Fleet selection for offshore wind farm operation and maintenance

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Fleet selection for offshore wind farm operation and maintenance

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What is past is prologue, and it's time to look forward.

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Abstract

With the development of society and the requirements for clean energy, offshore wind farms (OWFs) that can generate steady and continuous electricity have been built. With harsher weather conditions and more powerful wind resources, the wind turbines at offshore wind farms are significantly larger than those at onshore wind farms. The complex weather conditions and mechanical structure of wind turbines pose problems for their operation and maintenance (O&M).

The cost of vessel chartering significantly contributes to the overall cost of operating and maintaining an offshore wind farm. By selecting the optimal fleet mix for executing the maintenance, the vessel chartering cost can be reduced, reducing the operation and maintenance costs of the offshore wind farm. This reduces the levelized cost of energy from the offshore wind farm. This report developed a simulation and optimization model based on mixed integer linear programming to determine the optimal fleet mix for executing the maintenance tasks by minimizing the vessel acquisition cost. The Monte Carlo simulation is implemented to statistic an optimal strategy for chartering the vessels.

Chapter 1 introduces the offshore wind farm (OWF) and its operation and maintenance (O&M) activities. Chapter 2 provided a literature review on the latest progress of the offshore wind farm's operation and maintenance. Chapter 3 provides a simulation model for component wear, maintenance requirement generation, and maintenance task execution. The process of optimization is explained in detail. Chapter 4 presents the mathematical model of the optimizer, which arranges the vessels and executes maintenance tasks. Chapter 5 presents a case study based on the latest progress data. The Monte Carlo simulation yields the optimal initial purchased fleet mix derived based on the Monte Carlo simulation. Finally, Chapter 6 gives the conclusion and recommendations for future studies.

Keywords: Offshore wind farm, Operation and maintenance, Fleet mix problem, Vessel chartering and purchasing, Optimization, Mixed integer linear programming, Task scheduling

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List of abbreviation

- **OWF**: Offshore wind farm
- **O&M**: Operation and maintenance
- **DSS**: Decision support system
- **LCOE**: Levelized cost of energy
- **MILP**: Mixed integer linear programming
- **CTV**: Crew transfer Vessel
- **SES**: Surface effect ship
- **SAV**: Small accommodation vessel
- **MM**: Mini mother vessel
- **HLV**: Heavy lift vessel
- **JUV**: Jack-up vessel
- **OAV**: Offshore access vessel
- **FSV**: Field support vessel
- **MPV**: Multi purpose vessel
- **Opex**: Operational expenditure
- **FLP**: Facility location problem
- **VAC**: Vessel arrangement closeness

1

Introduction

1.1. Background

The goal of reducing greenhouse gas emissions has become imperative with society's development. Sustainable energy, particularly electricity, will be in high demand in the future. The wind farm, among the various sources of sustainable energy, plays an important role in generating electricity with the power of the wind. Based on the location, the wind farm can be classified into onshore and offshore wind farms.

Compared with onshore wind farms, offshore wind farms (OWF) are located above the ocean, where the wind exhibits consistently great power. The OWF's location allows the turbine to generate powerful electricity more efficiently. The offshore wind turbine has a larger scale to withstand harsher conditions, including stronger winds and severe weather conditions over the ocean. An offshore wind turbine in the North Sea has a rotor diameter of 222 m and a rated power of 15 MW [1]. In comparison, the turbine of an onshore wind farm has a rotor's diameter of 97–117 m and a rated power of around 1.5–3 MW [2]. The trend in OWF development is toward small-scale and distributed layouts. By the end of 2018, there were a total of 1409 proposed OWF projects. However, the number of completed OWFs was relatively small, standing at just 112. 53 wind farms are under construction, and 712 wind farms are in the planning stage [3].

Based on the size of the OWF shown in the figure 1.2 [4], it can be observed that approximately 96% of OWFs feature a relatively modest number of wind turbines, typically fewer than 120 units. Furthermore, a significant portion of these wind farms, which make up the majority, fall within the range of 0 to 40 wind turbines. This indicates a prevalent trend towards smaller-scale installations in OWF projects, emphasizing efficiency and adaptability in the utilization of wind energy resources. The latest large-scale wind farms have also adopted this layout, with multiple sub-farms arranged in a decentralized manner so that the wind turbines can cover as many areas as possible where wind resources are abundant, such as the Doggerbank offshore wind farm, which has a total of four sub-farms with 272 wind turbines in total [5].

1.2. Challenges of operation and maintenance of offshore wind farm

The OWF locations are far from the shore and must withstand harsher conditions above sea level. The wind turbine components are more susceptible to wear and tear than onshore wind turbines.farms. The OWFs are far away from the operation center to acquire strong and steady wind energy. Maintaining the wind turbine is critical to minimizing the downtime caused by component wear. The levelized cost of energy (LCOE) represents the cost of producing electricity over an OWF's lifetime. Compared to other energy resources like coal and nuclear power, wind energy has a higher LCoE, especially for OWFs [6]. This is mainly because the offshore wind farm is harder to maintain. The following factors contribute to the challenges of operating and maintaining an offshore wind farm:

- **The OWFs are far away from the shore**: With the increasing distance between the wind farms and the shore, the unavailability of the technicians reduces their accessibility to the wind turbines

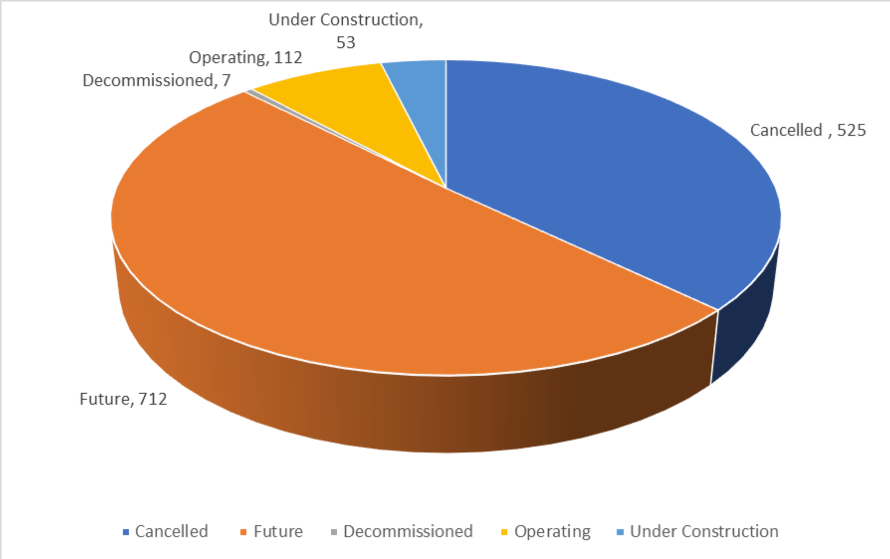

Figure 1.1: Overview of offshore wind projects

and increases the downtime during the wind turbine's failure. The operators will need to hire a fleet to transport the maintenance technicians and equipment to the wind turbines.

- **The uncertainty of the weather**: Unlike the onshore wind farm, which has roads towards the wind turbines, the technicians can drive directly to the wind turbines to perform maintenance. The OWF needs the technicians to travel to the wind turbines by vessel. The vessel's ability to sail normally to the wind turbines heavily depends on weather conditions [7]. Consider the wind turbines at the onshore wind farm. Offshore wind turbines have cut-in and cut-off speeds, which can be used to schedule maintenance. However, the accessibility of maintenance vessels is dependent not only on wind speed but also on wave height, which permits the vessel to travel to the wind turbines. If weather issues disrupt maintenance, the wind turbine will be offline for a long time, resulting in significant losses.

- **High maintenance costs**: Even after decades of development, the equipment for OWF operations is still relatively expensive. Although advanced equipment, such as motion-compensated gangways, has been applied to the vessels to make maintenance much easier than before [8]. The maintenance costs of OWFs are higher than the equivalent work on onshore wind farms.

- **Lack of maintenance resources**: The OWF amount is growing. As shown in figure 1.1, by the end of 2018, 712 offshore wind projects were planned and 53 OWFs were under construction. It is obvious that the requirements for operating and maintaining the OWF will increase significantly. The growing requirements lead to a shortage of experienced technicians for wind turbine maintenance. Training the new technicians for the wind farms requires a significant investment of resources. The technicians who have already been trained have to do the training repeatedly to ensure they can work safely and efficiently [9]. In this situation, adjusting the maintenance strategies and rearrangement of the technician's working hours can improve maintenance efficiency and effectively maximize maintenance resources.

- **Fleet selection for the maintenance execution**: To inspect and maintain offshore wind turbines, technicians must travel to the turbines with spare parts and tools. In this case, vessels are required to transport technicians and equipment. Choosing appropriate vessels is critical for the operators to achieve their goal of minimizing the OWF's total operating expenses. Operators face challenges related to fleet size and mix when choosing which types and models of vessels to deploy for transportation. This challenge includes determining the best fleet of vessels and infrastructure to support an OWF's operation and maintenance [10].

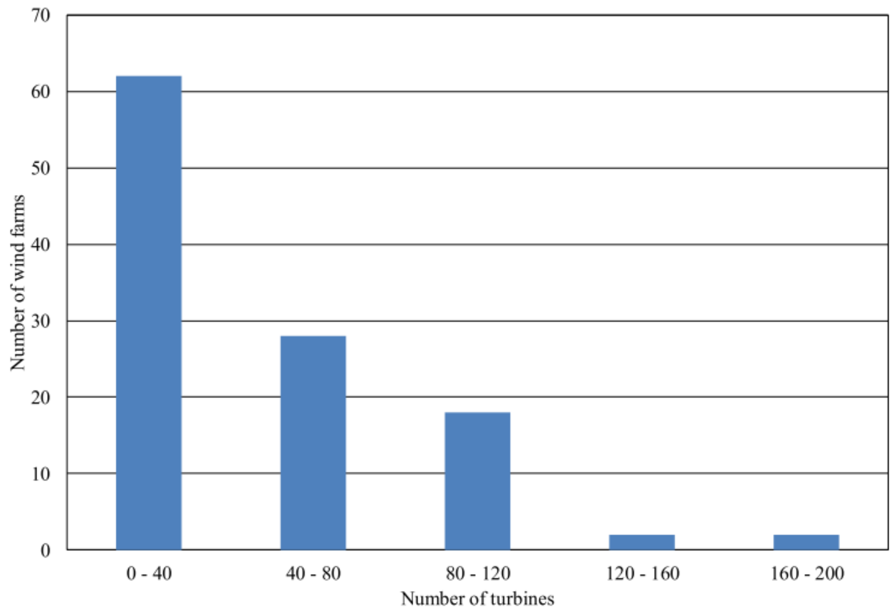

Figure 1.2: Number of wind farms and Number of turbines

1.3. Research question

The main research question of the thesis is to find an optimal vessel purchase and rental strategy for the offshore wind farm? The main research question comes with the following sub questions:

1. Review the latest progress of fleet mix problem for O&M of the offshore wind farm
2. How to build up the wind turbine maintenance simulation & vessel arrangement model? What kind of inputs are needed for the simulation model?
3. What optimization methods can be used to arrange the vessel for execute maintenance tasks?
4. How to identify the optimal fleet mix for maintenance execution by minimizing the vessel acquisition cost cost?
5. When chartering the vessels, how to present the annual fleet mix for the operator?
6. How the sensitivity factors that affect vessel acquisition cost?

1.4. Scope of the research

The thesis focuses on solving the fleet mix problem of transporting the technician for the O&M of the offshore wind farm. The thesis focuses on the mid-term optimization of the fleet mix problem, covering the first five years after the offshore wind farm became operational, starting at the beginning of 2001 and terminating at the end of 2005. The thesis aims to combine the vessel purchase strategy with the vessel charter strategy to reduce the vessel acquisition cost. The objective of the thesis is to minimize the vessel acquisition cost, including the vessel charter cost and vessel purchase cost. The thesis also takes the uncertainties from weather conditions and the remaining useful life (RUL) of the wind turbines' components into account. The thesis assumes that the weather condition of the whole simulation horizon is known at the beginning of the simulation, the vessels are sufficient to be chartered at any time, and the vessel costs remain stable during the simulation. By introducing this simulation model, the owner of the offshore wind farm can observe how many vessels are to be purchased in advance at the initial phase of the offshore wind farm's operation to minimize the vessel acquisition cost.

1.5. Scientific contribution

The thesis is an individual project under the supervision of Professor Xiaoli Jiang and Marco Borsotti, based on the components-wearing simulation model developed by Marco Borsotti. The components-wearing simulation model estimates the RUL of the components that follow the Weibull distribution and their age consumption on each day. Following the opportunistic maintenance strategy, the components wearing the simulation model generate maintenance tasks and finish the maintenance execution. By implementing the component-wearing simulation model, the maintenance log of the wind farm can be known.

However, there are still some limitations of the components wearing simulation model. Firstly, the model assumes that the maintenance of the components will be finished immediately as soon as the maintenance tasks are generated, which is unrealistic compared with reality. Secondly, under the condition-based opportunistic maintenance strategy, the maintenance cycle triggering time is highly dependent on the age consumption of the components, which is random. Therefore, the maintenance cycle can be generated during the winter, when the weather is severe for maintenance execution.

Therefore, the extension work is based on the component-wearing simulation model. In this thesis, the first contribution is a vessel chartering & tasks arrangement optimizer built to optimize the fleet mix for maintenance execution and generate the fleet mix for executing the maintenance on each day. The fleet mixes on each day are clustered into different vessel charter periods, furthermore transfer into vessel charter strategy. The second contribution is based on the vessel charter strategy, changing the initial vessel purchase amount, and observing the vessel charter cost. Adding up the vessel purchase cost, the vessel acquisition cost is concluded. By observing the vessel acquisition cost, it can be concluded which initial purchase fleet minimizes the ship acquisition costs. Another contribution is combining the preventive maintenance strategy with the aged-based opportunistic maintenance strategy, moving the maintenance tasks that will be generated in the winter period forward, and executing the maintenance before winter.

1.6. Thesis structure

The thesis aims to solve the research question of finding the initial vessel purchase fleet for the O&M of the offshore wind farm, with the sub-questions in Chapter 1. The literature review based on the latest progress is done in Chapter 2, where sub-question one is answered. Chapter 3 presents the structure of the simulation model, where sub-question two is answered. The core module of the simulation model is the task & vessel arrangement module that optimizes the vessel arrangement for executing the maintenance tasks, which is presented in Chapter 4. Therefore, the sub-question three is answered. Chapter 5 presents a case study based on the available research data. The optimal fleet mix and annual vessel charter strategy are presented, answering sub-questions 4 and 5. A sensitivity analysis of the model is presented, finding the sensitivity factors that affect the vessel acquisition cost of the simulation model. Therefore, the sub-question six is answered in the last chapter 6. The previous chapters will be summarized, and conclusions and recommendations will be given for future research.

2

Literature review

This chapter review the latest progress of the fleet selection and decision support system (DSS) that help the operator to make vessel charter strategy. Firstly, the maintenance strategies that been used in the O&M of the offshore wind farm is introduced. Next, the vessels that involves in the maintenance execution and their selecting consideration are presented. Finally, the decision support system that helps the operator to make decisions on vessel chartering from available research is reviewed.

2.1. Maintenance strategy

The offshore wind farm is located far away from shore, making maintenance hard to execute. To save maintenance resources and reduce maintenance costs, it's necessary to specify a maintenance strategy to maintain the components by maximizing their utilization and reducing the overall O&M cost. Here is a summary of the OWF's maintenance strategies that have been used in the O&M of the offshore wind farm.

- Corrective Maintenance: The maintenance based on the component's failure is only carried out when the failure has occurred, as shown in figure2.1 [11]. Corrective maintenance strategies can prevent unnecessary component maintenance and reduce technician inspections and visits. OWFs have a high failure rate and low system reliability. During the operation, unexpected failures may occur [12]. Corrective maintenance plays an important role in the offshore wind farm's O&M.

Figure 2.1: Corrective maintenance

- Preventive Maintenance: Unlike corrective maintenance, preventive maintenance follows the maintenance schedule based on component age, failure rates, and past maintenance information [13]. As shown in figure 2.2 [11], the technicians visit the wind turbines timely and execute the inspection and maintenance of the wind turbines.

- Condition-based Maintenance: Condition-based maintenance requires the sensors to collect the data of the wind turbine's components and update the data to the health diagnosis system, which prevents the major failures of the wind turbines and the huge downtime cost due to the failure [14]. As shown in figure 2.3 [11], when the diagnosis system detected the problem with the wind turbine, the operators dispatched the technicians to perform the maintenance.

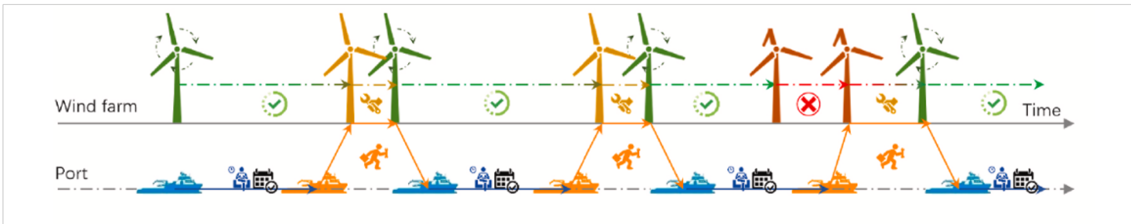

Figure 2.2: Preventive Maintenance

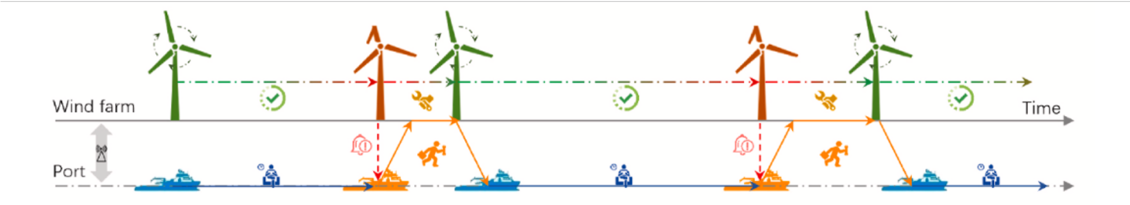

Figure 2.3: Condition-based maintenance

- Predictive Maintenance: The predictive maintenance is based on the sensors of condition-based maintenance, and the diagnosis system not only detects the failures of the wind turbines but also predicts when the components of the wind turbines will fail. As shown in figure 2.4 [11], the technicians can execute the maintenance before the wind turbine's components fail, reducing the maintenance cost due to unnecessary visits to the wind turbines.

