$ is the current temperature. New solution is accepted when its energy value is lower than that of the old solution. Otherwise, a random variable U from distributed uniform over (0,1) will be used to compare with the acceptance probability from the equation 11. If the value of U is smaller, the new solution is accepted[29].

The temperature decreases according to a cooling schedule. The most common cooling schedule follows an exponential decay curve. The shape of this curve is determined by the starting temperature T_0, the cooling factor α and the cooling step n, which can be expressed as:

$$T(n) = T_0 \alpha^n \tag{12}$$

For each temperature T, a sequence of accepted solution points need to be judged by the criterion expressed as equation 11, to reach a state of equilibrium. Once the equilibrium state has been achieved, the temperature is lowered to a new temperature as defined by the cooling schedule. The iterations of the algorithm keep running until the stopping criterion is met, and the system is considered to have frozen[29]. The stopping criterion can be setting the stopping temperature value, and the last iteration stops when the final temperature is lower than the stopping temperature[30].

The optimization process of this research Initially, as well as the first move of the optimization algorithm, an initial solution is generated randomly based on each decision variable's search domain. For each decision variable, it has its own search domain, the minimum value is the lower limit and the maximum value is the upper limit. A number is randomly chosen in this range and all three random numbers compose the initial solution. By applying this decision variable combination to the open-loop simulation model or feedforward simulation model, the simulation of the discrete events of an offshore wind farm under 20 scenarios will be executed, all the total costs of each scenario can be obtained, and the average cost of 20 scenarios will be calculated as the energy of the current move.

Next, a new solution will be generated. This can be realized by choosing one of the three decision variables randomly and generating a new random number based on its search domain and valuing it. Then the new number of the chosen decision variable and another two numbers of another two decision variables form the new solution. Again, by applying this new decision variable combination to the simulation model for the new costs under 20 scenarios, all total costs and the average cost, which is the energy of the new move, can be obtained.

Then a comparison between the initial solution and the new solution is performed by comparing their average costs obtained from the simulation model, 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, and 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) will be generated and compared with the current acceptance probability. If the value of the current 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.

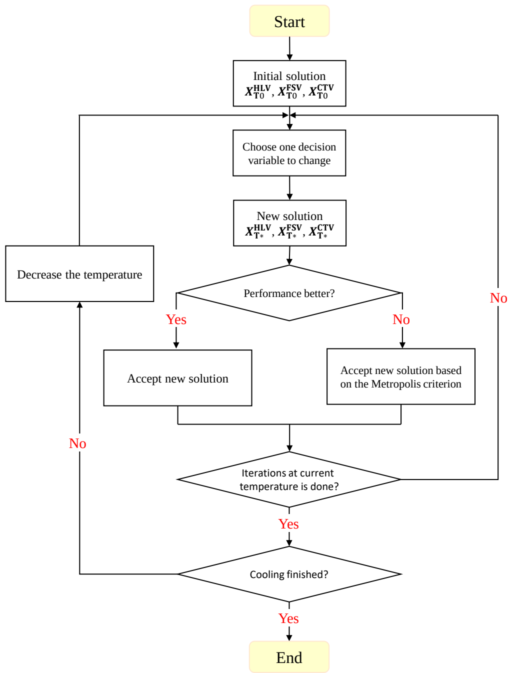


Fig. 8: The flow chart of the simulated annealing

Before jumping to the next move, the current temperature and the number of iterations at the current temperature should be always checked. There are a certain number of iterations at each planned temperature, only when all the iterations are done, can the temperature decreases. And the new temperature should be compared with the stopping temperature before starting the iterations at the new temperature. 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 will be 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 temperature is decreasing based on the cooling schedule, which is expressed as 12. In the very beginning, when the temperature is high, the acceptance for the new solution with higher energy is relatively and the as the temperature drops, the acceptance probability is lower and lower, and the cooling process is close to stable. All these steps iterate until the temperature is lower than the stopping temperature. All these procedures of the simulated annealing in this research is expressed as the flow chart shown in Figure 8.

V SIMULATION RESULTS

A The result of the long-term optimization

Decision variables and fleet configurations Based on the optimal decision variable result of $X^{\mathrm{HLV}}_{\mathrm{T}} = 6$, $X^{\mathrm{FSV}}_{\mathrm{T}} = 24$, $X^{\mathrm{CTV}}_{\mathrm{T}} = 150$, all values of vessel numbers to be chartered are presented in Table 12, where No. means the maintenance cycle number.

TABLE 12: THE VALUES OF CHARTERED VESSELS

No.	SET1	SET2	SET3	SET4	SET5	SET6	SET7	SET8	SET9	SET10	SET11	SET12	SET13	SET14	SET15	SET16	SET17	SET18	SET19	SET20
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	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Turbine information result Turbine information results consist of three parts, the result of the total electricity production of the offshore wind farm, the result of the time-based availability of the offshore wind farm, and the result of the power-based availability of the offshore wind farm.