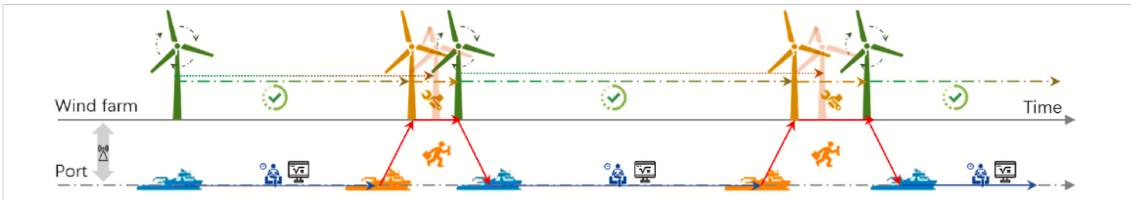

Figure 2.4: Predictive maintenance

2.2. Fleet Selection

Fleet selection is a significant consideration in the operator's decision-making process. O&M consists of a variety of vessels that transport equipment and technicians between wind turbines and operation centers. Different types of vessels provide varying job capacities, presenting unique advantages and challenges for O&M tasks.

2.2.1. Vessels for offshore wind farm operation & maintenance

Using vessels to transfer technicians and spare parts to the boat platform at sea level is the most common and effective approach to wind turbines. The table 2.1 summarizes the vessels that were involved in the O&M of the OWF from the available research that related to fleet selection optimization and OWF maintenance strategies.

During the On-Site and Maintenance (O&M) of the Offshore Wind Farm (OWF), the transportation of technicians, spare parts, and tools is a primary requirement. During maintenance, we primarily use the following transports to move technicians and supplies:

1. **Crew Transfer Vessel (CTV)**
   The most common type of vessel for wind turbine maintenance is the Crew Transfer Vessel, which transports technicians from the maintenance center to the offshore wind farm's wind turbines. There are three main types of CTVs in use today: monohulls, catamarans, and surface effect ships (SES).

Ref	Vessel Type										
	CTV			Crane Vessel		FSV					Aircraft
	Monohull	Catamaran	SES	HLV	JUV	SAV	MM	OAV	FSV	MPV	Helicopter
[15]		√									
[16]	√				√			√			√
[17]		√									
[18]					√						
[19]	√				√		√				√
[20]	√		√			√	√				
[21]	√				√				√	√	√
[22]	√	√				√	√		√	√	
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[24]	√			√					√		
[25]	√					√	√				
[26]	√		√			√	√				
[27]			√	√					√		
[28]	√			√							
[29]											
[30]	√				√						
[31]	√					√	√				

Table 2.1: Vessels involved in the offshore wind farm operation & maintenance

- **Monohull**: This kind of CTV has a single hull structure, which is similar to traditional vessels. The monohull CTV is typically used in the available research. The monohull design offers inherent stability to the vessel, making it suitable for traveling across harsh offshore conditions. The monohull vessels are also known for their good maneuverability, allowing the vessels traveling across the offshore wind farm to transport the crew among the wind turbines. The simple structure and easy-to-make characteristics of monohull CTVs make them widely used for offshore operations. Monohull CTVs have a significantly lower charter price and rental cost than catamaran CTVs. With the same capacity for carrying the technicians. The daily rental cost of the monohull CTV is 1750 £, while the catamaran CTV has a daily rental cost of 5000 £. [26]
- **Catamaran**: This type of CTV features a twin-hull design, with two parallel hulls connected by a deck structure, which improves the vessel's stability and efficiency. When compared to monohull vessels, catamarans have a higher speed and are more fuel efficient because their structure reduces hydrodynamic drag, allowing them to transport technicians faster and reduce travel time between the offshore wind farm and the operation center. The catamaran has a higher speed and limited significant wave height (Hs), allowing for a longer maintenance period. [26]
- **Surface Effect Ship (SES)**: This type of CTV can be considered an improvement to the catamaran design. The vessel has twin hulls and an air cushion. Unlike catamarans, which lower the vessel's water resistance, the SES uses a cushion to reduce friction between the hull and the water surface. The SES has a higher service speed but a far more expensive charter price [27].

2. **Crane Vessel**
Because they can lift components for wind turbine replacement maintenance tasks, as well as maintenance equipment and spare parts, crane vessels rank as the second most commonly used type of vessel in offshore wind turbine maintenance operations. The crane vessels are used less frequently than CTV because the components and equipment do not need to be lifted during minor repairs. Due to their design for different offshore conditions, Heavy Lift Vessels (HLV) and Jack-Up Vessels (JUV) are the crane vessels most commonly used for offshore wind turbine maintenance.

    - **Heavy Lift Vessel (HLV)**: This kind of vessel is designed to transport and install large components of offshore wind turbines, like blades or generators. This kind of vessel has a large open deck space to hold the large objects and a heavy lift crane to lift them up. The heavy lift vessel can carry everything needed for the operation during a single deployment. With the capacity to hold large objects and cranes, the heavy lift vessel has enormous size and ocean-going capabilities, which gives it the ability to stay offshore for a long time. In the study of [27], compared with CTVs that can only stay offshore for one shift, the heavy lift vessel has no time limitation to stay offshore.

- **Jack-Up Vessel (JUV)**: This kind of vessel plays the same role of carrying the objects and lifting them up as the heavy lift vessels. Unlike the heavy lift vessels that stay offshore, far away from the coast, the jack-up vessels are designed for operation in shallow water. The jack-up vessels are self-elevating platforms equipped with extendable legs that can stand on the seabed and raise the vessel above the water, which provide stability for the whole operation platform. For those offshore wind farms that stay in shallow water areas, the jack-up vessels are more suitable for operation & maintenance. In the study of [18], the jack up vessel has higher stability and is much more suitable for offshore wind farm projects than the heavy lift vessels. The drawbacks of the jack-up vessels also come from the jack-up legs that provide stability for the vessels. The study of [19] shows that the jack-up vessels operation water depth is restricted by the legs of the platform. The time spent jacking up and jacking down the legs for the platform will consume time for the operation.

3. **Operation Support Vessel**
Crew transfer vessels and crane vessels play an execution role in transferring the technicians and spare parts to the offshore wind turbine for maintenance. In spite of these, some operation support vessels are also used for the logistics support of the fleet. The following vessels are involved to provide support for the offshore operation:.

- **Field Support Vessel (FSV)**: This kind of vessel is designed to provide support to offshore operations, including offshore wind turbine maintenance. The FSV has a large deck space for carrying the object, equipment and technician to ensure everything can be carried out for the operation. Compared with other operation support vessels, the FSV is focused on carrying cargo, technicians and large equipment to the offshore wind farm.
- **Small Accommodation Vessel (SAV)**: This kind of vessel is designed to carry technicians. They are typically equipped with facilities and equipment to assist in maintenance, repair, and inspection tasks. The SAVs provide accommodation for technicians and storage for some small spare parts and tools. Compared with other operation support vessels, the SAVs are more focused on carrying technicians and providing onboard amenities and facilities for technicians during maintenance campaigns.
- **Mini Mother Vessel (MM)**: The mother vessel serves as a central hub for supporting multiple offshore activities, offering accommodation, storage, and logistical support for smaller vessels and crews. The mother vessel is used as an offshore base for the operation. For some large size mother vessels, the vessel is equipped with a helipad for the deployment of the helicopter or the daughter vessels that serve as the crew transfer vessels to transport the technicians between the mother vessel and the offshore wind turbines. In the study [20], the mother vessels offer comfortable living quarters for crew members and technicians working extended shifts offshore, which can save the time between transportation between the operation center and the offshore wind farm.
- **Offshore Access Vessel (OAV)**: This kind of vessel is designed to provide safe and efficient access to offshore wind turbines. The offshore access vessel normally has a robust hull design for stability in offshore conditions and motion compensated equipment to ensure the technicians can reach the offshore wind turbine. In the study [16], the OAVs are used to transfer the mid-size components from the OAV's deck to the turbine's lower platform.
- **Multi Purpose Vessel (MPV)**: The multipurpose vessels are capable of performing a wide range of tasks across offshore wind farm operations. The multipurpose vessels are equipped with helipads for the helicopters, a crane for transporting the components for maintenance, and a crew cabin to carry the technicians. It can be considered the complexity of crew transfer vessels, crane vessels and support vessels. It brings the benefits of executing multiple tasks by using one vessel equipped with different modular layouts, but also the drawback that it can not perform well for special tasks. In the study [21], the multipurpose vessel is used to execute several tasks with low requirements for each kind of vessel.

4. **Aircraft**
The aircraft can be used for the operation and maintenance of offshore wind turbines due to its fast deployment speed and no restriction from the wave condition. The aircraft that has been involved in the operation of the offshore wind farms is the helicopter. The helicopter plays a similar role with CTVs by transferring the technicians between the operation center and the wind turbines. The transportation mode of the helicopter makes it unaffected by the wave conditions at sea. When the sea conditions become worse and the CTVs cannot travel to the offshore wind farm. The helicopters are mainly used to transfer the technicians [16]. The helicopter also plays an important role in emergency maintenance due to its high travel speed. However, the operation price of this is normally 20 times higher than that of CTVs [16]. Hence, the operation of the helicopters is normally performed when the CTVs are not available or the maintenance needs to be done immediately to reduce the downtime cost.

2.2.2. Vessel Selection Consideration

The maintenance conditions of offshore wind farms are more severe than those of onshore wind farms. As a result, many vessel-specific considerations must be made during the selection process. The table 2.2 summarizes the influence factors that have been discussed in the available research.

Ref	Vessel influence factor					
	Vessel parameter				Climate	
	Capacity	Maximum deploy time	Vessel speed	Rental price	Wave Height (HS) limit	Safe wind speed
[15]	√		√	√	√	√
[16]	√		√	√	√	√
[17]	√		√	√	√	√
[18]				√	√	√
[19]	√	√		√	√	√
[20]		√			√	√
[21]	√	√			√	√
[22]	√	√			√	√
[23]				√	√	
[24]			√	√	√	
[25]	√		√	√	√	√
[26]	√		√	√	√	
[27]	√	√	√	√	√	√
[28]	√		√	√	√	√
[30]	√			√	√	√
[31]	√				√	√

Table 2.2: Consideration of choosing vessels

The factors that influence the vessel generally come from two aspects: the parameters of the vessel and the offshore climate conditions that affect the availability of the operation.

1. **Vessel parameter**
Vessel parameters influence the vessel's performance, capabilities and suitability for specific tasks; the parameters play a crucial role in the selection of vessels for offshore wind farm operations

   - **Capacity**: The maintenance of the wind turbines is related to professional equipment and technicians. Different kinds of wind turbines and maintenance activities need to involve different kinds of equipment and technicians. The capacity of the vessels needs to be taken into consideration to fulfill the special requirements of the maintenance activities. The capacity of the vessels is also related to the arrangement and scheduling of the maintenance activities. In the study [22], the maximum personnel amount that the CTV can carry is taken into account to set up the constraint of arranging the vessels to transport the technicians to the offshore wind farm.
   - **Maximum deploy time**: The vessel cannot be considered as it's available for dispatch all the time. Different kinds of vessels have varying periods of maximum stay offshore, which

brings challenges to the arrangement of the vessels. According to the study of [27], the CTVs can only be deployed for one shift, which means that after the CTV has been sent to the offshore wind farm in the morning, it should be sent back to the operation center. While the crane vessels can stay overnight in the offshore area,. To avoid the fuel cost between the operation center and the offshore wind farm, the crane vessels will stay offshore until all the maintenance tasks are finished, while the CTVs will transport the technicians between the offshore wind farm and the operation center every day.

- **Vessel speed**: The vessel's speed determines the travel time between the offshore wind farm and the operation center, as well as the travel time between wind turbines. The vessel's speed influences the amount of time it can spend on maintenance by affecting its travel time. A fast-moving vessel plays an important role in offshore wind farm operations by increasing the efficiency of transporting technicians and equipment. The study [22] takes into account the travel time between the offshore wind farm and the operation center, which is based on the vessel's speed.
- **Rental price**: The rental price of the vessels is related to the total cost of the operation and maintenance of the offshore wind farm by influencing the fleet's chartering and dispatching programs. The studies [26] and [25] have taken the vessel price into consideration. By considering the rental price of the vessels, the O&M cost of the offshore wind farm can be controlled, the investment return and sustainability of the offshore wind farm can be guaranteed.

2. **Climate**
The offshore wind farms are located in the ocean and are affected by the wind, waves, and tides. The vessels for the operation can handle those severe conditions over the ocean to ensure the maintenance can be done safely.

   - **Wave height**: Wave height directly affects the vessel's stability. Larger waves can cause significant motion, which can be uncomfortable for crew members and potentially jeopardize operations. To ensure a safe working environment, the vessels have a wave height limit that restricts their operation. In extreme cases, operations must be halted altogether until wave heights return to safe levels. All available studies consider the wave height limitation because it is related to operational safety.
   - **Wind speed**: Wind speed is another climate factor that influences operation safety. Strong winds can create hazardous conditions for crew members, increase the likelihood of collisions or accidents, and make personnel transfers more difficult and dangerous. Wind speed limits the operation of crane vessels; during the lifting and transporting of spare parts and equipment for maintenance, the crane vessels struggle to maintain and control the position of the objects.

2.2.3. Vessel Acquire Strategies

Choosing the right vessel acquisition strategy is crucial for the success of offshore wind farms in terms of economics and operations. Appropriate vessel acquisition adjustments can have a direct impact on the offshore wind farm's electricity price by reducing maintenance costs. According to available research, chartering vessels remains the most common and conventional method of obtaining vessels. Because the cost of purchasing the vessel is still relatively high. Several studies, including [28] and [21], proposed a vessel fleet mix for offshore wind turbine maintenance. Operators benefit from both flexibility and cost efficiency with this approach. offering the advantage of avoiding additional time and money spent on vessel maintenance because the vessel rental company includes it in the rental fee. Other studies, such as [29] and [21], demonstrate that using existing or purchased vessels for maintenance is a common practice. This method relieves operators of concerns about vessels that cannot be put into service due to the erratic vessel charter market, as well as the costs associated with mobilization during the vessel charter period. The findings demonstrate the importance of strategically acquiring the vessels, which not only reduces operational costs but also improves the overall efficiency and sustainability of the offshore wind farm. The [30] study also suggested a novel way to lower the cost of vessel charter: some operators buy the vessels together and share them.

2.3. Decision Support System

The Decision Support System (DSS) is computer-assisted software that gives clients information to aid in decision making. The goal of the DSS is to increase task scheduling efficiency by giving decision-makers access to specific data and models [32]. The DSS offers the most complete support for decision makers by supporting a range of decision levels and types of information [33].

2.3.1. Decision support system for operation & maintenance of offshore wind farm

The DSS for OWF maintenance planning is a comprehensive system to assist decision makers in optimizing the schedule of maintenance activities for offshore wind turbines. The system incorporates a variety of tools, models and data sources to provide information and decision support, allowing the operators to make maintenance decisions in the challenging environment of OWF [34]. The DSS for OWF has the following features:

- **Data integration**: Data integration is a critical aspect of OWF O&M's DSS. The system incorporates and integrates data from different subsystems, including weather forecasts, turbine health monitoring systems, and historical maintenance data. By consolidating data from these disparate sources, the DSS can provide a comprehensive overview of the current state of wind turbines. The DSS is capable of analyzing weather patterns to predict potential maintenance windows or identify issues with wind turbines. With the data collected from different subsystems and sensors, the failure of the wind turbines becomes predictable [35]. By integrating the data from the relevant systems, the DSS can anticipate and proactively address maintenance needs, ultimately minimizing downtime and maximizing the operational efficiency of the wind farm.
- **Resource optimization**: Resource optimization enables the operators to allocate resources effectively and efficiently for maintenance activities. The integration of data from various subsystems facilitates this process. The DSS can develop optimal maintenance scheduling solutions, scheduling the technicians and vessels effectively to reduce the overall cost and maximize productivity, considering constraints like weather limitations, maintenance execution type, and urgency of the tasks [36]. By optimizing resources in this manner, the DSS helps operators achieve cost savings and improve overall maintenance performance.
- **Risk analysis**: By using the data on the components of the wind turbines, the DSS allows decision makers to access and mitigate potential risks associated with the maintenance of the wind turbines. By analyzing the data on the wind turbine components, the system can predict the probability of component failure and generate risk mitigation strategies. It may recommend specific maintenance actions to address identified risks or suggest alternative strategies to minimize the impact of the failure [37]. By proactively addressing risks, such as component wear or environmental factors, the DSS helps prevent costly downtime and ensures the continued operation of the wind farm at optimal levels of performance and reliability.

The DSS helps the decision makers improve the quality of the maintenance, reduce the downtime of the wind turbines by executing the maintenance properly.

2.3.2. Mathematical model from available researches

The mathematical model is vital in the DSS since it allows operators to optimize their decision-making selections. Evaluate the impact of various decisions, taking into account the uncertainties in the parameters. The DSS mathematical model includes crucial characteristics such as modeling approach, objective functions, constraints, uncertainties, and a simulation horizon.

Modeling approach

The modelling approach plays an important role during the set up process of the mathematical model. The modelling approach can be classified into two categories: deterministic programming and stochastic programming. The table 2.3 summarized the modelling approach from the available research

- **Deterministic programming**: Deterministic programming is an optimization process based on the deterministic model, which assumes that the parameters and variables are all predicable

Ref	Modelling approach Deterministic programming	 Stochastic programming	Ref	Modelling approach Deterministic programming	 Stochastic programming
[19]	√	√	[38]	√	√
[20]		√	[10]		√
[22]		√	[27]		√
[39]	√		[28]		√
[23]	√		[31]	√	

Table 2.3: Modeling approach in available research

without uncertainties. The constraint and objective functions are all deterministic functions that do not take into account stochastic factors. Deterministic programming is usually applied to solve optimization problems without stochastic, where the parameters and variables can be measured and controlled exactly. For the stakeholders of the OWFs, deterministic programming can provide a more accurate and stable solution [38]. The study [39] used the 2-stage deterministic model to evaluate the optimal vessel fleet mix for offshore wind farm maintenance by determining which base and what kind of vessels should be involved. The studies [23] and [31] used deterministic programming to optimize the fleet mix problem with the known information of weather condition and component failure in advanced.

- **Stochastic programming**: Stochastic programming is an optimization method based on uncertainties, which allows some of the variables and parameters to be stochastic. The constraints and objective functions that consider the stochastic variables' uncertainties are represented by the probability distribution. The stochastic programming can fully consider the uncertainties and risks in the system, providing a more reliable result [19]. However, stochastic programming needs to consider the complex probability distribution; the computation time and computation cost are significantly higher than those of deterministic programming. The studies [20], [10], [27] and [28] used a 2-stage stochastic programming method to decide the vessels for the operation and task arrangement of the maintenance. The study [22] introduced a 3-stage stochastic model, where the fleet mix problem is solved in 2 stages instead of one, which takes more parameters into consideration.

Objective Function

The objective function is critical to the decision support system because it defines the goal and guides the system's optimization direction. From a mathematical perspective, the objective function is a formula that incorporates decision variables, which serve as the system's outputs, offering a structure for assessing and shaping the system's performance. Confirming whether to maximize or minimize the function is the overall goal of the objective function, which facilitates decision variable optimization. The objective function allows the DSS to make systematic and quantifiable decisions, ensuring that the system's actions align with the objectives.
Available research models primarily aim to reduce operational and maintenance costs. As a result, the objective functions are typically cost functions that include a variety of costs. The table 2.4 selects the papers that provide mathematical models that were used to solve the fleet mix problem and summarizes various types of costs that have been involved.
The available studies show the most widely used cost function is determined by the sum of different kinds of costs involved in the O&M and minimizes the costs to achieve optimization. The cost typically comes from acquiring the vessels from the OWF to execute the maintenance and the OWF's operations.

1. **Vessel charter cost**
   The charter costs come from the chartering of vessels for OWF maintenance, which accounts for a significant portion of the total cost. Additionally, it serves as the primary focus of the optimization process.

   - **Vessel & technician cost**: This represents the largest percentage of the OWF's total operating and maintenance costs. When operators decide to hire a vessel, the main expense of the vessel rental is the charter fee for using the vessel to move technicians and equipment from the operation center to the wind turbines. Every study takes into account the cost of

Ref	Cost					
	Vessel charter			Offshore wind farm		
	Vessel & technician cost	Vessel mobilize cost	Vessel travel cost	Downtime cost	Maintenance incomplete penalty	Fixed cost
[16]	√	√	√	√		√
[19]	√	√	√	√	√	√
[22]	√		√	√	√	√
[39]	√			√	√	√
[23]	√	√	√	√	√	√
[38]	√	√	√	√		
[24]	√	√	√			
[26]	√			√		
[10]	√		√	√	√	√
[27]		√	√	√	√	

Table 2.4: Cost function of available research

renting a vessel. Depending on the vessel charter strategy and length of the charter, we can determine the cost of the charter in terms of hours, days, or periods. The study [38] focuses on vessel travel; the rental cost is calculated by hours. The study [16] focuses on the vessel arrangement of the short-term chartered vessels, their study computes the charter costs in terms of days. Operators requiring long-term charters can calculate the vessel rental cost using a fixed charter period. Technician costs include salary, training, and other labor-related expenses. Skilled technicians are critical for carrying out maintenance activities, which directly contribute to the OWF's reliability and performance.

- **Vessel mobilization cost**: The vessel mobilization cost is the cost of transporting a vessel from the ship owner to the operators. When the vessel is rented to the operators, the mobilization cost must be calculated. Chartering more vessels allows for the completion of maintenance tasks ahead of schedule. However, transferring the vessels incurs a higher vessel mobilization cost. The studies [16] and [19] consider the vessel mobilization cost with the charter in of the vessel.
- **Vessel travel cost**: The vessel travel costs refer to the amount of fuel consumed while the vessel is in operation. The cost is related to the distance traveled during the transfer of technicians and equipment between the operation center and the wind turbines, which affects the arrangement of the vessels to execute the maintenance. The study [22] considers the travel cost of the vessels by calculating the travel time of vessels sent to execute the maintenance.

2. **Offshore wind farm cost**
Fleet arrangements and maintenance strategies primarily determine the OWF cost, which refers to the costs incurred during wind turbine maintenance. Various factors typically determine the cost of the OWF.

    - **Downtime cost**: Turning off the wind turbines is necessary for OWF maintenance. The production loss resulting from the maintenance shutdown is known as the downtime cost. The amount of electricity required during this time period determines the downtime cost. As a result, the cost of downtime is proportional to the wind speed and the time required for maintenance. Maintenance during periods of low wind speed, as well as reducing maintenance execution time, can significantly reduce production losses. All available research has taken into account downtime costs. The study [19] considers the maintenance execution time by calculating the downtime cost and maintenance execution time.
    - **Maintenance incomplete penalty**: For maintenance tasks that have not been completed during the pattern. The cost function incurs the penalty cost. This allows the system to schedule maintenance in a timely manner. The study [22] includes the penalty costs for preventive maintenance tasks that are not completed in the soft windows. The study [23] calculated the corrective maintenance that was not executed during the vessel visits.
    - **Fixed cost**: The fixed cost refers to the preparation for executing the maintenance tasks of the OWF, which is unaffected by the vessel's usage or pattern but related to the wind farm

itself. The fixed cost includes the cost of establishing a base for the operation. The study [39] considers the fixed cost of the operation base to determine how many bases should be used during OWF operations.

Constraints
The constraints limit the optimization model's cost function, which reflects the factors involved in maintenance scheduling and vessel chartering strategies. As the number of constraints increases, the model becomes more complex and requires more consideration. To achieve the model's optimization target, several constraints must be considered. The table 2.5 summarizes the constraints used in available research. Constraints are considered in the following major aspects:

Ref	Constraints								
	Vessel					Wind turbine maintenance		Port	
	wind turbine visit	Offshore work time	emission	seasonal constraints	Offshore staying time	Maintenance accomplishment	personnel onboard limitation	vessel capacity of harbor	vessel amount in base
[40]	√	√					√	√	
[16]		√						√	
[19]		√				√		√	√
[41]		√	√				√	√	
[39]							√	√	√
[23]		√				√			√
[22]	√	√			√			√	√
[38]		√					√	√	
[42]		√		√			√		
[43]	√	√						√	√
[10]						√	√	√	√
[27]	√	√				√		√	√
[44]	√	√					√	√	√
[45]	√							√	√
[46]	√	√				√	√		
[47]	√		√				√		√

Table 2.5: Constraints of available research

1. **Vessel**
   The vessel constraints ensure the chosen vessels meet operational and resource allocation requirements. By imposing constraints on the vessels, operators can optimize vessel selection and increase the efficiency of operation and maintenance activities. The constraints help to ensure that selected vessels are suitable for the wind farm's specific operating conditions, comply with relevant regulations and standards, offer the best value for money, and can be deployed efficiently based on resource availability and scheduling constraints. The vessel constraints are normally caused by the following factors:

   - **Offshore wind turbine visit limitation**: To prevent the case that the vessels are sent to the wind turbines repeatably, the constraints of wind turbine visit are set up. The study [40] introduces the constraint of limiting the vessels for transportation to only visit the wind turbines once to prevent the wind turbines from being visited more than once.
   - **Offshore operation time**: The offshore operation time of the vessels refers to the duration that vessels can operate in the offshore environment. Despite the favorable weather conditions, vessels have limitations on the operational hours related to the vessel types, equipment and technicians that carry them. The study [23] uses the offshore operation time as a limitation to calculate the vessel deployment amounts for executing the maintenance by dividing the maintenance execution time with the vessel operation time.
   - **Emission**: The goal of reducing greenhouse gas emissions involves considering the emissions of the vessels and using them as constraints to restrict their deployment. The studies [47] and [41] have taken emissions into account. By setting up total greenhouse gas emission thresholds, calculate the emissions of the vessels and helicopters during the operation.

- **Seasonal constraints**: Spring and summer are the best seasons to maintain the OWF because the wind and waves are more conducive to maintenance execution. Certain seasons, such as winter, prohibit maintenance. A seasonal constraint is applied to restrict the deployment of the vessels. The study [42] introduced a seasonal constraint to ensure that maintenance would not take place during the winter, avoiding bird migration and the maximum level of electricity demand.
- **Offshore staying time**: For vessels capable of staying offshore overnight, such as mother vessels or crane vessels. The constraints of offshore staying time limit the number of days that vessels can spend offshore. In order to minimize travel expenses between the OWF and base, we aim to prevent scenarios where the vessel stays out for multiple days. In the study [22], the constraints of determining the vessels that can stay offshore for several periods are introduced to limit the vessel's stay-out nights.

2. **Wind turbine maintenance**
The wind turbines' maintenance status constraints ensure that the vessels are deployed only when required. By introducing the constraints related to wind turbine maintenance, the operators can allocate the vessels effectively.

- **Maintenance accomplishment**: The maintenance accomplishment constraint is designed to penalize the wind turbine's uncompleted maintenance tasks during a specific time period. The constraints include a variety of penalty costs associated with incomplete or delayed maintenance. This includes energy losses in production as a result of maintenance delays, as well as increased maintenance costs. The studies [10] and [23] introduced two binary variables to represent whether the maintenance task was completed or not. The maintenance finished index, when added together, mandates the completion of all maintenance tasks to avoid penalties.
- **Personal onboard limitation**: The personal onboard refers to the quantity of technicians that are sent for the OWF maintenance. When scheduling maintenance execution, the technician allocation is critical. The number of people sent to the wind farm cannot exceed the number of available technicians at the base. In the study [10] and [42], restricting the number of technicians sent to the OWFs for maintenance should not exceed the number of technicians that are available in the base.

3. **Base**
The operators' base restricts the number of vessels they can deploy during the operation. The basic aspect's restrictions are based on the following factors:

- **Vessel capacity in the base**: The maximum number of vessels that the base can accommodate is known as its vessel capacity. The base's vessel capacity constraints are used to limit the number of vessels in the harbor, preventing the optimization model from employing a large number of vessels in a short period of time and allowing the simulation to be more closely related to the actual situation. The studies [16] and [19] introduced the constraints of limiting the vessel amount in the base to restrict the number of vessels chartered for the fleet. The constraints ensure that the optimization model makes recommendations that are both cost-effective and feasible.
- **Total amount of vessel in the base**: The base's vessel capacity limits the number of vessels available for wind farm operation and maintenance. The constraint of the total number of vessels in the base is used to determine the number of vessels that can be sent out for maintenance. The constraints are built to prevent the same vessel from being used for different tasks during the same period of time. The study [27] proposed the constraint that the vessels that are sent out for maintenance should not exceed the vessels that are available at that time.

Uncertainties
To make maintenance decisions, the decision support system needs the OWF's input data. The input data for the system is not always complete and accurate, which leads to errors in the system's decision making. The uncertainties come from many aspects, including the environment, technologies, or

random unpredictable errors. As a result, the decision support system needs to take uncertainties into consideration and make the system more robust. The table 2.6 summarizes the uncertainties from the available research. Apart from the research mentioned in the table 2.4 that provided their mathematical models. Available research that does not give their mathematical models but points out the uncertainties during the O&M of the OWF is also summarized. The available research typically considers the following aspects of uncertainty:

Ref	Uncertainty							
	Offshore wind farm uncertainty			Vessel uncertainty			Other	
	Component failure	Electricity demand	Operation time	Vessel spot rate	Vessel speed	Vessel mobilization time	Climate	Different solvers
[48]								√
[15]							√	
[16]						√	√	
[19]	√						√	
[20]		√					√	
[39]	√						√	
[23]	√							
[21]	√	√		√			√	
[22]	√	√		√			√	
[49]								√
[50]	√						√	
[24]	√							
[51]				√			√	
[25]	√	√	√				√	
[26]					√		√	√
[10]	√						√	
[52]	√						√	
[53]	√						√	
[27]	√						√	
[28]	√	√	√				√	
[29]		√					√	
[30]	√			√				
[31]	√						√	

Table 2.6: Uncertainties from available research

1. **Offshore wind farm uncertainty**

   - **Component failure**: Previous repair data or the wind turbine's working condition inform the maintenance schedule. The decision support system predicts the failure times of the components and arranges the maintenance time [54]. However, the components fail for many reasons, and the prediction of failure is not always accurate. The components may fail unexpectedly, resulting in system breakdown [10]. By taking the component failure uncertainties into account, the system becomes more robust to unpredictable failures and reduces the downtime cost by arranging the maintenance schedule.
   - **Electricity demand**: The market's demand for power has an impact on the OWF's maintenance schedule. When a wind turbine needs maintenance, it must be shut down, which results in downtime expenses and the wind turbine becoming unavailable [22]. Appropriately scheduling the wind turbines' shutdown helps minimize lost downtime while doing maintenance. The wind turbines' downtime losses correlate with the amount of electricity society needs. The market's erroneous predictions and a rise in electricity usage during the planned maintenance outage, which would necessitate continuing the work and incur significant downtime costs, are the sources of the uncertainty surrounding the electricity demand. The demand for electricity also has an impact on its market price [29]. It would be easier to choose the best time to do maintenance and minimize downtime losses if the cost of electricity was taken into consideration.
   - **Operation time**: The operation time refers to the wind turbine's maintenance execution time. The time spent on carrying out the maintenance results in the arrangement of the

vessels used for the deployment of the maintenance. Typically, when considering the maintenance execution time, the average maintenance time is used to simplify the model. However, the uncertainty of the maintenance execution time sometimes results in an additional maintenance hour requirement for the operation. The study [25] considers the maintenance execution time uncertainty, affecting the deployment and arrangement of CTVs to transfer technicians.

2. **Vessel uncertainty**

- **Vessel spot rate**: Typically calculated in days or weeks, vessel spot rates represent the vessel price for a specific future period. This is in contrast to long-term charters, where the rental price is fixed. Short-term optimization primarily uses the vessel spot rate, allowing for flexible adjustments based on market conditions. Many factors influence the vessel spot rate, including fuel prices, travel routes, seasons, and so on. The vessel spot rate influences the vessel rental price and vessel selection optimization. The studies [21] and [22] examine the impact of vessel spot rates on vessel charter costs by including uncertainties.
- **Vessel speed**: The vessel's speed determines the travel time between the OWF and the operation center, as well as the transportation time between wind turbines. Many factors, including weather and fuel consumption, influence the vessel's actual travel speed. The available research uses the vessel's average traveling speed to calculate transportation time and plan maintenance. The vessel's travel speed uncertainty would result in different maintenance times. The study [26] considers the uncertainty of vessel speed, which is influenced by sea conditions and maintenance strategies.
- **Vessel mobilization time**: The term refers to the duration required to transport the vessel from the ship owner to the OWF operator's harbor. The chartered vessel's arrival time affects the wind turbines' maintenance execution time slot. The vessel's mobilization time is uncertain, resulting in an unpredictable time slot for maintenance execution. The study [16] considers the uncertainty of the mobilization time of Jack-Up vessel due to the lack of available vessels from the ship owner. In this scenario, the duration of mobilization impacts the mobilization cost.

3. **Other uncertainties**

- **Climate**: The OWF's weather conditions directly affect the wind farm's operation and wind turbine maintenance. Severe weather conditions, like strong winds or storms, will pose a threat to maintenance and technicians. The advancement of weather forecast technology enables the prediction of future weather conditions. However, the weather forecast is not always accurate, even with the weather data from previous years [51]. The schedule that was planned years ago may not be executed due to sudden changes or unpredictable weather conditions [19]. Uncertainties of the weather also affect the availability of the equipment, which makes the maintenance schedule unable to execute properly [21]. By taking the weather uncertainties into account, the maintenance can be scheduled close to the estimated maintenance date and improve the maintenance accomplishment.
- **Different solvers**: due to variations in convergence criteria, heuristics, and algorithms. Applying different optimization solvers to the same problem can lead to different outcomes. The OWF fleet selection problem is solved using six different solvers in the study of [26], using the same case and input. Examine the variations between the results produced by various solvers. The comparison shows that the strategies and total costs of different solvers vary. This result illustrates how the solvers can introduce uncertainties into the solution.

Simulation Horizon
The simulation horizon is a factor that has a significant impact on the DSS output results. Different simulation horizons lead to different model optimization focuses. The simulation horizon selection will have an impact on the DSS's strategies. The table 2.7 summarizes the simulation horizon from the

Ref	Simulation horizon	Ref	Simulation horizon
[15]	1 year	[54]	1 year
[16]	short: 1-8 weeks long: 5 year	[24]	1 year
[17]	1 year	[51]	1 year
[18]	short: 3-16 weeks long: 1 year	[25]	3 days
[19]	1 year	[26]	1 year
[20]	3 months, 6 months, 1 year	[10]	1 year
[21]	25 year	[52]	3 months a period, total 25 years
[22]	1 year	[27]	1 year
[23]	1 year	[28]	1 year
[39]	1 year	[29]	1 year
[49]	1 year	[30]	1 year
[50]	20 year	[31]	1 year per period, 8 year in total

Table 2.7: Simulation time span of available research

available research. The case study's simulation horizon categorizes the available research into three distinct simulation horizons:
The simulation horizon of the DSS can be classified into the following 3 categories:

- **Short term**: The simulation horizon is less than a year. The DSS focuses on vessel arrangements and journeys. The majority of the studies focus on short-term optimization. This has the benefit of incorporating the entire year's seasons and weather into the modeling process, bringing the system closer to the real situation over time and making cost calculation easier. The research [25] has a simulation horizon of 3 days because it focuses on vessel routing for fleet maintenance. The research [20] set the simulation horizon of 3 months and 6 months to organize the execution of maintenance chores. Studies such as [10] and [39] have a one-year simulation horizon. This takes into account the overall weather conditions throughout the year.
- **Mid term**: The simulation horizon ranges from one to five years, allowing the DSS to conduct a comprehensive analysis of the maintenance strategies. The DSS focuses on fleet selection, aiming to assist the operators in choosing the most suitable vessels for executing the maintenance. The vessel selection process considers a variety of factors, including maintenance requirements and overall maintenance strategies. In particular, the DSS evaluates the benefits of long-term charter contracts over short-term contracts. A long-term charter contract typically results in a lower average daily price compared to a short-term charter contract due to the stability and predictability provided by long-term commitments. The study [16] utilized a simulation period of five years to analyze the charter cost associated with longer contracts.
- **Long term**: The simulation horizon is more than 5 years. Long-term simulations typically cover the OWF's entire lifetime. The DSS focuses on the overall cost of operating and maintaining the OWF. The large simulation time range enables the DSS to prepare for the whole operational life of the OWF, increasing the wind farm's long-term profitability. The study [52] chose the 25-year simulation horizon to calculate the entire operation cost of OWFs.

2.3.3. Solving the mathematical model

Solving methods
After the mathematical model is developed for the decision support system. The next step is to find the optimization problem-solving methods. The table 2.8 summarizes the mathematical model solving methods from the available research.

1. **Mixed integer programming (MIP) solution algorithm**
    - **Branch and cut**: The branch and cut approach is commonly used for addressing integer programming problems. To tackle linear programming problems, the approach first loosens integer restrictions. If it achieves fractional solutions, the approach divides the problem into

Ref	Model solve						
	MIP solution		Heuristic			Metaheuristic	
	Branch and cut	L shaped	Greedy Heuristic choice	Genetic Algorithm	Labeling Algorithm	GRASP	Dantzig-Wolfe decomposition
[19]	√						
[20]						√	
[22]	√						
[39]							
[23]			√				
[38]							
[10]	√						
[27]	√				√		√
[28]		√					
[31]	√						
[47]				√			

Table 2.8: Optimization methods from available research

subproblems with varying constraints on the chosen variables. The solutions to the subproblems are compared to each other to determine the best solution. Cutting planes based on problem constraints are used to tighten model relaxation and improve solution quality. The process of branching, solving, and cutting persists until the discovery of the ideal solution. The studies [10] and [19] employ branch and cut approaches to address the optimization model's MILP problems. The branch and cut method is used to solve deterministic programming models because it provides a systematic way to tackle difficult optimization problems through efficient exploration of the solution space. The study [31] build up an optimization model using deterministic programming and solve it using the branch and cut approach. Stochastic programming models also employ the branch and cut method due to its ability to manage parameter uncertainties. The studies [22] and [27] applied this strategy to handle stochastic programming problems.

- **L-shaped method**: Since it can break down problems into master problems and subproblems, the L-shaped method is used to solve two-stage stochastic MILP problems. The feasibility cuts are used to solve and update the master problem. Once the master problem is resolved, the subproblems are resolved through optimal cuts. To solve the stochastic model, the L-shaped approach is used in the study [28]. Decisions are made in two phases: prior to the implementation of uncertainties, decisions are made, and following the implementation of uncertainties, decisions are adjusted.