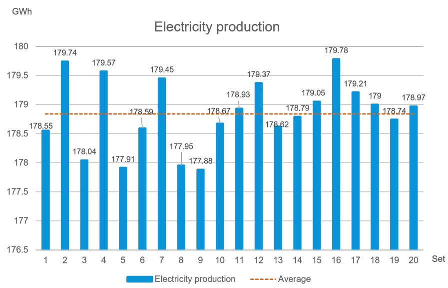


Fig. 9: The result of wind farm electricity production

For the result of the total electricity production of the offshore wind farm, all 20-scenario values and average values are shown in Figure 9. Therefore, weather conditions, including wave height and wind speed, vary between the various scenarios, and electricity production, which is derived from equation 6, is different, respectively. When turbines are operating well and wind speeds are appropriate for producing energy, the value of electricity produced can be higher than in more adverse circumstances.

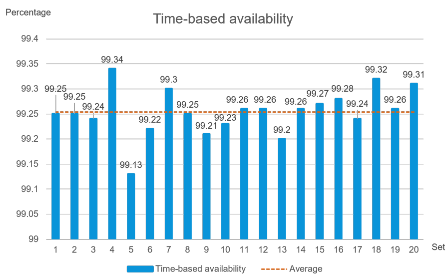


Fig. 10: The result of time-based availability

Based on the actual power produced by the turbines, the value for electricity production for each scenario is determined. The power generated by turbines operating over a planned period of time can be used to calculate theoretical power output. The cost loss is the difference between these two values multiplied by the electricity cost.

Figure 10 displays the result of the offshore wind farm's time-based availability, which is another output of the turbine information. This represents an average of the proportions of the overall working time for each turbine to the planning time horizon. All of these values vary because of the various scenario parameters and discrete event developments.

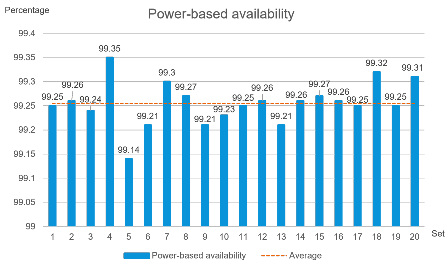
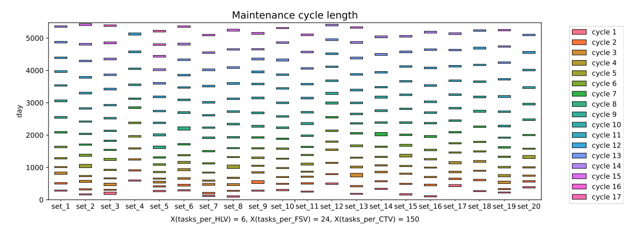


Fig. 11: The result of power-based availability

The outcome of the offshore wind farm's power-based availability is depicted similarly in Figure 11. During a planning time period, all turbine information reflects the overall state of the offshore wind farm.

Maintenance cycle information The results of the turbine information are divided into two categories: the maintenance cycle length (days), and the cost of extended maintenance cycles

Figure 12 displays all the data for the maintenance cycle length result. The relative location of each maintenance cycle of each scenario to the entire time horizon is shown in the top portion of Figure 12, from a down-to-up perspective to the Y-axis. And the width of each bar depicts the relative length of each maintenance cycle. As can be seen, all of the bars are complete, which means that under any circumstance, the wind farm's 15-year time horizon will not cause any maintenance cycles to be disrupted.



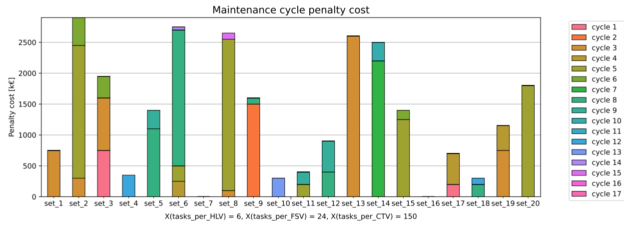
Unit: day	X(tasks_per_HLV) = 6, X(tasks_per_FSV) = 24, X(tasks_per_CTV) = 150																			
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10	set_11	set_12	set_13	set_14	set_15	set_16	set_17	set_18	set_19	set_20
cycle 1 length	37	34	75	38	45	38	37	45	38	46	34	48	33	39	45	39	64	37	33	43
cycle 2 length	47	39	33	38	38	55	48	33	89	34	43	35	44	35	37	54	48	48	37	45
cycle 3 length	75	66	77	43	55	52	60	61	44	34	40	36	112	50	41	41	51	34	75	42
cycle 4 length	37	41	33	40	37	64	42	42	37	38	35	49	58	39	40	34	70	60	68	39
cycle 5 length	40	103	42	50	42	65	33	109	52	33	64	42	35	39	85	45	39	39	50	96
cycle 6 length	49	68	67	52	50	39	39	36	38	46	41	51	59	42	63	49	37	39	44	34
cycle 7 length	48	42	37	55	42	45	45	33	47	42	40	50	49	104	49	56	44	46	48	41
cycle 8 length	57	42	42	42	82	104	51	47	61	54	48	68	43	47	52	47	48	64	38	52
cycle 9 length	60	41	44	52	66	55	44	52	56	46	64	69	49	60	44	50	52	53	54	56
cycle 10 length	44	45	51	45	47	51	44	51	56	52	53	52	51	66	50	54	52	48	48	56
cycle 11 length	55	56	46	55	47	45	52	48	50	47	56	44	56	42	47	51	51	43	59	51
cycle 12 length	47	54	56	67	52	51	54	55	59	47	50	51	49	50	48	49	51	62	46	60
cycle 13 length	52	46	50	-	52	50	57	54	60	66	47	56	60	60	54	49	46	45	47	46
cycle 14 length	46	55	56	-	59	61	47	45	43	48	51	53	57	59	51	59	56	-	42	-
cycle 15 length	-	60	59	-	55	47	48	62	57	33	50	-	43	-	-	-	-	-	44	-
cycle 16 length	-	-	49	-	51	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 17 length	-	-	-	-	53	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
total	694	792	817	577	873	822	701	773	787	666	716	704	798	732	706	677	709	618	733	661