2. **Heuristic**

- **Greedy heuristic choice**: This technique involves selecting the locally optimal option at each stage, without considering the long-term effects globally. Deterministic programming uses this approach due to its ease of understanding and computational efficiency, which allows for a straightforward selection of options that yield immediate benefits. The challenge of arranging the vessels to perform the repair was solved by the study [23] using the greedy heuristic approach.
- **Genetic algorithm**: Natural selection and genetics serve as inspiration for the genetic algorithm, a heuristic search and optimization method. Conventional techniques frequently use it to resolve complicated optimization issues like nonlinear programming. The genetic algorithm operates by first producing solutions and then evolving until it discovers the best one. Nonlinear programming was utilized in the research [47] to construct the optimization model, as the problem was too difficult for the conventional approaches to solve. The genetic algorithm is employed in this instance to resolve the issue.
- **Labeling algorithm**: The labeling algorithm is one type of heuristic that systematically searches the solution space. It's a kind of heuristic search algorithm that methodically investigates the solution space. Often used to make discrete decisions, the labeling algorithm creates and labels potential solutions until it determines the best one. In the study [27], the labeling algorithm was used to produce the best maintenance schedule for the wind turbines.

3. **Metaheuristic**

    - **GRASP**: The Greedy Randomized Adaptive Search Procedure is known as the GRASP approach. It is a metaheuristic optimization problem-solving algorithm. The GRASP method employs a combination of randomization and greedy algorithms to search the solution space and identify superior solutions. The GRASP avoids the solver running into local optimal solutions by using a random search for the best solutions, in contrast to the greedy heuristic option. The GRASP is used in the study [20] as a metaheuristic technique to optimize the fleet's vessel layout.
    - **Wolfe-decomposition**: In stochastic programming, the Wolfe decomposition technique is used to break down a large-scale stochastic optimization issue into more manageable and smaller subproblems. Because the stochastic programming model must account for parameter uncertainties, it is a large-scale decision model. By taking advantage of the problem's structure, the Wolfe-decomposition technique can break down the objective function and constraints into parts that rely on distinct subsets. This approach is used in the study [27] to solve the stochastic model. In contrast to the standard decomposition, the Wolfe-decomposition designated a portion of the subproblems as master problems.

Solvers
After the cost function and constraints have been defined, the solvers are required for the optimization model. Table 2.9 summarizes and outlines the available research that has executed case studies and shown the simulation results.

Ref	FICO Xpress	CPLEX	Other Solvers	Ref	FICO Xpress	CPLEX	Other Solvers
[19]	√			[25]		√	
[20]	√			[26]			StrathOW-OM NOWIcob MAINTSYS ECUME MARINTEK ECN
[23]		√		[52]	√		
[21]	√			[10]	√		
[22]	√			[27]	√		
[39]		√		[29]		√	
[55]			Gurobi	[30]			C++ 17
[24]			Mermaid	[31]	√		

Table 2.9: Solvers of available research

Existing research commonly employs commercial solvers like FICO Xpress and IBM CPLEX. Commercial solvers assist operators in making decisions on various computing platforms by adapting more effectively to diverse computer systems. Software businesses develop and regularly tune commercial solvers, enabling faster optimization with each iteration of the solver's version.

- **FICO Xpress**: A commercial optimization solver for linear programming (LP), mixed integer linear programming (MILP), quadratic programming (QP), and so on. Xpress is available on most common computer platforms and also provides several interfaces and a callable library for several programming languages [56].
- **CPLEX**: A commercial solver designed to tackle large-scale linear problems. The software provides several interfaces and supports different programming languages. The optimizer is accessible through the modeling system [57].
- **Gurobi**: The Gurobi is a high-performance commercial optimization solver for mixed integer linear programming (MILP). The gurobi provides high-performance branch-and-cut solving methods and parallel computation [58]. Compared with other commercial solvers like Cplex, Gurobi is extremely efficient when it comes to dealing with MIP issues [59]. Due to its ability to solve large-scale models, the Gurobi solver is widely used in the task scheduling or vessel routing of the OWFs O&M [55].

- **Other solvers**: In some cases, general commercial solvers, such as FICO Xpress or CPLEX, do not perform as expected. Hence, some papers will use other optimizers to generate feasible, optimal solutions. Self-developed optimizer like NOWIcob, which is developed to optimize maintenance strategies and reduce maintenance costs specifically for OWFs [26].

2.4. Summary

In this chapter, the latest progress of the fleet mix problem from the vessels involved in the maintenance of the offshore wind farm and the decision support system that helps the operator to arrange the vessels is reviewed.

It can be observed from table 2.1 that the CTV, FSV, and CVs are widely used in the maintenance of wind turbines. As shown in the table 2.2, when selecting the vessels for executing the maintenance. The seaworthiness of the vessel under different weather conditions is the most important parameter. All the available research takes the wave height limitation for the vessel into consideration, as well as the wind speed for the vessel. The parameters related to the vessels like the capacity and rental price are also widely considered in the available research. As shown in table 2.7, most of the available research considers short-term optimization, which means the simulation horizon is around 1 year. Therefore, for the vessel acquire strategies. All the available research considers chartering the vessels since purchasing is not cost-effective for a short simulation horizon.

For the model setup in the available research. All of the references that provide mathematical models for optimization either choose to use deterministic programming or stochastic programming. The objective function, which shows the tendency of the optimization, includes the costs that need to be minimized for the vessels. As shown in table 2.4, The downtime cost and vessel travel cost are considered in all the available research since it's related to the vessel deployment and operation. The vessel charter cost and vessel mobilization cost are widely considered since they are related to the vessel chartering strategy. The constraints, that limit the boundary of the optimization. As shown in table 2.5, the constraints come from three aspects, including the vessel, wind turbines, and the port. The offshore working time of the vessels is mostly considered since it's related to the operation. The vessel capacity of the harbor is also been widely taken into consideration since it refers to the maximum vessel amount that the harbor can hold, limiting the endless increase in the number of vessels for charter. Seasonal constraint like winter is only considered in one reference, but still worth exploring since the weather is seasonal and harsh weather conditions in the winter limit the vessel deployment. The uncertainties of the offshore wind farm mostly come from the component failure and the offshore climate condition as it is shown in table 2.6. The former brings uncertainties to the maintenance tasks generation, while the latter makes the execution of the maintenance uncertain. To solve the optimization problem, mixed integer linear programming is mostly used in the available research since it provides an exact solution for the problem. As shown in table 2.9, commercial solvers like FICO Xpress or CPLEX are mostly used in the available research since commercial solvers have better adaptability across different computing platforms.

Based on the available research. In the thesis, the most popular vessels CTV, FSV, and HLV are taken into consideration. When deploying the vessel to the offshore wind farm, weather conditions like wind speed and wave height are taken into consideration, as well as the vessel capacity, charter cost, and so on. To figure out the initial purchase fleet for the offshore wind farm. A longer period of 5 years is taken into consideration. To arrange the vessel deployment and corresponding charter strategy, the mixed integer linear programming (MILP) is applied and commercial solver Gurobi is used because of its better adaptation to the other modules of the simulation model. The goal of the optimization model is to minimize the vessel acquisition cost. Therefore, the cost related to vessel deployment like vessel charter cost, vessel traveling cost, and so on will be taken into consideration. The two uncertainties that have the greatest impact on the results, weather conditions and component failure are considered as the uncertainty factors. Further details will be explained in the next chapter.

3

Simulation Model Structure

In this chapter, the methodology that has been used to build up the simulation model will be presented. Firstly, the terminologies and assumptions used in the simulation model are illustrated. Next, the component wearing simulation model that developed by Marco Borsotti is presented. Finally, the component wearing and vessel arrangement simulation model that builds up based on the component wearing simulation is presented.

3.1. Terminology and assumptions

Due to the complexity of the offshore wind farm maintenance process, many real-life factors need to be considered. Therefore, specific assumptions need to be made when constructing the simulation model to ensure that the model can be simplified and, at the same time, close to the actual situation. At the same time, considering that different terms have different meanings in various studies, explaining some terms involved in the simulation model is necessary.

- **Time step**: The model simulates the offshore wind farm's operation and maintenance (O&M) process following the time. The simulation time step defines how the simulation model moves from one point in time to the next, referring the discrete interval between each calculation and update within the simulation. The model's simulation time step is one day and will be referred to as a time step in later content. In this thesis, the time step of the simulation model is one day
- **Maintenance cycle**: The maintenance cycle refers to a maintenance blog containing the maintenance tasks generated on the same day. When the age consumption of one of the components reaches the threshold for triggering maintenance, the system generates the maintenance cycle. It sends it to the optimizer for vessel and task arrangement.
- **Maintenance period**: The maintenance period is a start-to-finish time that is used to perform all maintenance tasks in the maintenance cycle. In this thesis, the maintenance period is assumed to be 90 days after the generated maintenance cycle.
- **Maintenance execution time**: The maintenance execution time refers to the time spent on the maintenance of the components during the optimization of the vessel and task arrangement. The maintenance execution time in the simulation model is calculated by hours, which refers to the hours spent on executing the maintenance task. The time spent executing maintenance tasks is considered constant and remains unaffected by weather conditions. Multiple vessels are required to execute maintenance tasks. The maintenance execution time solely accounts for the hours all vessels are available to complete the task.
- **Maintenance execution**: Different kinds of maintenance are executed independently, even if the tasks are on the same wind turbine. A wind turbine with multiple components must be maintained in the maintenance cycle. The maintenance tasks are performed independently by different maintenance groups and can be considered to be executed simultaneously, unaffected by others. The maintenance execution time equals the component's maintenance duration. The maintenance task is considered finished.

- **Simulation horizon**: The simulation horizon of the model refers to the number of days between the simulation start time and end time. At the beginning of the simulation, a day number counter in the model is set to zero and plus one after each time step. When the day number counter reaches the simulation horizon, the simulation will stop. In this thesis, the simulation horizon is set to 5 years, which refers to 1825 days.
- **Weather condition**: The weather conditions, including wave height and wind speed, independently influence whether the vessels operate. The weather condition covers the whole day and is assumed to be constant for 1 hour (equal to 24 periods in one day).
- **Component**: The components' lifetimes are independent, and the wearing process is only related to the RUL (Remain Useful Life) and time. The component can only be maintained once during each maintenance cycle. The components in a maintenance cycle will not be considered in other maintenance cycles.
- **Technicians and spare parts**: It is assumed that spare parts are always available in the operation center, and each vessel can carry all the spare parts for executing the maintenance tasks. The number of technicians in the operation center is unlimited, and they can be deployed to the vessels for maintenance at any time.
- **Vessel charter length**: The vessel charter period represents the period from the day the vessel starts to be chartered until the day the vessel charter contract terminates. Each kind of vessel has a minimum charter period and an extended charter period. If the vessel requires fewer days than the minimum charter period, it must still be chartered for the entire minimum period. The operator can extend the vessel's charter period at the end of the minimum charter period. The vessel that has been chartered during the extended charter period must be chartered till the end of the extended charter period.
- **Vessel mobilization time**: The mobilization is an action that transfers the vessel from the ship owner to the operator, and it takes a few days for the vessel to travel between the ship owner and operator, which is called the mobilization period. To show the impact of mobilization on vessel chartering, when the vessel's charter contract ends, the ship owner will move the vessel back from the operator, and the operator needs to move the vessel from the operator for the next charter period. In this case, the same vessel would not be available for at least two mobilization periods between two charter contracts.
- **Vessel travel distance**: The simulation model considers the vessel deployment and chartering for the maintenance execution of the wind turbines. Therefore, vessel routing and travelling on wind farms are not part of the scope of the research. The travelling distance of the vessel in the simulation model refers to the distance that the vessel travels from the port to the offshore wind farm. Travelling within the wind farm is not considered.
- **Vessel travelling time**: The travelling speed of the vessels between the operation centre and the offshore wind farm is assumed to be constant, and the travel time is calculated by the distance divided by the average travel speed. The simulation model is focused on the vessel and task arrangement. In this case, the inter-transit times between each wind turbine are assumed to be ignored.

3.2. Component wearing simulation model

The component wearing simulation model is developed by Marco Borsotti (will be referred to as Marco's model later in this paper). Marco's model simulates the component wearing, maintenance generation, and execution of the wind turbines on the offshore wind farm. Marco's model includes data input, component wearing and monitoring module, maintenance cycle generation & execution module, and the data output module. Figure 3.1 shows the flow chart of the initial model.

3.2.1. Model input data

Marco's model assumes the lifetime of the components follows the Weibull distribution. Therefore, the Weibull shape parameter and Weibull scale parameter of the components serve as the input data of

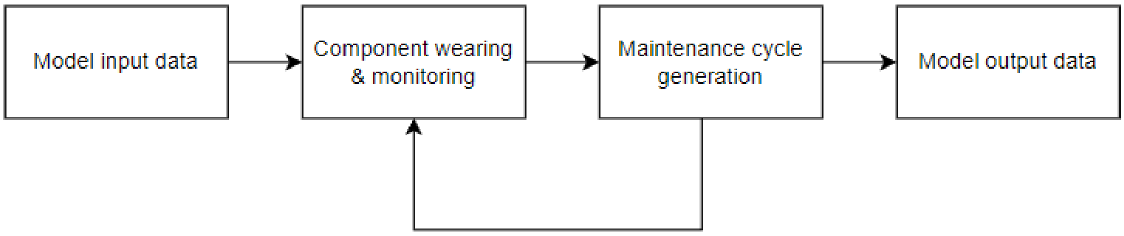

Figure 3.1: Component wearing simulation model

the components. The table 3.1 shows the component information inputs of the component wearing & monitoring module.

No	Item	Unit
1	Number of wind turbines	turbines
2	Simulation horizon	day
3	Component name	-
4	Component shape	-
5	Component scale	-
6	Component replacement cost	keur
7	Component major repair cost	keur
8	Component minor repair cost	keur
9	Component replacement time	hour
10	Component major repair time	hour
11	Component minor repair time	hour
12	Component replacement probability	-

Table 3.1: Input data of Marco's model

The input [1] shows the number of wind turbines in the OWF, which is related to the size of the components' RUL matrix generation in this module. The input [2] refers to the simulation horizon of the simulation model. The inputs [3-5] are the components' names and the shape and scale parameters of the components. The component's RUL is generated using the input [3, 4], following a Weibull distribution. The inputs [6-11] show the cost and time of maintaining the components. The input [12] represents the probability of replacing the component after it reaches the replacement life threshold. The RUL and age consumption of the components are estimated and converted into output and updated daily to the maintenance requirement generation part.

3.2.2. Component wearing and monitoring

The component wearing and monitoring module simulates the wearing and degradation of the components during the operation of the offshore wind farm and establishes the age consumption of the components. At the beginning of the simulation, the matrices that refer to the components' remaining useful life (RUL) and age consumption and the corresponding wind turbine number are established. The equation 3.1 shows how the RUL of the components is calculated using the Weibull distribution [60]. The age consumption of the components is 0 at the beginning of the simulation. However, when the day number increases, the age consumption of the components adds up to the inverse of the RUL. The equation 3.2 shows how the age consumption of the component increases by the day.

$$\text{RUL}_{\text{true}} = \lambda\,(-\ln(U))^{\frac{1}{\alpha}}\,, \quad U \sim \text{Unif}(0,1) \tag{3.1}$$

$$\text{Age consumption}_{\text{d+1}} = \text{Age consumption}_{\text{d}} + \frac{1}{\text{RUL}} \tag{3.2}$$

The component wearing and monitoring module simulates the RUL, and the age consumption of the components increases over time. Sending the age consumption of the components to the next module,

the maintenance cycle generation module. When the maintenance tasks are finished, the RUL and age consumption of the components are changed; the table 3.2 shows the age consumption reduction of the components when the corresponding maintenance is executed. When the component has been replaced, the RUL of the components will be regenerated.
At each simulation time step, the component wearing and monitoring module sends the matrix containing the components' age consumption to the next module, the maintenance cycle generation module. In the following module, the age consumption of the components is monitored and used to generate the maintenance cycle.

3.2.3. Maintenance cycle generation

Marco's model generates the maintenance maintenance cycles following the age-based opportunistic maintenance strategy. The maintenance cycle generation module monitors the age consumption of the components. When the age consumption of the components reaches the threshold of replacement (Zone 4), the maintenance cycle is triggered, and the age consumption of the rest of the components is checked to see whether they reach the threshold of major maintenance (Zone 3) or minor maintenance (Zone 2) [61]. If so, the components needing major or minor maintenance will be added to the maintenance cycle. When the maintenance cycle is generated, the components are assumed to be repaired immediately. The maintenance execution data will be stored as model output data and sent back to the component wearing and monitoring module. The table 3.2 shows the age consumption threshold for different types of maintenance.

Maintenance type	Component age consumption (%)	Zone	Maintenance age reduction	Component's RUL	Vessel type
No maintenance	[0,50)	Zone 1	-	-	-
Minor maintenance	[50,80)	Zone 2	30%	Keep remain	CTV
Major maintenance	[80,95)	Zone 3	50%	Keep remain	FSV
Replacement	[95,100)	Zone 4	New component	Regenerate	HLV

Table 3.2: Maintenance strategy

Figure 3.2 illustrates the logistics of age-based opportunistic maintenance, and the algorithm 1 in the appendix illustrates how the maintenance cycles are generated in the simulation model under the condition-based opportunistic maintenance strategy.
The maintenance cycle generation module assumes that all the maintenance tasks in the maintenance cycle can be executed and finished immediately. The maintenance cycle containing the maintenance tasks and finish time is generated and sent back to the component wearing and monitoring module, where the age consumption and RUL of the corresponding components will be reset.