Fig. 12: The result of the maintenance cycle length

The bottom portion of Figure 12 shows the specifics for the number of maintenance cycle days. It is clear that the number of maintenance cycles may 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 not easy to initiate the maintenance cycle, thus the amount of maintenance cycles will be less.

The length also changes for each maintenance cycle. The workload during this time period and the weather conditions may have an impact on this. All maintenance jobs can be completed more quickly when the weather is conducive for task performance as opposed to when it is not. Also, each maintenance cycle requires less time if there are fewer maintenance activities, therefore its duration falls in direct proportion.

The majority of each maintenance cycle often lasts fewer than 60 days. The daily penalty cost and any vessel-related expenses will be assessed once the soft time limit has been exceeded. Figure 13 depicts all of the numbers for the former cost, which was the result of the penalty cost associated with extended maintenance cycles outside of the soft time range. As can be seen, the cost of the penalty is 0 for every maintenance cycle with a duration of fewer than 60 days, and for cycles of more than 60 days, the cost of the penalty is calculated by multiplying the number of days above 60 days by the daily penalty.



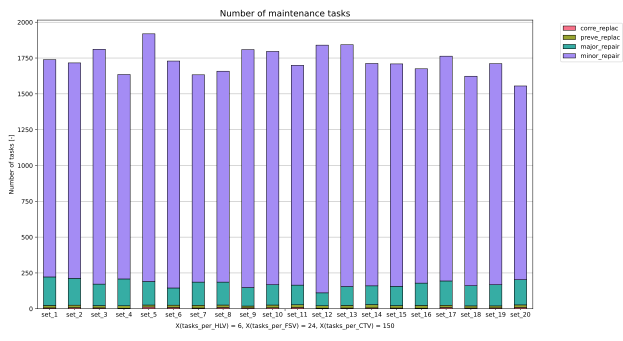
Unit: k€	X(tasks_per_HLV) = 6, X(tasks_per_FSV) = 24, X(tasks_per_CTV) = 150																			
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10	set_11	set_12	set_13	set_14	set_15	set_16	set_17	set_18	set_19	set_20
cycle 1	0	0	750	0	0	0	0	0	0	0	0	0	0	0	0	0	200	0	0	0
cycle 2	0	0	0	0	0	0	0	0	1500	0	0	0	0	0	0	0	0	0	0	0
cycle 3	750	300	850	0	0	0	0	100	0	0	0	0	2600	0	0	0	0	0	750	0
cycle 4	0	0	0	0	0	250	0	0	0	0	0	0	0	0	0	0	500	0	400	0
cycle 5	0	2150	0	0	0	250	0	2450	0	0	200	0	0	0	1250	0	0	0	0	1800
cycle 6	0	450	350	0	0	0	0	0	0	0	0	0	0	0	150	0	0	0	0	0
cycle 7	0	0	0	0	0	0	0	0	0	0	0	0	0	2200	0	0	0	0	0	0
cycle 8	0	0	0	0	1100	2200	0	0	100	0	0	400	0	0	0	0	0	200	0	0
cycle 9	0	0	0	0	300	0	0	0	0	0	200	500	0	0	0	0	0	0	0	0
cycle 10	0	0	0	0	0	0	0	0	0	0	0	0	0	300	0	0	0	0	0	0
cycle 11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
cycle 12	0	0	0	350	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0
cycle 13	0	0	0	-	0	0	0	0	0	300	0	0	0	0	0	0	0	0	0	0
cycle 14	0	0	0	-	0	50	0	0	0	0	0	0	0	0	0	0	0	-	0	-
cycle 15	-	0	0	-	0	0	0	100	0	0	0	-	0	-	-	-	-	-	0	-
cycle 16	-	-	0	-	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 17	-	-	-	-	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
total	750	2900	1950	350	1400	2750	0	2650	1600	300	400	900	2600	2500	1400	0	700	300	1150	1800

Fig. 13: The result of the cost related to prolonged maintenance cycles

Maintenance tasks information

The results of the maintenance tasks information include two parts, the number of maintenance activities of each type, and the costs of maintenance activities of each type.

For the number of maintenance activities of each type, all the values are shown in Figure 14 What can be seen from the figure is that, the number of

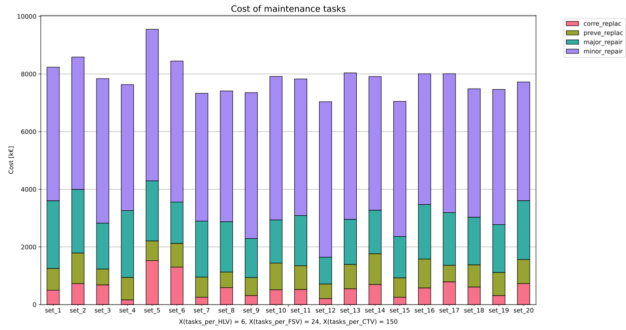


Unit: -	X(tasks_per_HLV) = 6, X(tasks_per_FSV) = 24, X(tasks_per_CTV) = 150																			
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10	set_11	set_12	set_13	set_14	set_15	set_16	set_17	set_18	set_19	set_20
corre_replac	6	8	6	3	12	9	5	9	6	7	9	4	5	6	5	4	9	5	6	9
preve_replac	17	17	16	18	14	16	19	17	13	19	19	17	18	23	17	19	15	15	14	18
major_repair	199	187	150	187	164	120	162	160	129	142	137	90	132	131	134	156	170	141	148	176
minor_repair	1517	1504	1639	1427	1729	1584	1447	1472	1661	1628	1534	1729	1688	1552	1553	1496	1569	1462	1543	1352
total	1739	1716	1811	1635	1919	1729	1633	1658	1809	1796	1699	1840	1843	1712	1709	1675	1763	1623	1711	1555

Fig. 14: The result of the number of maintenance tasks

minor repairs takes the dominant place in all the maintenance tasks, followed by the number of major repairs and preventive replacements, and the corrective replacement has the least number. This result can be affected by the maintenance strategy, where the component age and the corresponding zone and age reduction are defined. If the range of each zone changes, the proportion of each task type will change accordingly. Also, the amount of tasks can be influenced by the component's lifetime. The longer lifetime each component has, the fewer task number there will be because it takes longer days to enter the repair zones and it needs no maintenance for a longer time after each repair.

While for the cost of maintenance activities of each type, all the values are shown in Figure 15.



Unit: k€	X(tasks_per_HLV) = 6, X(tasks_per_FSV) = 24, X(tasks_per_CTV) = 150																			
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10	set_11	set_12	set_13	set_14	set_15	set_16	set_17	set_18	set_19	set_20
corre_replac	500.0	730.0	685.0	165.0	1525.0	1300.0	255.0	590.0	315.0	515.0	525.0	210.0	550.0	700.0	255.0	580.0	790.0	610.0	315.0	730.0
preve_replac	755.0	1060.0	550.0	780.0	685.0	825.0	700.0	540.0	625.0	925.0	825.0	505.0	845.0	1065.0	675.0	1000.0	575.0	770.0	800.0	835.0
major_repair	2348.75	2206.25	1591.25	2316.25	2082.5	1432.5	1941.25	1747.5	1352.5	1497.5	1738.75	930.0	1561.25	1510.0	1432.5	1892.5	1827.5	1651.25	1661.25	2041.25
minor_repair	4632.5	4590.5	5013.0	4370.5	5258.5	4891.0	4433.0	4534.0	5061.0	4978.0	4737.0	5393.0	5082.0	4636.0	4687.0	4534.5	4817.0	4455.5	4687.5	4115.5
total	8236.25	8586.75	7839.25	7631.75	9551.0	8448.5	7329.25	7411.5	7353.5	7915.5	7825.75	7038.0	8038.25	7911.0	7049.5	8007.0	8009.5	7486.75	7463.75	7721.75

Fig. 15: The result of the cost of maintenance tasks

The proportion of each task type of each scenario is different from that in the previous figure. This happens because the cost of each maintenance type on each component varies. For example, the cost of corrective replacement of each component is much more expensive than the cost of minor repairs of each component. Even though the number of corrective replacements is very few, the total cost of it still climbs sharply, which leads to its increasing proportion on cost bars.

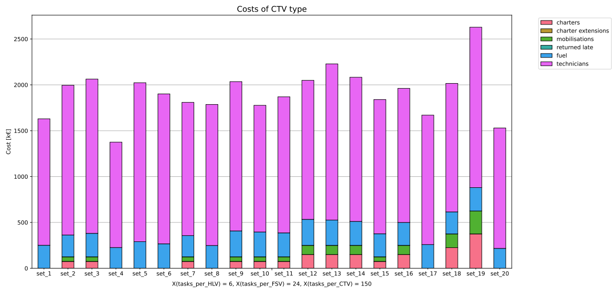
Vessel charter cost

The results of the vessel charter information include five parts, the number and cost of charters of each vessel type, the number and cost of extended charter periods of each vessel type, the number and cost of mobilizations of each vessel type, the total number of days and cost of the late-returned chartered vessel of each vessel type, and the cost of technicians.

For the numbers of the chartered vessels of each maintenance cycle, all the values are listed in Table 12.