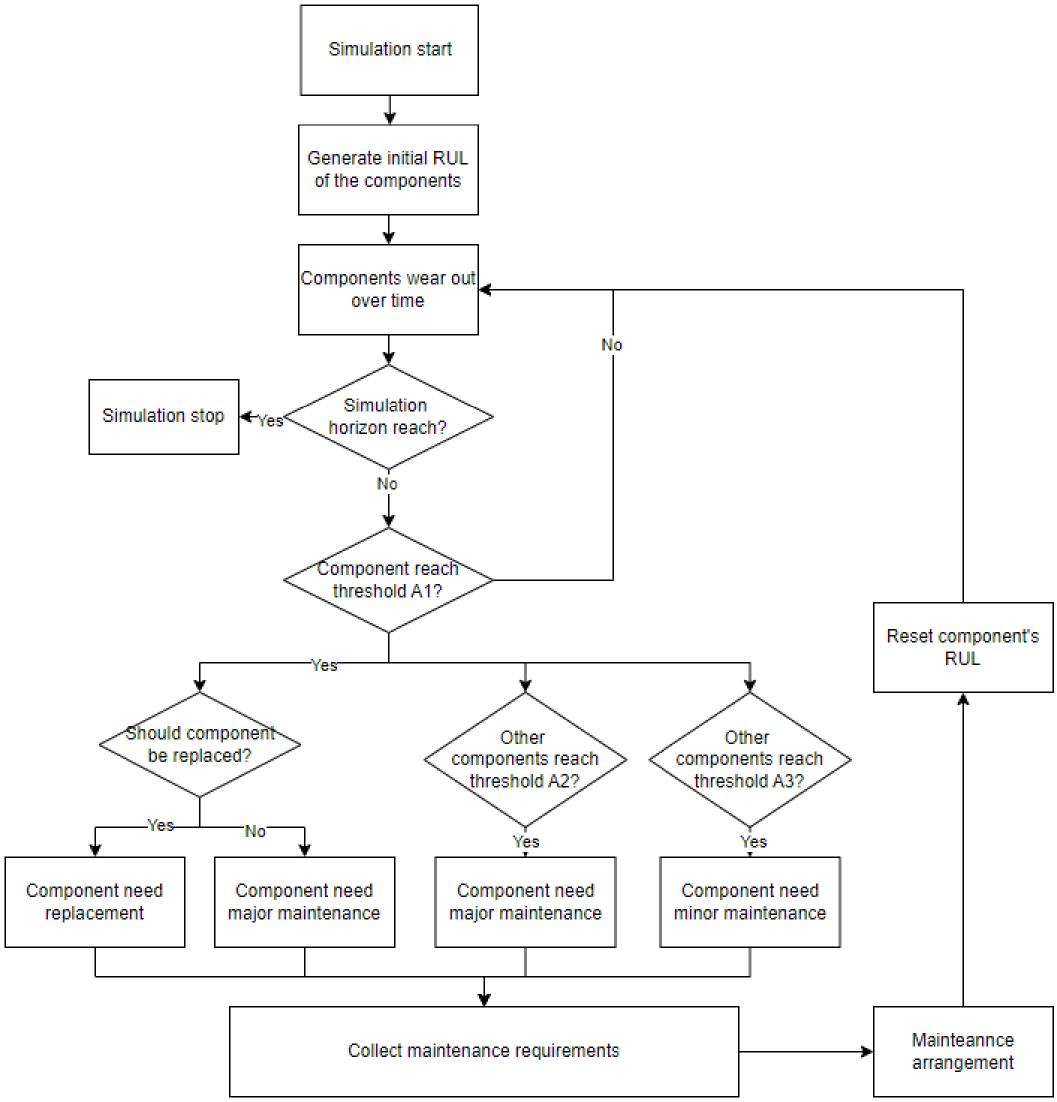

Figure 3.2: Opportunistic maintenance logistics

3.2.4. Model output data

Marco's model generates the maintenance blog of the components in the wind turbines during the whole simulation horizon. The table 3.3 shows the output data contained in the maintenance blog of Marco's model.

No	Item	Unit
1	Maintenance cycle	-
2	Turbine number	-
3	Component name	-
4	Maintenance type	-
5	Age consumption	-
6	Maintenance date	YYYY-MM-DD
7	Maintenance duration	hour

Table 3.3: Output data of Marco's model

The output [1] indicates the maintenance cycle number during the simulation horizon. The output [2,3] shows the component name and its corresponding wind turbine that needs maintenance. The output

[4,5] shows the component's maintenance type and the age consumption value when the maintenance cycle is generated. The output [6] indicates the date the maintenance cycle is generated. The output [7] represents the maintenance duration for executing the maintenance of the component.

3.3. Component wearing and vessel arrangement simulation model

Marco's model presents the components wearing, maintenance cycle generation, and maintenance execution, which simulates the components' degradation and maintenance of the offshore wind farm. However, there are still some disadvantages in Marco's model:

- **Maintenance complete immediately**: Marco's model assumes that the components will be repaired immediately when the maintenance cycle is triggered. However, technicians and equipment are required to transfer to the wind turbines to execute maintenance tasks, resulting in the maintenance tasks not being finished immediately. The finish time for the maintenance tasks will be delayed by a couple of days, which will affect the age consumption reduction of the components and further affect the generation of the following maintenance cycles. In this case, choosing the appropriate fleet and arranging the maintenance tasks for each maintenance cycle is necessary.
- **Maintenance cycle generation time**: The age-based maintenance strategy generates the maintenance cycle when one of the components reaches the age-consumption threshold of replacement. Therefore, the maintenance cycle generation time is related to the components' RUL and age consumption value, which are random numbers following the Weibull distribution. Thus, the maintenance cycles can be generated at any time of the year. However, during certain times of the year, such as winter, performing maintenance tasks is unsuitable for vessels traveling. The maintenance cycle generated in the winter period might lead to the maintenance tasks being unable to be performed, resulting in the wind turbines turning off and producing downtime costs. In this case, avoiding the maintenance tasks generated in the winter period is necessary.

Based on Marco's model's drawbacks, a component wearing and vessel arrangement simulation model was developed (which will be referred to as the current model later in this paper). Compared with Marco's model, the current model has the following improvements.

- **Maintenance tasks arrangement**: In contrast to assuming the immediate component repair. The current model incorporates the task and vessel arrangement module in the feedback loop between the maintenance cycle generation module and the component wearing & monitoring module. The maintenance cycle is generated and sent to the task and vessel arrangement module, where the maintenance task execution date and corresponding vessels for executing the maintenance will be arranged. The maintenance tasks' finish days are returned to the component wearing & monitoring module to reset the components' age consumption and RUL.
- **Introduce preventive maintenance**: An age-based preventive maintenance strategy is introduced to avoid the maintenance cycle being initiated in the winter period. The maintenance cycle containing replacement and major maintenance is created and executed before the winter period of every year. Avoiding the maintenance cycle triggered by age-based opportunistic maintenance in the winter period.
- **Generate vessel charter strategy after simulation**: Introducing the preventive maintenance strategy makes both opportunistic and preventive maintenance strategies can trigger the maintenance cycles. For the two maintenance cycles with the generation date close to each other, the two maintenance periods might overlap. To solve the overlapping problem, the vessel chartering strategy will not be created for each maintenance cycle. Instead, the vessel requirements for executing the maintenance every day are stored and sent to the vessel charter strategy generation module after the simulation stop, in which the vessel charter strategy is generated based on the initial vessel purchase amount and vessel requirement.

Figure 3.3 shows the flow chart of the current model. The two additional modules that arrange the vessel and generate vessel charter strategy based on Marco's model are highlighted.

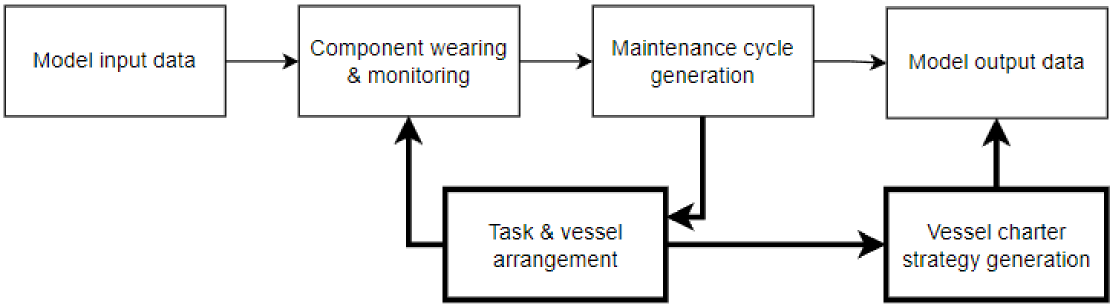

Figure 3.3: Component wearing and vessel arrangement model

3.3.1. Input data

The component wearing and vessel arrangement model involves the task scheduling for the maintenance execution and vessel arrangement for transporting the technicians to the offshore wind farm. Therefore, apart from the wind turbine data already shown in table 3.1. The extra information related to the vessel chartering, vessel deployment and vessel arrangement is also considered.

- **Vessel inputs**
  The input data that is related to the vessel chartering is shown in table 3.4

No	Item	Unit
1	Travel cost	keur
2	Fuel cost	keur/ton
3	Fuel consumption	ton/h
4	Travel speed	km/h
5	Rental cost	keur/day
6	Mobilize cost	keur
7	Overnight cost	keur/night
8	Operation cost	keur
9	Limit wave height	m/s
10	Limit wind speed	m/s
11	Maximum parallel teams	team/vessel
12	Technician capacity	person
13	Mobilize time	day
14	Initial charter length	day/period
15	Extended charter length	day/period

Table 3.4: Input data of vessel

The inputs [1] show the one-way travel cost of the vessel from the operator center to the offshore windfarm, which is calculated by the inputs [2-4], the fuel consumption of the vessel per hour, the travel speed of the vessel, fuel price, and the input [1] from table 3.5, the distance between the operation center and the wind farm. The inputs [5, 6] are the rental and mobilization costs of the vessel. When a vessel is chartered, the mobilization cost is calculated once, while the rental cost varies based on the number of days the vessel is chartered. The input [7] represents the vessel's overnight stay cost. When the vessel needs to be deployed for many days, it can stay overnight at the offshore wind farm to reduce travel costs between the wind farm and the operation center. The input [8] is the operation cost of the vessel; when the vessel is deployed to execute the maintenance, the operation cost is calculated. The inputs [9, 10] are the vessel's weather restrictions. When the weather condition of the specific hour is higher than the vessel's wind speed and wave height, the vessel is considered non-operational at that hour, and the maintenance execution will be suspended and continue until the next operational hour. The input [11, 12] shows the maximum parallel team the vessel can carry and the vessel's capacity to carry technicians between the operation center and the offshore wind farm. The input [13–15] shows the vessel's mobilization time and day limit for each charter period. The vessel must return to the ship owner after the charter period ends and move from the ship owner when the next charter period starts. In this case, the time gap between the two charter periods must be greater than the vessel's mobilization time. The vessel charter begins with an initial charter length and can be extended after the initial charter period.

- **Wind farm inputs**
  The inputs that are related to the maintenance execution of the wind farm are shown in table 3.5

No	Item	Unit
1	OWF distance	km
2	WT downtime cost	keur / day
3	Shift start	hh
4	Shift end	hh
5	Technician requirement	person
6	Minor maintenance team requirement	team
7	Major maintenance team requirement	team
8	Replacement team requirement	team

Table 3.5: Input data of wind farm

The input [1] shows the distance between the OWF and the operation center. The input [2] shows the wind turbine's maintenance downtime cost. The inputs [3, 4] indicate the working period of the day for the maintenance shift. The inputs [5-8] show the technician requirements and the repair team needed for component maintenance.

3.3.2. Component wearing & monitoring

Compare with the component wearing & monitoring module in Marco's model. In the component wearing and vessel arrangement simulation. The matrices represent the estimated failure, replacement, major maintenance, and minor maintenance days for the components established. The estimated maintenance days of the components are calculated by the age consumption threshold and the RUL of the components. The equation 3.3 to 3.6 shows the computations for the estimated. The estimated maintenance days refer to the day numbers that components run into the corresponding zone shown in table 3.2.

$$EFD_{component} = day + (1 - Age_{component}) * RUL_{component} \tag{3.3}$$

$$ERD_{component} = day + (A1 - Age_{component}) * RUL_{component} \tag{3.4}$$

$$EMD_{component} = day + (A2 - Age_{component}) * RUL_{component} \tag{3.5}$$

$$EMIND_{component} = day + (A3 - Age_{component}) * RUL_{component} \tag{3.6}$$

$A1$: Age consumption threshold of component runs into Zone 4, which is 0.95 in table 3.2

$A2$: Age consumption threshold of component runs into Zone 4, which is 0.8 in table 3.2

$A3$: Age consumption threshold of component runs into Zone 4, which is 0.5 in table 3.2

3.3.3. Maintenance cycle generation

The maintenance cycle generation module generates the maintenance cycles that must be sent into the task & vessel arrangement module, apart from the aged-based opportunistic maintenance strategy used in Marco's model. The aged-based preventive maintenance strategy is combined with the age-based opportunistic maintenance strategy.

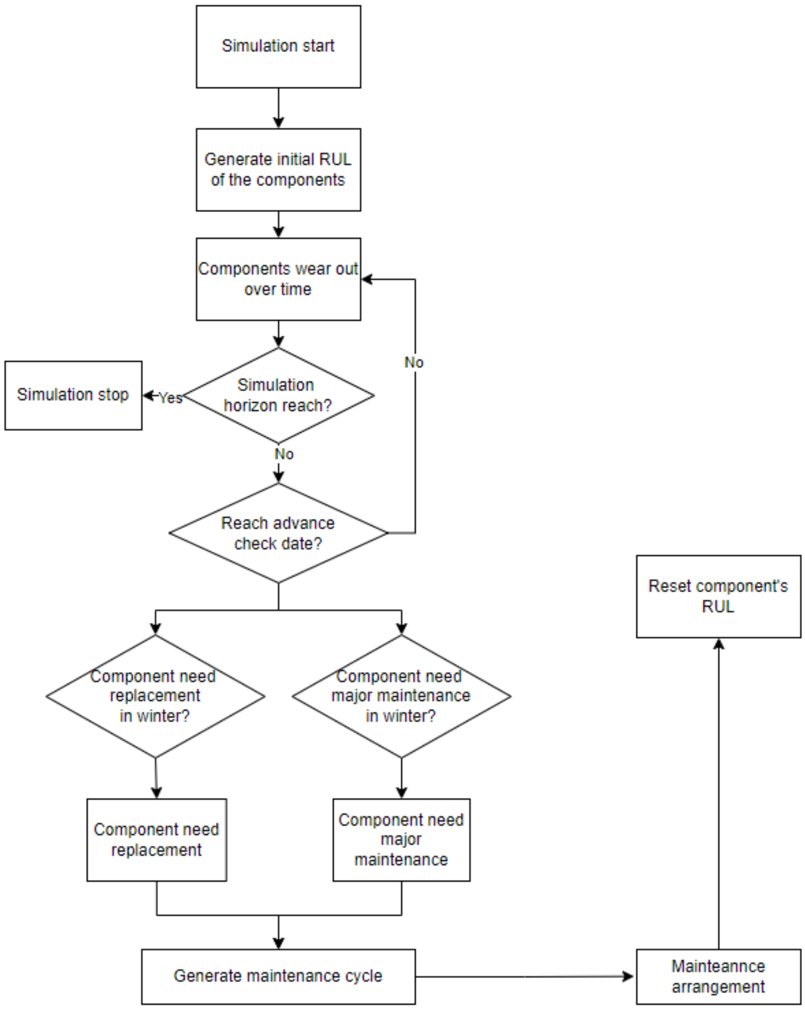

Figure 3.4: Age-based preventive maintenance logistics

The O&M of the offshore wind farm is highly related to the area's weather conditions. Weather conditions such as wave heights and wind speed significantly affect maintenance execution by limiting the accessibility of vessels transporting the technician and equipment from the operation center [11]. Maintenance on offshore wind farms cannot occur throughout the year. The severe winter weather may make it impossible for the technicians to perform the necessary maintenance [52]. Suppose the failure happens during the winter season. In that case, it is possible that technicians will not be able to access the wind turbines for repairs, leading to a prolonged period of downtime and significant revenue losses.

To prevent failure during the winter season, A preventive maintenance strategy is introduced to combine with the age-based opportunistic maintenance strategy. The 12 months of the year are divided into the winter period and the non-winter period based on the suitability of the season. During the winter period, the vessels are difficult to travel, and a penalty will be applied if the vessels are still deployed. Under this maintenance strategy, a preventive component inspection is executed before the start of the winter period, which is a couple of months before. The monitoring system checks the RUL and estimates the components' failure dates. Suppose the components fail during the winter when maintenance is hard to execute. If possible, the maintenance requirement is generated, and maintenance tasks will be carried out before the winter. The winter period starts in November and ends in March of next year, and the components' preventive inspection will take place in September since its monthly production is the lowest [62]. Figure 3.4 illustrates the logistics of preventive maintenance, and the algorithm 2 in the appendix illustrates how the maintenance cycles are generated in the simulation model under the preventive maintenance strategy.

The age-based opportunistic and preventive maintenance strategies run parallel in the maintenance cycle generation module. Combining the two maintenance strategies, the overall maintenance logistics can be described in the appendix in the figure A.1.

3.3.4. Task & vessel arrangement

The maintenance cycle generation module generates the maintenance cycle, which is then sent to the task & vessel arrangement module for arranging the vessel and maintenance tasks execution time. The task & vessel arrangement module arranges the maintenance task execution and vessel deployment based on the vessel's capacity, sea-keeping ability, weather conditions, task requirements, and maintenance cost. Each maintenance task's start and finish times are arranged and transferred to the component wearing and monitoring module as the feedback loop. The maintenance task execution and vessel deployment data are stored as the model output data.

The combination of the age-based opportunistic maintenance strategy and the age-based preventive maintenance strategy overlaps the problem of two maintenance cycles. The preventive check of the components takes place in September, which means the maintenance period of the maintenance cycle triggered by the age-based preventive maintenance strategy covers the time until November, while the rest time of September and October. There is still a chance that the age-based opportunistic maintenance strategy will trigger the maintenance cycle. In this case, the two maintenance cycles are overlapped with each other. Since the vessel arrangement is for a single maintenance cycle, when two maintenance cycles overlap, a situation occurs in which a vessel in one of the maintenance cycles parks in the harbour when it is idle and does not perform the tasks in the other maintenance cycle. More vessels are hired to perform the maintenance tasks.

To prevent the situation in which maintenance cycles overlap, many vessels are chartered for a short period and then rapidly become empty again. At each maintenance, the vessel charter strategy would not be determined. The task & vessel arrangement module generates the vessel requirement each day, giving the vessel requirement to the vessel charter strategy generation module, where the vessel charter strategy will be generated based on the vessel requirement. To prevent significant variations in the daily vessel requirement, resulting in an excessive number of vessels being chartered. A vessel arrangement closeness based on the Euclidean distance calculation method from the FLP (Facility Location Problem) is introduced to evaluate the closeness of the vessel arrangement on each day.

The FLP (facility location problem) is a classical optimization problem in spatial planning that focuses on selecting the optimal location for the facilities to minimize cost and maximize service efficiency. The problem entails determining the location of facilities, such as warehouses or factories, to meet client demands while minimizing total costs.

According to this concept, the optimizer arranges the vessels and tasks for the current maintenance period. The vessels arranged during the previous maintenance cycle are considered the demanding points. The term facility refers to the vessels that must be arranged during this maintenance period. The optimizer arranges the vessels as close to the existing vessel arrangement. Figure 3.5 shows a small example of a 2-dimensional area. This figure presents the process of finding facilities for existing demand points, converting the facilities into demand points, and then finding new facilities. The locations of the facilities are chosen based on minimizing the total Euclidean distance of the facilities and demanding points. The equation 3.7 shows the calculation of Euclidean distance between each point [63].

$$\text{Distance} = \sum d_{ij} = \sum \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2} \tag{3.7}$$

d_{ij} : Euclidean distance between point i and j
X_i, X_j : Coordinates of point i and j on the x-axis
Y_i, Y_j : Coordinates of point i and j on the Y-axis

As shown in figure 3.5, the demand points are generated and shown in step 1, while in step 2, the facilities that fulfil the requirement of minimizing the distance towards the demand points are generated and presented. In step 3, the facilities generated in step 2 are transferred into new demand points and combined with the previous demand points generated in step 1. The new facilities are then generated in step 4.

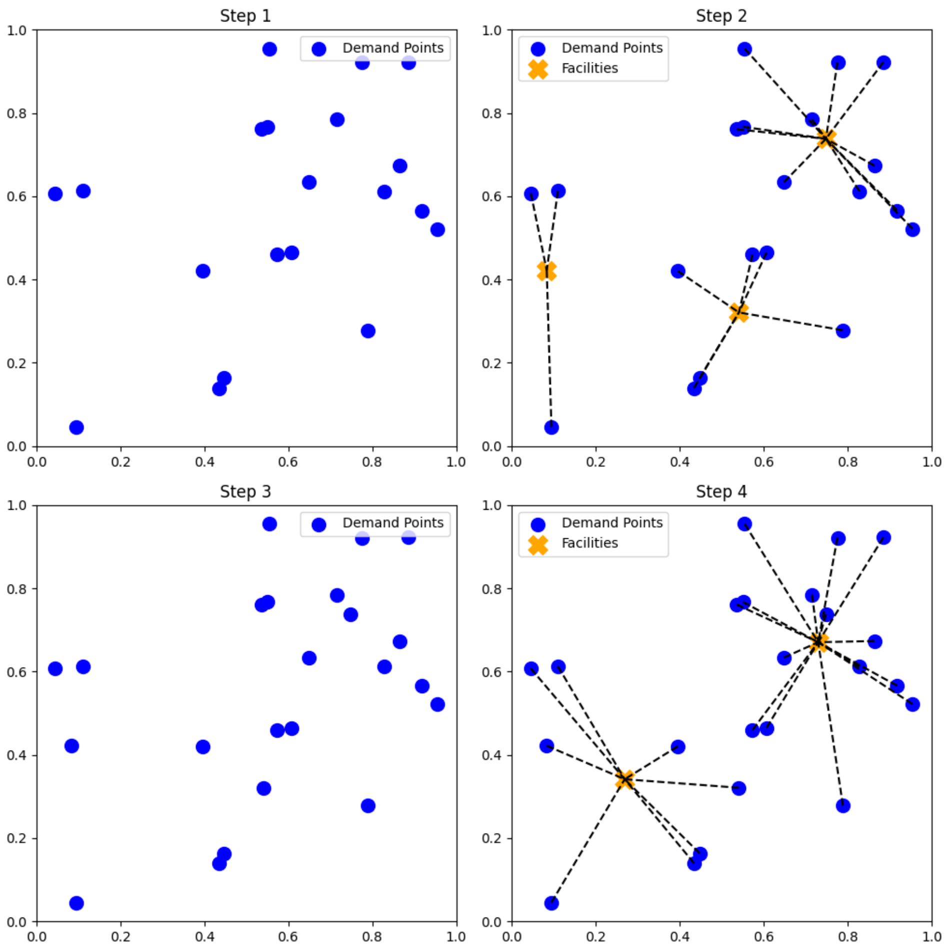

Figure 3.5: 2-D Facility location problem example

Convert the 2-D plane to a 1-D line. As shown in figure 3.6. The demand points are the existing vessel rental requirement, and the facilities are the new vessel rental arrangement. The X-axis in the original FLP problems is considered the day number during the simulation. The Y axis in original FLP problems is the vessel and its corresponding number. When arranging the new vessels at each maintenance cycle, the closeness of the vessel arrangement is considered in the objective function, minimizing the closeness of the vessel arrangement. Therefore, the vessel arrangements are more compact with each other, resulting in increased utilization of the vessels and reduced charter and mobilization costs brought by unnecessary additional vessel charter contracts. The calculation of the vessel arrangement closeness (VAC) is shown in equation 3.8:

$$\text{VAC} = \sum_{d \in D_g} \sqrt{(d * U_{ijd} - d * R_{ijd})^2} \tag{3.8}$$

d : Day number during the simulation

D_g : Day numbers of the maintenance period

U_{ijd} : Existed vessel arrangement, a binary value that represent whether the vessel i number j is hired or not on specific day d

R_{ijd} : New vessel arrangement, a binary value that represent whether the vessel i number j is hired or not on specific day d

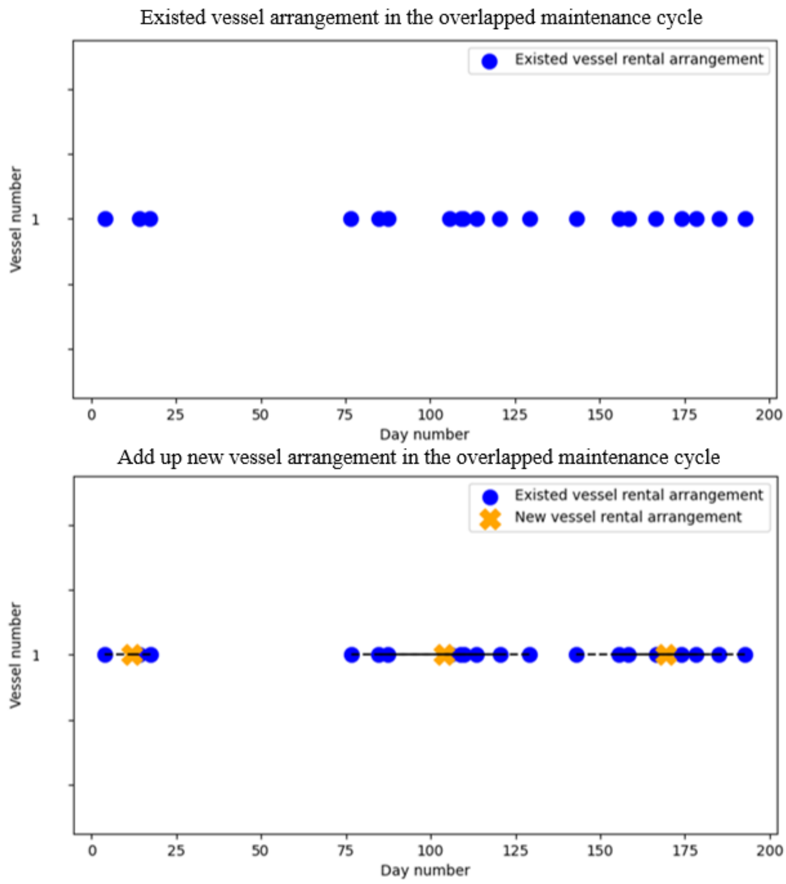

Figure 3.6: Arrange new vessel in overlapped maintenance cycle

3.3.5. Vessel charter strategy generation

The task & vessel arrangement module arranges the vessels individually to prevent overlap or proximity to each maintenance cycle, which could result in unnecessary mobilization costs for vessel chartering. After arranging all the vessels for maintenance, the vessel charter strategy generation module will generate the vessel charter strategy. For the overlapping and close maintenance cycles, the vessel charter strategy generation module extends the individual vessel charter period to cover these maintenance cycles, reducing unnecessary costs.

After generating the vessel arrangement for each maintenance cycle and deducting the initial purchase amount, chartering fulfils the remaining vessel requirements. In this case, the matrix of vessel rental requirements throughout the whole simulation horizon is generated. Agglomerative clustering will be used to group the vessel rental arrangement into different clusters based on the day number of the vessel rental requirement. After the classification, each cluster will become a rental period for the vessel.

Agglomerative clustering is a hierarchical clustering method that builds nested clusters from the bottom. Agglomerative clustering involves merging the most similar clusters at each step until a specific number of clusters is achieved. Agglomerative clustering involves different linkage methods, which determine how the distance between the clusters is calculated during the process. Among various linkage methods, the ward linkage method is particularly effective for producing compact and spherical clusters [64]. The vessel rental strategy, which does not have a specific number of clusters, aims to minimize the total vessel charter cost. In this scenario, the ward linkage method is appropriate.

Using the data from figure 3.6, the vessel rental arrangements are turned into data points that indicate the days the vessels must be chartered. The vessel charter requirement is turned into different charter periods by implementing the clustering algorithm. The process of dividing the demand for chartering into clusters is based on minimizing the total charter cost. The result of the example is shown in figure 3.7.

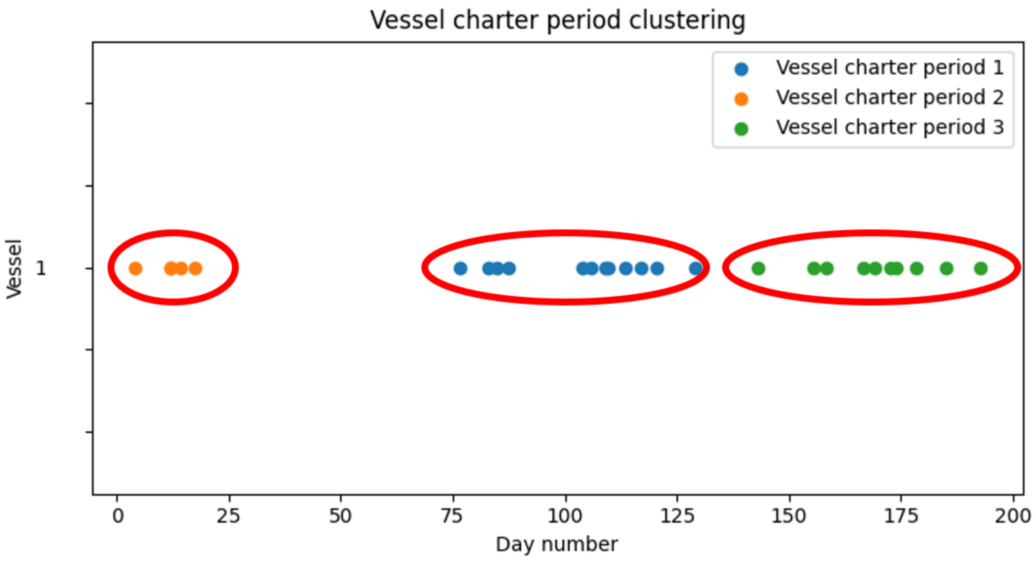

Figure 3.7: Clustering the vessel charter periods

3.3.6. Output data

The output data of the current model considers the maintenance blog of the whole simulation horizon, the maintenance cycle distribution, and the vessel charter strategy under different initial purchase amounts. Table 3.6 shows the output data from the current model.

Maintenance blog		
No	Item	Unit
1	maintenance cycle	-
2	First day	-
3	Last day	-
4	turbine	-
5	component	-
6	type	-
7	age consumption	-
8	maintenance require time	YYYY-MM-DD
9	duration	hour
10	maintenance strategy	-
11	repair cost	keur
12	maintenance start day	YYYY-MM-DD
13	maintenance finish day	YYYY-MM-DD
Vessel charter strategy		
No	Item	Unit
14	Vessel type	-
15	Vessel number	-
16	Charter start time	YYYY-MM-DD
17	Charter end time	YYYY-MM-DD
18	Charter period	day
19	Rental cost	keur
20	Mobilize cost	keur
21	Vessel cost	keur
22	Initial CTV purchase amount	-
23	Initial FSV purchase amount	-

Table 3.6: Output data of current model

The output [1] refers to the maintenance cycle number during the whole simulation, which is the same as the output [1] in table 3.3. The output [2,3] indicates the day number of the beginning and end of the maintenance cycle. The output [4-9] shows the turbine number, component name, maintenance type, and age consumption when the maintenance cycle is generated; the maintenance cycle generates time and maintenance duration for each maintenance task. The output [4-9] corresponds to the output [2-7] in table 3.3. The output [10] indicates that the maintenance cycle is triggered under the age-based opportunistic or age-based preventive maintenance strategy. The output [11] refers to the repair cost of the component, a fixed cost related to the component's name and maintenance type. The output [12,13] is the maintenance start day and maintenance finish day of the maintenance tasks.
In the vessel charter strategy part, the output [14,15] refers to the vessel type and its corresponding number that needs to be chartered. The output [16-18] represents the charter start date and termination date of the vessel and the length of the charter period of the vessel. The output [19,20] shows the vessel rental and mobilization costs when chartering the vessel. Moreover, the output [21] vessel cost refers to the sum of vessel charter and mobilization costs. The output [22.23] shows the initial purchase amount of the vessels.

3.4. Summary

This chapter presents Marco's model and current model which developed based on Marco's model. The current model combines the age-based opportunistic maintenance strategy and age-based preventive maintenance strategy to generate maintenance cycles. They aim to prevent opportunistic maintenance strategy generating maintenance cycles in the winter period. To solve the problem of two maintenance cycles triggered by two different maintenance strategies overlapping with each other, vessel arrangement closeness is introduced to make the vessel arrangements close to each other in two maintenance cycles overlapping maintenance periods. After the vessel arrangement is generated, the vessel charter strategy under different initial purchase amounts is generated. Therefore, the repeat chartering of vessels for different maintenance cycles can be eliminated.

4

Mathematical model

The previous chapter introduced the structure of the current model, which is used to simulate the operation and maintenance of the offshore wind farm. The most significant change between Marco's model and the current model is a task & vessel arrangement module, which receives the maintenance tasks from the maintenance cycle generation module, arranging the maintenance tasks execution date and corresponding vessel deployment. In general, the task & vessel arrangement module solves a multi-objective arrangement problem that includes task and vehicle scheduling. The mixed integer linear programming (MILP) is applied to acquire the exact solution. Firstly, the initial vessel and task arrangement optimization model that is accurate to the number of each single vessel is present. Next, the improved model for arranging the tasks and vessels with the adjustment from the initial model is presented. Finally, the solver used to solve the MILP problem is given.

4.1. Initial Vessel and task arrangement model

The mathematical model is formulated for the vessel and task arrangement of the maintenance process. The mathematical model is formulated for the vessel and task arrangement of the maintenance execution. The model specifies the start and finish dates of the maintenance cycle, each maintenance task, and the vessel arrangement required for execution. Using a mixed interlinear programming approach, the optimization model formulates a vehicle scheduling and task scheduling problem for a fixed period. The task and vessel arrangement model is divided into three distinct parts. The first part identifies the vessels purchased or chartered and decides whether the vessel needs a charter during the maintenance period. The second part is the vessel arrangement, which specifies the vessels dispatched to the wind farm for maintenance. The third part is dedicated to task scheduling. This part arranges the days on which maintenance tasks will be executed. The following section presents and explains the mathematical model of the initial vessel and its arrangement.

4.1.1. Sets

A: Wind Turbine Sets
I: All vessel types
J_b: The number set of purchased vessel
J_r: The number set of chartered vessel
K: All maintenance task types
C: Turbine's components set
L: Load type for maintenance
T_{kc}: Set of maintenance tasks of component c and work type k, $c \in C, k \in K$
G: Maintenance requirement groups set
D: Simulation horizon of the model
D_g: Maintenance period of each maintenance cycle, $g \in G$
H: Hours set of a day

4.1.2. Parameters

$Cost_i^{Rent}$: Charter cost for vessel type i , $i \in I$
$Cost_i^{Travel}$: Travel cost of vessel type i, $i \in I$
$Cost_t^{Delay}$: Delay cost of maintenance task t, $t \in T_{kc}$
$Cost_i^{Mobilized}$: Mobilization cost of vessel type i, $i \in I$
$Cost_{td}^{Pe}$: Penalty cost of task t execute maintenance in the winter period on day d, $t \in T_{kc}, d \in D$
$Duration_t$: Duration of maintenance task t, $t \in T_{kc}$
$Capa_{tl}^{Require}$: Capacity require for maintenance task t and load type l, $t \in T_{kc}, l \in L$
$Capa_{il}^{Provide}$: Capacity that vessel type i can provide for load type l, $i \in I, l \in L$
$VA_i^{limitation}$: Vessel amount limitation for type i, $i \in I$
$D_g^{Initial}$: Maintenance require day of group g, $g \in G$
A_{ih}: Available working hours h of vessel type i of the day, $h \in H, \in I$
U_{ijd}: Existing vessel rental arrangement $i \in I, j \in J_b \cup J_r, d \in D$
D_i^{stay}: Maximum stay offshore time of the vessel, $i \in I$

4.1.3. Decision variables

VA_i^{buy}: Vessel type i initial purchase amount$i \in I$

SA_{td}: Total amount of vessels that have been used for task t on day d, $d \in D_g, t \in T_{kc}$

$$R_{ijd} = \begin{cases} 1, \text{if vessel type i number j is rented on day d } i \in I, j \in J, d \in D_g, \\ 0, \text{otherwise} \end{cases}$$

$$Rent_{ij} = \begin{cases} 1, \text{if vessel type i number j is rented in this group, } i \in I, j \in J \\ 0, \text{otherwise} \end{cases}$$

F_t: First day of the maintenance $t \in T_{kc}$

L_t: Last day of the maintenance $t \in T_{kc}$

VAC_{ij}:Vessel arrangement closeness of vessel type i number j. $i \in I, j \in J_b \cup J_r$

4.1.4. Auxiliary variables

Arranging the execution of maintenance tasks is not an optimization goal since it is out of the scope of the research. However, scheduling vessels to perform the corresponding tasks each day can affect vessel chartering and the vessel charter strategy. Therefore, the auxiliary variables that schedule the vessels to perform the tasks are necessary.

$$\alpha_{ijtd} = \begin{cases} 1, \text{if vessel type i number j deployed for task t on day d, } i \in I, j \in J \\ 0, \text{otherwise} \end{cases}$$

$$\beta_{td} = \begin{cases} 1, \text{if maintenance activities t is scheduled on day d, } t \in T_{kc}, d \in D_g \\ 0, \text{otherwise} \end{cases}$$

$$\lambda_{ijd} = \begin{cases} 1, \text{if vessel type i number j is deployed on day d to execute the maintenance } i \in I, j \in J, d \in D_g \\ 0, \text{otherwise} \end{cases}$$

$$S_{ijd} = \begin{cases} 1, \text{if vessel type i number j stay overnight on day d, } i \in I, j \in J \\ 0, \text{otherwise} \end{cases}$$

h_{td}: Hours spent on executing task t on day d, $t \in T_{kc}, d \in D_g$

4.1.5. Objective Function

The model has two distinct objective functions based on the type of maintenance cycle. Both aim to minimize the overall cost of the entire maintenance cycle. The difference between the two objective functions comes from the definition of the delay cost endured during maintenance. The cost function for the opportunistic maintenance cycle is displayed as follows:

Objective function for opportunistic maintenance cycle

$$\min Z = \sum_{i \in I} \sum_{j \in J_r} Cost_i^{Rent} * (\sum_{d \in D_g} R_{ijd}) \tag{4.1}$$

$$+ \sum_{i \in I} Cost_i^{Travel} * (\sum_{j \in J_b \cup J_r} \sum_{d \in D_g} \lambda_{ijd} - \sum_{j \in J_b \cup J_r} \sum_{d \in D_g} S_{ijd}) \tag{4.2}$$

$$+ \sum_{i \in I} (Cost_i^{night} * \sum_{j \in J_b \cup J_r} \sum_{d \in D_g} S_{ijd}) \tag{4.3}$$

$$+ \sum_{i \in I} (Cost_i^{Mobilized} * \sum_{j \in J_r} Rent_{ij}) \tag{4.4}$$

$$+ \sum_{t \in T_{kc}} (\beta_{td} * Cost_t^{Delay}) * (d - D_g^{Initial}), d \in D_g, g \in G, d > D_g^{Initial} \tag{4.5}$$

$$+ \sum_{t \in T_{kc}} (L_t - F_t) * Cost_t^{downtime} \tag{4.6}$$

$$+ \sum_{t \in T_{kc}} \sum_{d \in D_g} Cost_{td}^{Pe} * \beta_{td} \tag{4.7}$$

$$+ \sum_{i \in I} \sum_{j \in Jb \cup J_b} VAC_{ij} \tag{4.8}$$

The opportunistic maintenance cycle's objective function is to reduce the overall cost of executing maintenance tasks. The cost of chartering the vessels during the maintenance period is reflected in the vessel charter cost 4.1, which is calculated by the sum up of the daily rental cost of the vessels and the number of days that the vessels are chartered. The equation 4.2 accounts for the transportation costs incurred by the vessels travelling between the offshore wind farm and the operation center. The travel cost is calculated by vessel travel cost per travel times the vessel travel amount. The vessel travel amount each day is the number of vessels deployed to the offshore wind farm minus the number of vessels that stay overnight in the offshore wind farm. The equation 4.3 considers the scenario when the vessel can stay at the offshore wind farm overnight and do maintenance work the following day, eliminating the need for travel between the offshore wind farm and the operation center. The equation 4.4 refers to the mobilization cost of the vessel, which is calculated by the number of vessels that have been chartered in the maintenance period. The equation 4.5 computes the cost associated with delays in opportunistic maintenance.