Each combination of three numbers illustrates the chartered number of each vessel type in each maintenance cycle in each scenario, the first number is for the HLV type, the second number is for the FSV type and the third number is for the CTV type respectively. What can be known from the result is that HLV is required in every maintenance cycle because either the preventive replacement or corrective replacement is the trigger of starting the maintenance and both of them need HLV type. All the chartered values for HLV are 1 because the number of its task types is always small. For most cases, 1 FSV and 1 CTV are sufficient, and because of one owned vessel, the chartered CTV is 0. However, there are still some cases in which more FSV and CTV are required, and these happen in the middle or in the latter part of the planning time horizon. This is because in the former part of the time planning horizon, most components are in good status and maintenance can catch the pace of their aging. As aging goes on, the general components' status becomes worse and more maintenance tasks are required, thus more vessels are necessary.

For all the costs of CTV type, all the values are shown in Figure 16.



Unit: k€	X(tasks_per_HLV) = 6, X(tasks_per_FSV) = 24, X(tasks_per_CTV) = 150																			
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10	set_11	set_12	set_13	set_14	set_15	set_16	set_17	set_18	set_19	set_20
charters	0	75.0	75.0	0	0	0	75.0	0	75.0	75.0	75.0	150.0	150.0	150.0	75.0	150.0	0	225.0	375.0	0
charter extensions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
mobilisations	0	50.0	50.0	0	0	0	50.0	0	50.0	50.0	50.0	100.0	100.0	100.0	50.0	100.0	0	150.0	250.0	0
returned late	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
fuel	250.9	238.0	255.8	226.3	290.4	266.8	231.5	248.5	282.5	270.9	261.2	283.4	276.0	261.1	251.3	249.7	258.7	239.9	255.1	216.9
technicians	1379.1	1632.9	1682.1	1148.9	1732.8	1634.4	1452.8	1537.7	1627.8	1381.3	1484.0	1516.2	1702.3	1572.0	1463.8	1462.2	1411.2	1400.8	1748.8	1312.8
total	1629.9	1995.9	2062.9	1375.2	2023.2	1901.2	1809.3	1786.2	2035.3	1777.2	1870.2	2049.6	2228.3	2083.1	1840.0	1961.9	1669.8	2015.8	2628.9	1529.7

Fig. 16: The cost of CTV

It can be seen from this figure that the costs of both technicians and fuel cannot be ignored and show up in every scenario. For some scenarios, the owned CTV is enough for all the maintenance tasks, therefore, there is no charter cost and the corresponding mobilization cost. And for those scenarios with charter cost and mobilization cost, these two costs are positively correlated. And for all the scenarios, no charter extension cost or return-late cost because there is no charter extension decisions and all CTV vessels return to the base before its charter ends.

For HLV and FSV types, the proportion of each vessel cost is different, mainly because the charter cost is relatively higher than other costs, and for the HLV type, this cost is the most significant cost among all the vessel costs.

Vessel travel cost The results of the vessel travel information only have one part: the fuel cost for traveling, which is included in Figure 16 as one part of the vessel cost.

Vessel utilization The results of the vessel utilization information include nine parts, the time spent on traveling to the base, the time spent on traveling to the site, the time spent on inter-transit travel, the time restricted by weather conditions, the time of idling at the base during each maintenance cycle, the time restricted by shift hours, the time spent on maintenance tasks, the time of idling on-site during each maintenance cycle, and the time spent on jacking up/down.

For the time distribution of CTV type, all the values are shown in Figure 17. The histogram on top of the picture shows the time distribution for owned CTV and the histogram below it shows the time distribution for chartered CTV.

For owned CTV, most of the time is spent idling either at the base or on-site. Due to the constraints from the weather and shift, the time on the traveling caused by bad weather conditions and shift end also takes an important proportion, where the weather conditions attribute even more. No time is used for repairs because the main function of the CTV is to deliver teams to the turbines. However, the time of traveling between the site and base and the time of inter-transit occupy a minority, which can be used for an important consideration by wind farm operators/developers.

For chartered CTV, its time distribution of each scenario is very similar to that of owned CTV. Because the owned CTV is preferred to be used when executing the maintenance tasks, for some scenarios, what can happen is that no more CTV needs to be chartered, hence "Not applicable" shows up and there is no time distribution information.

B The result of the short-term optimization

The term short-term horizon is used to describe a duration of a maintenance cycle and the feedforward open-loop simulation-optimization model is used for relatively short-term optimization, the optimal decision variable of each maintenance cycle can be obtained as well as the corresponding model outputs.

In order to make a good comparison, the same weather condition data of 20 scenarios generated in the open-loop simulation-optimization model and the same wind farm situation at the beginning of each maintenance cycle, including the detailed turbine information and turbine component information, will be applied for the feedforward open-loop simulation-optimization model.

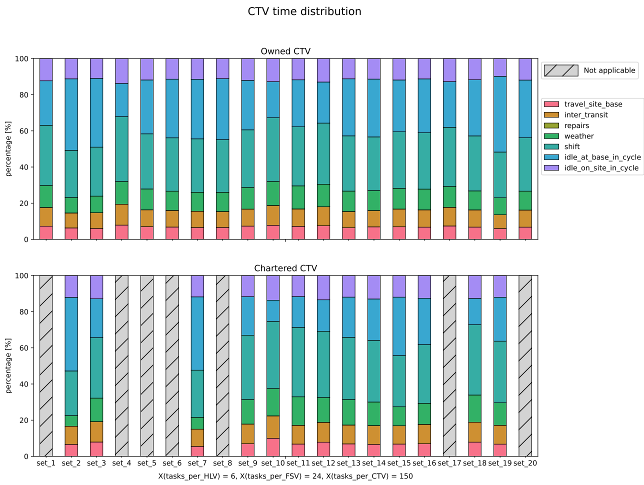


Fig. 17: The result of CTV time distribution

Simulation model output Similarly, as the framework in Figure 3 shows, the simulation model outputs, including the turbine information, maintenance cycle information, maintenance tasks information, vessel charter cost, vessel travel cost and vessel utilization, can all be obtained after the simulation is performed. All outputs focus on one maintenance cycle, and more details of one maintenance cycle can be known. Compared with the results obtained from the open-loop simulation-optimization model, the optimal decision variables obtained from the feedforward open-loop simulation-optimization model for each maintenance cycle may be different, resulting in the same or lower-cost situations. In other words, judged by the total cost of each maintenance cycle, the optimal decision variables of fleet configuration obtained from the determined open-loop simulation-optimization model may not be the optimal ones for each maintenance cycle.

From maintenance cycle No. 1 to maintenance cycle No. 6, even though the optimal decision variables are different, the corresponding fleet configuration and other outputs are all the same from two models. When it comes to maintenance cycle No. 7, different optimal decision variables lead to different fleet configurations and other different outputs, and these decision variables are summarized in Table 13.

TABLE 13: OPTIMAL DECISION VARIABLES OF TWO MODELS

Cycle No.	Optimal decision variables from long-term optimization	Optimal decision variables from short-term optimization
Cycle 1	$X_T^{HLV} = 6, X_T^{FSV} = 24, X_T^{CTV} = 150$	$X_T^{HLV} = 19, X_T^{FSV} = 18, X_T^{CTV} = 35$
Cycle 2		$X_T^{HLV} = 22, X_T^{FSV} = 26, X_T^{CTV} = 61$
Cycle 3		$X_T^{HLV} = 3, X_T^{FSV} = 26, X_T^{CTV} = 92$
Cycle 4		$X_T^{HLV} = 23, X_T^{FSV} = 27, X_T^{CTV} = 128$
Cycle 5		$X_T^{HLV} = 5, X_T^{FSV} = 27, X_T^{CTV} = 136$
Cycle 6		$X_T^{HLV} = 5, X_T^{FSV} = 24, X_T^{CTV} = 154$
Cycle 7		$X_T^{HLV} = 5, X_T^{FSV} = 22, X_T^{CTV} = 116$

In the later content, as representatives in both situations, maintenance cycle No.1 and cycle No.7 are taken as examples, most important results will be displayed and detailed analyzed. While more details of the outputs of maintenance cycle 7 can be checked in Appendix.

The comparison of results of the maintenance cycle No.1 from two models By using the same weather condition data for both the open-loop simulation-optimization model and the feedforward open-loop simulation-optimization model, all the optimal results from the heuristic algorithm are listed in Table 14. The second column is the results of the short-term optimization and the last column is the results of the long-term optimization.

TABLE 14: THE COMPARISON OF THE FLEET CONFIGURATION OF MAINTENANCE CYCLE 1

Scenario No.	The fleet configuration from long-term optimization	The fleet configuration from short-term optimization
Scenario 1	1, 0, 0	1, 0, 0
Scenario 2	1, 0, 0	1, 0, 0
Scenario 3	1, 0, 0	1, 0, 0
Scenario 4	1, 1, 0	1, 1, 0
Scenario 5	1, 1, 0	1, 1, 0
Scenario 6	1, 1, 0	1, 1, 0
Scenario 7	1, 0, 0	1, 0, 0
Scenario 8	1, 0, 0	1, 0, 0
Scenario 9	1, 0, 0	1, 0, 0
Scenario 10	1, 1, 0	1, 1, 0
Scenario 11	1, 0, 0	1, 0, 0
Scenario 12	1, 0, 0	1, 0, 0
Scenario 13	1, 0, 0	1, 0, 0
Scenario 14	1, 0, 0	1, 0, 0
Scenario 15	1, 0, 0	1, 0, 0
Scenario 16	1, 0, 0	1, 0, 0
Scenario 17	1, 1, 0	1, 1, 0
Scenario 18	1, 0, 0	1, 0, 0
Scenario 19	1, 0, 0	1, 0, 0
Scenario 20	1, 1, 0	1, 1, 0

Based on the results above, it can be seen that even the decision variables are different. The fleet configurations of all scenarios could be the same. What is more, all costs from 20 scenarios are also significant results and the cost of 20 scenarios of the maintenance cycle No.1 from two models are shown in Table 15.

It can be seen that, in maintenance cycle No.1, the different decision variables obtained from two models lead to the same fleet configuration and finally lead to the same costs.

This information reveals that, the optimal fleet configuration obtained from the open-loop simulation-optimization model can be applicable for this maintenance cycle for the minimum average cost, while in this case, the feedforward open-loop simulation-optimization model has no influence on this maintenance cycle, in other words, it cannot improve the decisions better.

This usually happens when the dynamics in the offshore wind farm are not that drastic, for example, at the very beginning of the operation of a wind farm. Under this situation, all maintenance tasks can be fixed fast and orderly, tasks are not piled up and no more productivity loss shows up. Also with no more extension of the charter or no penalty because of exceeding the soft time window.