The components require immediate maintenance regarding the maintenance cycle generated by an opportunistic maintenance strategy. In this scenario, the delay cost is computed to ensure the maintenance tasks are scheduled as soon as possible. The equation 4.7 aims to assign penalties to maintenance jobs organized in the winter period, which is not appropriate for maintenance. The penalty cost is related to the number of tasks scheduled in the winter period. The equation 4.8 refers to the vessel arrangement closeness between the current vessel rental arrangement in the current maintenance cycle and previous vessel rental arrangements from the previous maintenance cycles. Its purpose is to prevent the scenario where many vessels are rented simultaneously and quickly become idle.

Objective function for preventive maintenance cycle

$$\min Z = \sum_{i \in I} \sum_{j \in J_r} Cost_i^{Rent} * (\sum_{d \in D_g} R_{ijd}) \tag{4.9}$$

$$+ \sum_{i \in I} Cost_i^{Travel} * (\sum_{j \in J_b \cup J_r} \sum_{d \in D_g} \lambda_{ijd} - \sum_{j \in J_b \cup J_r} \sum_{d \in D_g} S_{ijd}) \tag{4.10}$$

$$+ \sum_{i \in I} (Cost_i^{night} * \sum_{j \in J_b \cup J_r} \sum_{d \in D_g} S_{ijd}) \tag{4.11}$$

$$+ \sum_{i \in I} (Cost_i^{Mobilized} * \sum_{j \in J_r} Rent_{ij}) \tag{4.12}$$

$$+ \sum_{t \in T_{kc}} (-\beta_{td}) * (d - D_g^{Initial}), d \in D_g, g \in G \tag{4.13}$$

$$+ \sum_{t \in T_{kc}} (L_t - F_t) * Cost_t^{downtime} \tag{4.14}$$

$$+ \sum_{t \in T_{kc}} \sum_{d \in D_g} Cost_{td}^{Pe} * \beta_{td} \tag{4.15}$$

$$+ \sum_{i \in I} \sum_{j \in Jb \cup J_b} VAC_{ij} \tag{4.16}$$

The preventative maintenance cycle's objective function is largely similar to the opportunistic maintenance cycle's. The equations from 4.9 to 4.12 and from 4.14 to 4.16 remain unchanged compared to the equations from 4.1 to 4.4 and from 4.6 to 4.8. The only distinction is in the calculation of the delay expense. The estimated date for major maintenance or replacement of components in preventative maintenance occurs far after the maintenance cycle has been completed. This implies that the maintenance tasks are performed in advance before any components reach the threshold that triggers the need for maintenance. In this case, it is necessary to repair the components as late as possible. In such a case, a negative delay cost is implemented to move the maintenance chores as far back as feasible.

4.1.6. Auxiliary equations

Equations that express relationships between variables are not in the objective function and do not constrain variables as constraints. Therefore, these equations are defined as auxiliary equations.

$$VAC_{ij} = \sum_{i \in I} \sum_{j \in Jb \cup J_b} \sqrt{(\sum_{d \in D_g} [(d * R_{ijd}) - (d * U_{ijd})]^2)} \tag{4.17}$$

$$VA_i^{buy} = \sum_{j \in J_b} R_{ijd}, i \in I, d \in D \tag{4.18}$$

The equation 4.17 illustrates how the vessel arrangement closeness is calculated. The equation 4.18 indicates that if the vessel is purchased at the beginning of the simulation, it can be considered already chartered and used for the operation.

4.1.7. Constraints

Constraints of vessel acquisition

$$VA_i^{buy} \geq 0, i \in I \tag{4.19}$$

$$Rent_{ij} = 1, \text{if} \sum_{d \in D_g} R_{ijd} > 0, i \in I, j \in J_r \tag{4.20}$$

$$Rent_{ij} = 0, \text{if} \sum_{d \in D_g} R_{ijd} = 0, i \in I, j \in J_r \tag{4.21}$$

$$\sum_{j \in J_b \cup J_r} (R_{ijd} + U_{ijd}) \leq VA_i^{limitation}, i \in I, j \in J, d \in D_g \tag{4.22}$$

$$R_{ijd} + U_{ijd} \leq 1, i \in I, j \in J, d \in D_g \tag{4.23}$$

$$R_{ijd} \in \{0, 1\}, i \in I, j \in J_r \tag{4.24}$$

$$Rent_{ij} \in \{0, 1\}, i \in I, j \in J_r \tag{4.25}$$

Constraint 4.19 restricts that the vessel purchase amount should be a positive value. The constraints 4.20 and 4.21 indicate whether the chartered vessel is used during the maintenance period. The constraint 4.22 limits the vessel amount of each day should not exceed the maximum capacity of the corresponding vessel of the port. The constraint 4.23 limits that the vessel cannot be arranged on the same day for different maintenance cycles. The constraint 4.24 and 4.25 determine the domains of the decision variables R_{ijd} and $Rent_{ij}$.

Vessel arrange constraint

$$\sum_{d \in D_g} \beta_{td} \geq \frac{Duration_t}{(T^{end} - T^{start})}, t \in T_{kc} \tag{4.26}$$

$$\sum_{i \in I, j \in J} \lambda_{ijd} * Capa_{il}^{Provide} \geq \sum_{t \in T_{kc}} \beta_{td} * Capa_{tl}, , d \in D_g, l \in L \tag{4.27}$$

$$S_{ijd} \leq \lambda_{ijd} \tag{4.28}$$

$$S_{ijd} \leq \lambda_{ij(d+1)} \tag{4.29}$$

$$S_{ijd} = 0, i = 0 \tag{4.30}$$

$$\sum_{d=d}^{d=d+D_i^{stay}} S_{ijd} \leq D_i^{stay} \tag{4.31}$$

$$\beta_{td} \in \{0, 1\}\, t \in T_{kc}, d \in D_g \tag{4.32}$$

$$\lambda_{ijd} \in \{0, 1\}, i \in I, j \in J, d \in D_g, t \in T_{kc} \tag{4.33}$$

Constraint 4.26 imposes a low boundary on the total amount of days allocated to each maintenance task. The constraint 4.27 indicates that the capacity of the vessel dispatched each day must exceed the capacity needed to carry out the maintenance task on that day. The constraints 4.28 and 4.29 state that if the vessel is required to stay overnight at the offshore wind farm, it must be deployed on both the current day and the next day. The CTVs cannot stay overnight at the offshore wind farm. Therefore, the constraint 4.30 sets a limitation on the ability of CTVs to stay overnight. The constraints 4.32 and 4.33 define the ranges within which the decision variables β_{td} and λ_{ijd} can take values.

Task schedule constraint

$$\sum_{d \in D_g} h_{td} \geq Duration_t, t \in T_{kc} \tag{4.34}$$

$$h_{td} \leq \sum_{h \in H} \left[\sum_{i \in I} \sum_{j \in J_b \cup J_r} \alpha_{ijtd} * W_{idh} * A_h \right], t \in T_{kc}, d \in D_g, h \in H \tag{4.35}$$

$$m * \lambda_{ijd} \geq \sum_{t \in T_{kc}} \alpha_{ijtd}, i \in I, j \in J_b \cup J_r, d \in D_g \tag{4.36}$$

$$m * \beta_{td} \geq h_{td}, t \in T_{kc}, d \in D_g \tag{4.37}$$

$$L_t \geq D_g^{Initial} \tag{4.38}$$

$$L_t \geq d * \beta_{td} \tag{4.39}$$

$$F_t \leq d * \beta_{td} + m * (1 - \beta_{td}) \tag{4.40}$$

$$\alpha_{ijt} \in \{0, 1\}, i \in I, j \in J_b \cup J_r \tag{4.41}$$

$$h_{td} \geq 0, t \in T_{kc}, d \in D_g \tag{4.42}$$

The constraint 4.34 states that the total hours allocated to each maintenance task must exceed the required duration for the given task. The constraint 4.35 indicates that the hours spent on the task each day should not exceed the available working hours of the vessel under the weather conditions and maintenance shift of the corresponding day. The constraint 4.36 indicates that if the vessel is deployed for executing the maintenance tasks, then the vessel must be deployed to the offshore wind farm on that day. The constraint 4.37 states that the maintenance execution hour can only be calculated for the task that has been arranged on that day. The constraint 4.38 and 4.39 indicate that the maintenance task finish day number should be larger than the day number that the maintenance task is generated and the day number that the task has maintenance execution. The constraint 4.40 indicates that the maintenance task starting day number should be smaller than any day that has maintenance execution. The constraints 4.41 to 4.42 specify the bounds for the decision variables α_{ijt} and h_{td}.

4.2. Improved vessel and task arrangement model

The initial vessel and task arrangement model has already provided the ability to arrange the task and vessel for executing the maintenance tasks. The model also offers methods for organizing the tasks and vessels. However, some drawbacks prevent the model from performing as expected. The following problems are from the initial model:

- **Significant computational demand**: The initial model offers a detailed level of precision, encompassing the scheduling of each vessel daily as well as the arrangement for chartering the vessels. The details of arranging each single vessel lead to a significant computational burden throughout the optimization procedure. The optimization process involves a range of 80,000 to 160,000 binary decision variables. This results in the optimizer's inability to generate an initial and realistic solution within a predetermined time frame. The vessel and task arrangement transform into an insolvable model. The initial model has variables that involve multiple dimensions. The variable α_{ijtd} is four-dimensional. The extra dimension of the variables will lead to a huge increment in the model's complexity.

- **Delay cost affect solving process**: the delay cost for maintenance cycles created by preventive and opportunistic maintenance strategies is different. Cycles created by preventive maintenance strategies have a negative delay cost, while periods created by opportunistic maintenance strategies have a positive delay cost. The initial goal of establishing a delay cost is to ensure that the maintenance date is moved as far as possible to maximize the component's remaining life under the same vessel charter strategy. A high value on delay cost will increase the trend of moving the maintenance forward in the maintenance cycle triggered by an age-based opportunistic maintenance strategy or backward in the maintenance cycle triggered by an age-based preventive maintenance strategy. A small value on delay cost will turn the model from integer linear programming to normal linear programming; introducing continuous parameters will significantly increase the computation time. Making the vessel more challenging to solve.

To improve the computation speed and eliminate the effect of the delay cost. The improved vessel and task arrangement model has been developed. The notable change in the improved model is eliminating the vessel number set. Instead, the primary focus is on vessel quantity. In the initial vessel and task arrangement model, binary variables that represent the status of a specific vessel are summed up together in the constraints. The improved vessel and task arrangement model uses integer variables to represent the sum of the binary variables. As a result, the model's redundancy is reduced, and the computation speed is improved. The improved model also eliminates the delay cost from the initial vessel and task arrangement model, thereby preventing the optimization model from encountering a non-integer in the objective function. The consideration of multiple vessels being deployed to execute a single maintenance task is also eliminated because it increases the computational demand. The improved model is shown below:

4.2.1. Sets

I: Vessel Types
K: Work types
C: Turbine's components set
L: Load type for maintenance
T_{kc}: Set of maintenance tasks of component c and work type k, $c \in C, k \in K$
G: Groups of maintenance requirements
D: Simulation horizon of the program
D_g: Maintenance window of each group, $g \in G$
H: Hours of a day

4.2.2. Parameters

$Cost_i^{Rent}$: Charter cost for vessel type i , $i \in I$
$Cost_i^{Travel}$: Travel cost of vessel type i, $i \in I$
$Cost_t^{Downtime}$: Downtime cost of maintenance task t, $t \in T_{kc}$
$Cost_i^{Mobilized}$: Mobilization cost of vessel type i, $i \in I$
$Cost_{td}^{Pe}$: Penalty cost of task t out of optimal maintenance period on day d, $t \in T_{kc}, d \in D$
$Duration_t$: Duration of maintenance task t, $t \in T_{kc}$
$Capa_{tl}^{Require}$: Capacity requirement for maintenance task t and load type l, $t \in T_{kc}, l \in L$
$Capa_{il}^{Provide}$: Capacity that vessel type i can provide for load type l, $i \in I, l \in L$
$VA_i^{limitation}$: Vessel amount limitation for type i, $i \in I$
VP_i: Vessel type i amount limitation in the port $i \in I$
$D_g^{Initial}$: Maintenance require day of group g, $g \in G$
D_t^{next}: Next stage remain days of component A_h:Available working hours of the day, $h \in H$
U_{id}: Existing vessel rental arrangement, how many vessels are already used on that day $i \in I, d \in D$
D_i^{stay}: Maximum stay offshore time of the vessel, $i \in I$
VA_i^{buy}: Vessel type i initial purchase amount $i \in I$

4.2.3. Decision variables

β_{td}: 1 if maintenance activity t is scheduled on day d, 0 otherwise,$t \in T_{kc}, d \in D_g$
R_{id}: Amount of vessel type i rented on day d $i \in I, j \in J, d \in D_g$,

h_{td}: Hours spent on executing task t on day d, $t \in T_{kc}, d \in D_g$
F_t: First day of the maintenance $t \in T_{kc}$
L_t: Last day of the maintenance $t \in T_{kc}$

4.2.4. Auxiliary variables

α_{itd}: Amount of vessel type i deployed for task t on day d, $i \in I, t \in T_{kc}, d \in D_g$
λ_{id}: Amount of vessel type i deployed to execute the maintenance on day d $i \in I, d \in D_g$
PF_{id}: Amount of vessel type i travel from port to wind farm on day d $i \in I, d \in D_g$
FP_{id}: Amount of vessel type i travel from wind farm to port on day d $i \in I, d \in D_g$
S_{id}: Amount of vessel stay overnight on day d, $i \in I, d \in D_g$
$Rent_i$: Amount of vessel rented in this maintenance cycle $i \in I$
VAC_i: Vessel arrangement closeness of vessel type i $i \in I$

4.2.5. Objective function

$$\min Z = \sum_{i \in I} Cost_i^{Rent} * (\sum_{d \in D_g} R_{id}) \tag{4.43}$$

$$+ \sum_{i \in I} Cost_i^{Travel} * (\sum_{d \in D_g} PF_{id} + FP_{id}) \tag{4.44}$$

$$+ \sum_{i \in I} (Cost_i^{night} * \sum_{d \in D_g} S_{id}) \tag{4.45}$$

$$+ \sum_{i \in I} (Cost_i^{Mobilized} * Rent_i) \tag{4.46}$$

$$+ \sum_{t \in T_{kc}} (L_t - F_t) * Cost_t^{downtime} \tag{4.47}$$

$$+ \sum_{t \in T_{kc}} \sum_{d \in D_g} Cost_{td}^{Pe} * \beta_{td} \tag{4.48}$$

$$+ \sum_{i \in I} VAC_i \tag{4.49}$$

The objective function of the improved vessel and task arrangement model is to reduce the overall cost of executing the maintenance tasks. The vessel charter costs are indicated by 4.43. The equation 4.44 represents the travel cost of the vessels that transport the technicians and maintenance teams between the offshore wind farm and the operation center. The equation 4.45 indicates the cost of having the vessels stay overnight at the offshore wind farm. The equation 4.46 refers to the mobilization cost of the vessel. The equation 4.47 indicates the downtime cost of maintaining the wind turbines. The equation 4.48 indicates the penalty cost that the maintenance tasks are executed in the winter period, which will penalize the operator. The equation 4.49 refers to the Vessel arrangement closeness between the vessel rental arrangement of the current maintenance period and previous maintenance periods. Its purpose is to prevent the scenario where a large number of vessels are rented simultaneously and then quickly become idle.

4.2.6. Auxiliary equation

$$Rent_i = max(R_{id}) \tag{4.50}$$

$$S_{id} = \sum_{d=0}^{d} (PF_{id} - FP_{id}) \tag{4.51}$$

$$\lambda_{i(d+1)} = S_{id} + PF_{i(d+1)} \tag{4.52}$$

$$VAC_i = \sum_{i \in I} \sqrt{(\sum_{d \in D_g} [(d * R_{id}) - (d * U_{id})]^2)} \tag{4.53}$$

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4.2.7. Constraints

Vessel acquire amount constraint

$$R_{id} + U_{id} \leq VA_i^{limitation}, i \in I, d \in D_g \tag{4.54}$$

$$VA_i \geq 0 \tag{4.55}$$

$$R_{id} \geq 0 \tag{4.56}$$

$$Rent_i \geq 0 \tag{4.57}$$

The constraint 4.54 restricts the number of vessels hired each day and should not exceed the limitation of the port. The constraints 4.55 to 4.57 indicates the bounds for the decision variables VA_i, R_{id} and $Rent_i$.

Task arrangement constraint

$$\sum_{d \in D_g} \beta_{td} \geq \frac{Duration_t}{(T^{end} - T^{start})}, t \in T_{kc} \tag{4.58}$$

$$\sum_{i \in I} \lambda_{id} * Capa_{il}^{Provide} \geq \sum_{t \in T_{kc}} \beta_{td} * Capa_{tl}, , d \in D_g, l \in L \tag{4.59}$$

$$\lambda_{id} \leq VA_i + R_{id} \tag{4.60}$$

$$\lambda_{id} \geq S_{id} \tag{4.61}$$

$$\lambda_{i(d+1)} \geq S_{id} \tag{4.62}$$

$$\beta_{td} \in \{0, 1\} \, t \in T_{kc}, d \in D_g \tag{4.63}$$

$$\lambda_{id} \geq 0, i \in I, d \in D_g, t \in T_{kc} \tag{4.64}$$

The constraint 4.58 restricts the minimum days spent on each maintenance task. The constraint 4.59 shows that the capacity of the vessel that has been deployed on each day should provide more capacity than the requirements from the maintenance tasks. The constraint 4.60 shows that the number of vessels deployed should not exceed the number of vessels already purchased and chartered. The constraints 4.61 and 4.62 indicate that the number of vessels that stay overnight in the offshore wind farm should be less or equal to the number of vessels deployed to the offshore wind farm on that day and the following day. The last two constraints, 4.63 and 4.64, specify the bounds for the decision variables β_{td} and λ_{id}.