The comparison of results of the maintenance cycle No.7 from two models In Table 16, different fleet configurations of 20 scenarios for maintenance cycle No.7 from two models are shown. In the column of the fleet configuration results from the feedforward open-loop simulation-optimization model, all those cells with a symbol $*$ mean, in the corresponding scenarios, the fleet configurations from two models are different.

TABLE 15: THE COMPARISON OF COST RESULTS OF MAINTENANCE CYCLE 1

Scenario No.	The cost of long-term optimization (€)	The cost of short-term optimization (€)
Scenario 1	4396891.79	4396891.79
Scenario 2	4411375.31	4411375.31
Scenario 3	9403774.88	9403774.88
Scenario 4	5040613.53	5040613.53
Scenario 5	5397289.24	5397289.24
Scenario 6	5013036.97	5013036.97
Scenario 7	4434399.63	4434399.63
Scenario 8	4562000.18	4562000.18
Scenario 9	4417705.21	4417705.21
Scenario 10	5192341.40	5192341.40
Scenario 11	4388206.96	4388206.96
Scenario 12	4604420.68	4604420.68
Scenario 13	4364126.66	4364126.66
Scenario 14	4638477.66	4638477.66
Scenario 15	4527178.00	4527178.00
Scenario 16	4476406.35	4476406.35
Scenario 17	6891685.62	6891685.62
Scenario 18	4419319.65	4419319.65
Scenario 19	4358279.06	4358279.06
Scenario 20	5073151.05	5073151.05
Average cost	5000533.99	5000533.99

TABLE 16: THE COMPARISON OF THE FLEET CONFIGURATION OF MAINTENANCE CYCLE 7

Scenario No.	The fleet configuration from long-term optimization	The fleet configuration from short-term optimization
Scenario 1	1, 1, 0	1, 1, 1*
Scenario 2	1, 1, 0	1, 1, 0
Scenario 3	1, 1, 0	1, 1, 0
Scenario 4	1, 2, 0	1, 2, 1*
Scenario 5	1, 1, 0	1, 1, 0
Scenario 6	1, 1, 0	1, 1, 0
Scenario 7	1, 1, 0	1, 1, 0
Scenario 8	1, 1, 0	1, 1, 0
Scenario 9	1, 1, 0	1, 1, 1*
Scenario 10	1, 1, 0	1, 1, 0
Scenario 11	1, 1, 0	1, 1, 0
Scenario 12	1, 1, 0	1, 1, 1*
Scenario 13	1, 1, 0	1, 1, 1*
Scenario 14	1, 1, 0	1, 1, 1*
Scenario 15	1, 1, 0	1, 1, 0
Scenario 16	1, 1, 0	1, 1, 1*
Scenario 17	1, 1, 0	1, 1, 1*
Scenario 18	1, 1, 1	1, 1, 1
Scenario 19	1, 1, 0	1, 1, 0
Scenario 20	1, 1, 0	1, 1, 1*

For Scenario 1 of the maintenance cycle No.7, the decision variable of $X_{\mathrm{T}}^{\mathrm{HLV}}$ of the feedforward open-loop simulation-optimization model is much lower than that of the open-loop simulation-optimization model, which leads to one more vessel to charter. While another two decision variables do not lead to different vessel charters of HLV and FSV.

Similarly, the fleet configuration of Scenario 4, Scenario 9, Scenario 12, Scenario 13, Scenario 14, Scenario 16, Scenario 17 and Scenario 20 from two models are different from each other.

Again, apart from the fleet configuration results, as the objective function of the optimization method, all the costs of 20 scenarios of two models should be focused and those results are shown in Table 17.

TABLE 17: THE COMPARISON OF COST RESULTS OF MAINTENANCE CYCLE 7

Scenario No.	The cost of long-term optimization (€)	The cost of short-term optimization (€)
Scenario 1	6577189.08	6765999.86*
Scenario 2	5995901.54	5995901.54
Scenario 3	5850322.76	5850322.76
Scenario 4	7408707.57	7498570.16*
Scenario 5	5757230.95	5757230.95
Scenario 6	6301044.66	6301044.66
Scenario 7	6284698.99	6284698.99
Scenario 8	5710159.48	5710159.48
Scenario 9	6279967.34	6156518.62*
Scenario 10	6106325.71	6106325.71
Scenario 11	5993455.48	5993455.48
Scenario 12	6366115.08	6451259.61*
Scenario 13	6390971.76	6508824.62*
Scenario 14	14868310.08	7617911.33*
Scenario 15	6105300.86	6105300.86
Scenario 16	6679004.89	6689015.71*
Scenario 17	6227309.01	6347917.61*
Scenario 18	6924475.09	6924475.09
Scenario 19	6175207.24	6175207.24
Scenario 20	6278026.66	6434574.82*
Average cost	6713986.21	6383735.76

As seen from the results, accordingly, each scenario previously with different fleet configuration results has different costs. In all these scenarios, the costs of 7 scenarios: Scenario 1, Scenario 4, Scenario 12, Scenario 13, Scenario 16, Scenario 17 and Scenario 20 from the feedforward open-loop simulation-optimization model, are even higher than the costs from the long-term optimization. While only the costs of Scenario 9 and Scenario 14 are the opposite. However, the average cost, the most objective function of the simulated annealing, has a lower value from the feedforward open-loop simulation-optimization model and a higher one is obtained by the open-loop simulation-optimization model. This is because the decrease in Scenario 14 is much higher than the sum of the increment of any other scenario.

The most influential reason behind the cost decrease in Scenario 14 can be told from the maintenance cycle length. From Figure 12, it can be seen that, in the open-loop simulation-optimization model, Scenario 14 of maintenance cycle No.7 has a length of 104 days, which is extremely high, while the cycle length of any other scenario of maintenance cycle No.7 is lower than 60 days, which is the soft time window set in this research. This over-long maintenance cycle length leads to extra costs including costs caused by the extension of the charter, more maintenance tasks and the penalty of exceeding the soft time window. By choosing different decision variables and the fleet configurations are changed accordingly, and the cost of this extreme scenario can be spread across other scenarios. From Figure 18, it can be seen that, the cycle length of Scenario 14 dramatically decreases to 62 days, together with a little cycle length decrease in Scenario 4, Scenario 9, Scenario 12, Scenario 13, Scenario 16 and Scenario 20.

Unit: day	X(tasks_per_HLV) = 5, X(tasks_per_FSV) = 22, X(tasks_per_CTV) = 116																			
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10	set_11	set_12	set_13	set_14	set_15	set_16	set_17	set_18	set_19	set_20
cycle 1 length	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 2 length	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 3 length	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 4 length	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 5 length	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 6 length	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
cycle 7 length	48	42	37	47	42	45	45	33	33	42	40	41	36	62	49	55	44	46	48	39
total	48	42	37	47	42	45	45	33	33	42	40	41	36	62	49	55	44	46	48	39

Fig. 18: The cycle lengths of maintenance cycle 7 of the short-term optimization

Even though more vessels are chartered in some scenarios, which leads to an increment of the cost correspondingly, the decrease in other scenarios also takes a dominant influence and the average cost will be affected. Thus, the balance between the fluctuation of many factors is found and shown as the new decision variables and fleet configuration. Also, the result of maintenance cycle No.7 shows that, the optimal decision variables and fleet configuration of the open-loop simulation-optimization model may not be the optimal ones for every maintenance cycle, while the feedforward open-loop simulation-optimization model could strongly fill this gap.

VI CONCLUSION

Operation and maintenance (O&M) costs are the most significant part of an offshore wind farm while the cost of fleet size and mix is the most contribution. It is necessary to minimize the fleet configuration cost nowadays when offshore wind farms are receiving more and more support. In this research thesis,

Compared with state-of-the-art research, this thesis contributes a decision-making tool for fleet size and mix problems for offshore wind farms on a simulation-optimization method, so that optimal decision-making can be obtained after a number of iterations. The open-loop simulation model with the optimization method is applied for a long-term optimization of the fleet size and mix of a 15-year offshore wind farm, and the feedforward simulation model with the optimization method is used for a short-term optimization of the fleet size and mix of each maintenance cycle of the same wind farm.

The result shows that, the presented feedforward simulation model for fleet size and mix problems of an offshore wind farm gives a different perspective for the optimal fleet configuration in comparison with the previous papers and previous work. There are many advantages to the proposed feedforward simulation model together with the optimization algorithm. Firstly, this model starts simulation from a given state including the statuses of each turbine component. What is more, this model focuses on each maintenance cycle, thus the decision-making is more suitable for relatively short-term optimization and is more flexible. Especially, the optimal decision variables are regarded as the estimation of the maintenance tasks for each vessel type in one maintenance cycle, one optimal long-term optimization may not be always accurate for a short-term optimization, while at this point, the optimal results for each maintenance cycle obtained from the proposed feedforward simulation model can be more accurate and be given as a reference for wind farm operators and researchers when they perform a prediction or analysis.

At the same time, there are some limits to the proposed model and the optimization algorithm. For example, the search domain of each decision variable in this research is connected to the size of the wind farm with some estimation, it should be adjusted accordingly if the size of the wind farm is changed. Also, due to the time limit of this project, the iteration of the decision variables is chosen as only 200 and it is very small compared with the massive search area, which is 375000. Thus the obtained optimal result is relatively optimal. With more computation time, the result can be more decent. Also, the case study is based on previous research, and the weather data is generated by the Weibull distribution but not the historical weather data in reality. If more available real data can be applied to this model and compared the result from this model to the decision made in the past, the results can be more persuasive and the model can be improved more specifically.

In the future, some directions can be still improved based on this study. For example, the mothership and daughter ship can be considered in the model as different vessel types with more realistic functions. Also, introducing the fluctuating electricity price into the model is another direction, which has been done by some papers using mathematical models. Similarly, the technician numbers can be considered in a dynamic way in the model, so that maximum technicians are not always equipped in the very vessel when performing the maintenance tasks. Plus, considering some task type crossing, so that one task type can be performed by different vessels and the priority should be re-arranged accordingly. Lastly, converting the simulation model to practice use in the industry area is the most vital long-term direction of future work.

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