Task schedule constraint

$$\sum_{d\in D_g} h_{td} \geq Duration_t, t \in T_{kc} \tag{4.65}$$

$$h_{td} \leq \sum_{h\in H}\left[\sum_{i\in I} \alpha_{itd} * W_{idh} * A_h\right], t \in T_{kc}, d \in D_g, h \in H \tag{4.66}$$

$$m * \lambda_{id} \geq \sum_{t\in T_{kc}} \alpha_{itd}, i \in I, d \in D_g \tag{4.67}$$

$$m * \beta_{td} \geq h_{td}, t \in T_{kc}, d \in D_g \tag{4.68}$$

$$\lambda_{id} + U_{id} \leq VA_i^{buy} + R_{id} \tag{4.69}$$

$$L_t \geq D_g^{Initial} \tag{4.70}$$

$$L_t \geq d * \beta_{td} \tag{4.71}$$

$$F_t \leq d * \beta_{td} + m * (1 - \beta_{td}) \tag{4.72}$$

$$F_t \leq D_t^{next} \tag{4.73}$$

$$\alpha_{ijt} \in \{0, 1\}, i \in I, j \in J_b \cup J_r \tag{4.74}$$

$$h_{td} \geq 0, t \in T_{kc}, d \in D_g \tag{4.75}$$

The constraint 4.65 indicates that the total hours spent on the tasks should be more than the duration of the maintenance task. The following constraint 4.66 limits the hours spent on each maintenance task on each day, which is less than the weather permit operational hours of the vessel that was arranged to execute the maintenance task. The following constraint, 4.67 indicates that the vessels sent for executing the maintenance task each day should not exceed the vessel operating at the offshore wind farm. The constraint 4.68 restricts that once a maintenance task has maintenance hours on a given day, the maintenance task is considered as arranged on that day. The constraint 4.69 restricts that considering the maintenance periods of different maintenance cycles overlap with each other, the number of vessels that deployed on each day should not exceed the number of vessels that have been purchased and chartered. The constraints 4.70 and 4.71 indicate that the maintenance finish day of each task should be after any days that execute the maintenance and the day that the maintenance request is generated. The constraints 4.72 and 4.73 indicate that the first maintenance day of the tasks should be before any maintenance execution day and before the components run into the next stage of wearing. The constraints 4.74 and 4.75 illustrate the boundary of the decision variables α_{itd} and h_{td}.

4.3. Solver for optimization

The vessel & task arrangement module is an optimization model based on mixed integer linear programming. As the maintenance tasks amount in each maintenance cycle increase, the scale of the problem also increases, resulting in the computation time increase and huge demand on the computation resource. To solve the problem quickly and accurately, choosing a suitable solver is crucial□

As explained in the previous chapters, many potential solvers, such as CPLEX or Gurobi, can be used to solve the MILP problems since the Monte Carlo simulations need to execute multiple simulations to obtain the final result. Computational speed is the priority factor when choosing a solver.

When solving the same linear programming problem, compared with other commercial solvers, Gurobi performs better at computation speed. When solving the same linear programming problem, Gurobi has 33% less computation time compared with commercial solver CPLEX and 57% less computation time compared with the most popular solver, FICO Xpress [65]. As a result, Gurobi is chosen as the solver of the mathematical model.

4.4. Summary

This chapter presents the equations used by the optimizer to arrange the vessels and tasks. The initial model provides an accurate optimal solution for the number of each vessel, but it has significant redundancy and leads to extreme computational demands. In this case, the improved optimization model that focuses on the vessel's quantity is developed. The improved mathematical model replaces the summation of the individual vessels in the initial model with integer variables that indicate the number of vessels. The model provides the optimal solution with a shorter computation time. In the next chapter, the close-loop simulation model with the improved task and vessel arrangement optimization model will be compared with an open-loop simulation model with a simulated-annealing optimization algorithm as the model verification.

5

Case Study

The previous chapter presents the mathematical model of the optimizer. This chapter will perform a case study based on the current model with the corresponding data. Firstly, the input data of the case study will be shown. Secondly, a Monte Carlo simulation is implemented to determine the minimum number of iteration amount. Next, the sensitivity study based on a small-sized offshore wind farm is presented, aiming to find the sensitivity factors that affect the vessel charter cost. Finally, the case study of 3 different size offshore wind farms is presented, giving the result of the optimal initial purchase fleet and vessel charter recommendation for each month.

5.1. Simulation input data

During the model simulation, the maintenance strategy of age-based opportunistic and time-based preventive maintenance is implemented. The input data of the opportunistic maintenance strategy is shown in table 3.2. The winter period is from November to April next year, with the preventive maintenance check in September [62]. The input data related to the offshore wind farm is shown in table 5.1. The values of offshore wind farm distance from shore comes from [66]. The electricity price comes from [61] and the wind turbine power comes from [60]

No	Input	Value	Unit
1	Number of wind turbines of the small size offshore wind farm	20	turbine
2	Number of wind turbines of the medium size offshore wind farm	50	turbine
3	Number of wind turbines of the large size offshore wind farm	100	turbine
4	Distance from shore	25	km
5	Simulation horizon	5	year
6	Shift 1 start	1:00	hh:mm
7	Shift 1 end	11:00	hh:mm
8	Shift 2 start	13:00	hh:mm
9	Shift 2 end	23:00	hh:mm
10	Maintenance period	90	day
11	Wind turbine power	3	MW
12	Electricity price	150	Eur/kwh
13	Downtime cost	10,800	Eur/day

Table 5.1: Parameters of the offshore wind farm and turbines

The case study presents three different sizes of offshore wind farms. As shown in figure 1.2, the small offshore wind farm with a wind turbine amount between 0 and 40 is still dominant because their technology is more mature. As a result, the wind turbine amount of the small size offshore wind farm in the case study was chosen as the average number 20. The medium-sized offshore wind farm with a wind turbine amount between 40 and 80 takes up the second highest occupation since the installation and operation cost of the single wind turbine decreases as the wind turbine amount increases. Based

on the available research, the amount of wind turbines in the medium size offshore wind farm is selected as 50 [61]. A large offshore wind farm with a wind turbine between 80 and 120 can significantly reduce power generation costs due to the increasing wind turbine amount, which can dilute the installation and maintenance costs. As a result, most of the multiple wind farms currently under construction have more than 80 wind turbines. In the case study, the large size offshore wind farm's wind turbine amount chose the average number of 100.
The downtime cost calculation of the wind turbine is based on its rated power and electricity price, which is shown in equation 5.1

$$\text{Downtime cost} = P_{electric} * P_{wind} * 24 \tag{5.1}$$

$P_{electric}$: Electricity price (Eur)
P_{wind} : Wind turbine power (W)

The parameters related to the components' lifetime are shown in table 5.2. All the component's data comes from [60].

Component	Weibull shape parameter (days)	Weibull scale parameter
Blades	3	3,000
Bearing	2	3,750
Gearbox	3	2,400
Generator	2	3,300
Shaft	1.5	7,500

Table 5.2: Lifetime parameters for the component

The components' maintenance duration and cost are shown in table 5.3. The replacement duration and cost data comes from [60]. The minor repair cost of the blade, bearing, gearbox and generator comes from [67]. The duration and maintenance cost of minor maintenance and major maintenance of the blade, bearing, gearbox and generator comes from [68] and [69]. For the component shaft, the duration and maintenance cost of major and minor maintenance comes from [70]. The data of technician requirements for three different types of maintenance comes from [61]

Maintenance type	Component	Duration(h)	Cost (Eur)	Technician (person)
Replacement	Blades	288	90,000	8
	Bearing	36	10,000	
	Gearbox	231	230,000	
	Generator	81	60,000	
	Shaft	144	232,000	
Major maintenance	Blades	18	25,000	6
	Bearing	12	3,750	
	Gearbox	16	18,750	
	Generator	14	5,000	
	Shaft	42	14,000	
Minor maintenance	Blades	9	4,000	3
	Bearing	6	1,000	
	Gearbox	8	5,000	
	Generator	7	1,500	
	Shaft	18	1,000	

Table 5.3: Parameters of repair time, repair cost and technician amount on components

The parameters related to the vessels are concluded in table 5.4. The input [1-10] and [13,14] are all come from [16]. The charter price of CTV and FSV comes from [59], and the charter price of HLV comes from [70]. For the vessel purchase cost, the purchase cost of CTV comes from [70], and the purchase cost of FSV comes from [71].

The vessel travel cost of each type of vessel transfer between the offshore wind farm and the operation center is calculated by the travel speed, fuel consumption, and fuel cost from table 5.4 and the distance between the offshore and the operation center in table 5.1. The travel cost is calculated by equation 5.2.

No	Input	Value			Unit
		CTV	FSV	HLV	
1	Travel speed	44	25	20	km/h
2	Technician on board	12	12	24	person
3	Maximum parallel team	4	1	1	team
4	Limit wave height	1.7	2	2.8	m
5	Limit wind speed at sea	25	25	36.1	m/s
6	Limit wind speed at hub	-	-	15.3	m/s
7	Mobilization time	7	21	30	day
8	Minimum charter length	30	30	30	day
9	Extend charter length	15	15	15	day
10	Fuel consumption	0.24	0.2	0.55	mt/h
11	Charter price	2,000	33,000	290,000	Eur/day
12	Purchase cost	3,000,000	20,250,000	-	Eur
13	Mobilization cost	50,000	200,000	800,000	Eur/ mobilization
14	Fuel cost	300	300	450	Eur/ton
15	Travel cost	100	100	600	Eur/travel

Table 5.4: Vessel related parameters

The travel cost calculation of the vessel is based on the vessel travel speed, the distance between the port and the offshore wind farm, hourly fuel consumption of the vessel, and the fuel cost of the vessel in table 5.4, which is shown in equation 5.2

$$C_{travel} = \frac{D}{V_t} * HC_{fuel} * C_{fuel} \tag{5.2}$$

C_{travel} : Vessel travel cost
D : Distance between the port and the offshore wind farm
V_t : Vessel travel speed
HC_{fuel} : Hourly fuel consumption of the vessel
C_{fuel} : Cost of the fuel

The data that generates the synthetic weather data is shown in table 5.5. The input[1-4] comes from [72]. The input data of relevant height above sea comes from [61], and the input data of the wind speed coefficient comes from [16].

The weather limits the vessels' ability to perform maintenance tasks. The met-ocean wind speed and

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

Table 5.5: Table of parameters related to wind and wave characteristics

wave height significantly influence the vessel's operation. The synthetic climate data is generated by using Weibull distribution. For different heights of wind speed, the equation 5.3 shows the calculation of wind speed at different heights [16].

$$\frac{v_2}{v_1} = (\frac{h_2}{h_1})^a \quad (5.3)$$

v_1 : wind speed at height h_1
v_2 : wind speed at height h_2
a : constant of wind power law equation

5.2. Monte Carlo simulation convergence analysis

The uncertainties come from the Components' RUL and weather conditions at the offshore wind farm. The former uncertainties make the maintenance tasks in the maintenance cycle and the maintenance cycle generation date uncertain. The latter uncertainty decides whether the vessel can execute the maintenance task at the offshore wind farm. These uncertainties affect the maintenance cycle generation, task and vessel scheduling in the task & vessel arrangement module, and the vessel charter strategy generation. To eliminate the uncertainties, the Monte Carlo simulation is applied. The convergence analysis of the Monte Carlo simulation is necessary to estimate how many iterations are needed. In the convergence analysis, the Monte Carlo simulation iteration amount is increased, presenting the average vessel total charter cost under different iteration amounts. The charter probability heat map will be given when the iteration amount reaches 50,100, 200, 500, and 1000.

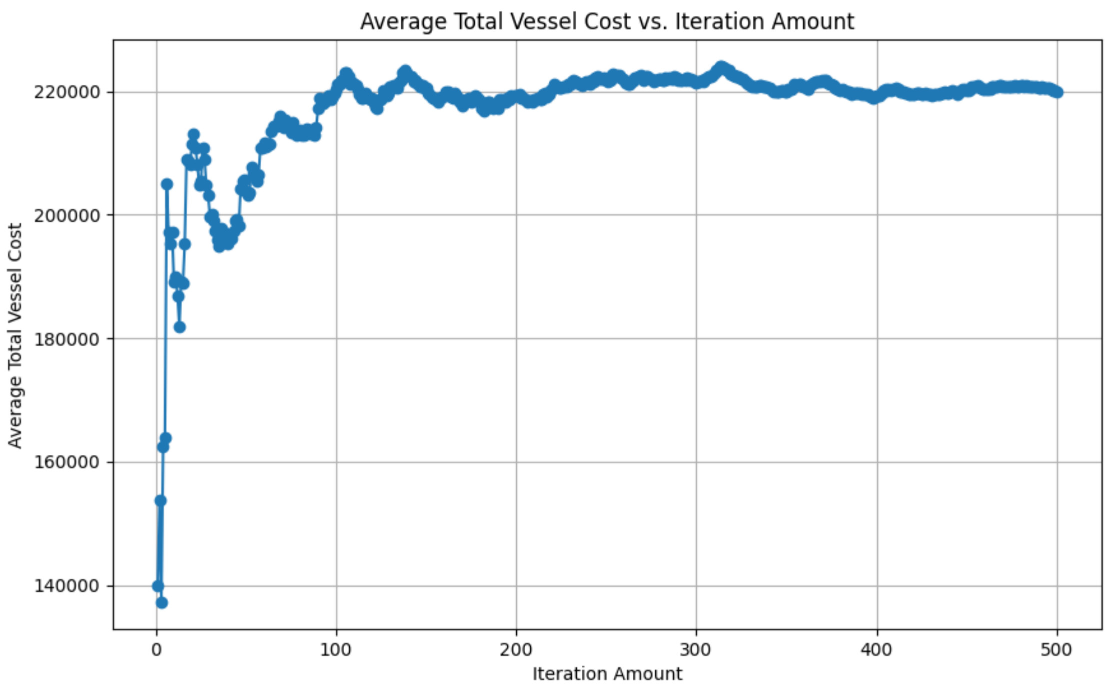


Figure 5.1: Average vessel total charter cost under different iteration amount

According to the implementation results above, the average total vessel cost becomes stable after the iteration amount reaches a certain number of times. As shown in figure 5.1, after the iteration amount reaches 200, the average total cost of each scenario stabilizes at 220,000 keur. Stabilized average total cost represents the number of vessels and the charter period for the vessels to become stable. To reduce the computation amount to carry out the subsequent implementation, the 200-times iteration will be chosen for subsequent implementation.

5.3. Sensitivity analysis

Sensitivity analysis is essential for model verification. The simulation model is designed with many input parameters, and the sensitivity analysis can determine the sensitive factors affecting the model output. At the same time, the sensitivity analysis can verify the reasonableness and credibility of the model and improve the model's accuracy by observing the simulation model's response to the changes of inputs and judging whether the model changes according to the expectation.
The sensitivity analysis uses the small size offshore wind farm with 20 wind turbines for the simulation. The simulation horizon is five years. The input data will be changed to analyze the sensitivity factors that affect the vessels' chartering strategies. To observe how the sensitivity factors affect the vessel acquisition cost. The following sensitivity factors are chosen for the sensitivity analysis, which will be further illustrate in each subsection.

- Weather scale parameter
- Vessel charter length
- Age consumption threshold
- Wind turbine amount
- Maintenance duration
- Maintenance period length
- Vessel arrangement closeness (VAC) coefficient
- Vessel charter cost

5.3.1. Changing weather scale parameters

The weather influences maintenance execution by limiting whether the vessel is operational during specific hours, directly affecting the available maintenance execution hours of each day. The available maintenance execution hours of the day further affect the maintenance task execution and vessel deployment of each day. Therefore, weather conditions can be considered a sensitivity factor for analysis. The synthetic weather data follows the Weibull distribution and is generated at the beginning of the simulation. In this sensitivity analysis, the scale parameter of the weather will increase and decrease by 50% to observe the changes in the maintenance execution. The modified weather parameters are shown in table 5.6

No	Item	Baseline value	Modified value (increase)	Modified value (decrease)	Unit
1	Weibull shape parameter of wind speed (at 21 m)	2.43	2.43	2.43	-
2	Weibull scale parameter of wind speed (at 21 m)	8.58	12.87	4.29	m/s
3	Weibull shape parameter of wave height	1.58	1.58	1.58	-
4	Weibull scale parameter of wave height	1.1	1.65	0.55	m
5	Relevant height above sea	5	5	5	m
6	Wind speed coefficient	0.1	0.1	0.1	-

Table 5.6: Weather parameters with modified value

The simulation results of changing weather scale parameters are shown in table 5.13 and figure 5.3. Increasing the weather scale parameter gives weather data a higher value when generated. Representing the weather is more severe. In contrast, decreasing the weather scale parameter provides the weather with data with a lower value when generated. Representing the weather is more gentle. However, the task & vessel arrangement module aims to arrange all the tasks execution in a fixed maintenance period by minimizing the downtime cost and making the vessel arrangement on each day more stable. Therefore, the maintenance period will be fully used in the task & vessel arrangement. The changing weather data can only affect the vessel arrangement each day but cannot affect how many days the maintenance tasks are executed. As shown in table 5.7, changing the weather scale parameter increases the average maintenance period length by 1.56% and 2.39%, leading to the vessel charter cost slightly increase.

	Average maintenance period length (day/period)	Variation
Baseline	53.55	-
Weather scale parameter *0.5	54.39	1.56%
Weather scale parameter *1.5	54.83	2.39%

Table 5.7: Average maintenance period length under different

5.3.2. Changing charter length of the vessels

The vessel charter starts with a fixed charter length and then decides whether the charter length needs to be extended. In the closed-loop simulation model, The clustering algorithm clusters the vessel chartering requirement together with the fixed length of the chartering period. Finding the optimal chartering strategy based on the vessel's total cost. For those vessels that only need to be chartered for a few days, the minimum charter length still needs to be obtained, as well as the vessel charter contract, resulting in the vessels staying idle in the port.
By changing the vessel charter length, the charter period of the vessel can be terminated earlier or later. This affects the vessel charter cost. In this sensitivity analysis, the minimum charter length of the vessels will increase and decrease by 50% to observe how the chartering length affects the total cost. The modified vessel charter length is shown in table 5.8

Vessel	Baseline		Increase by 50%		Decrease by 50%	
	Minimum charter length(days)	Extend charter length (days)	Minimum charter length(days)	Extend charter length (days)	Minimum charter length(days)	Extend charter length (days)
CTV	30	15	45	22	15	7
FSV	30	15	45	22	15	7
HLV	30	15	45	22	15	7

Table 5.8: Vessel charter length with modified value

As shown in table 5.13 and figure 5.3, the charter cost of the vessels decreased with the decrease in charter length. The reason is that the number of days the vessels are deployed is far lower than the vessel charter length, which leads to a low utilization of the vessels. In this case, reducing the charter length of the vessels can reduce the charter cost when the vessels are not being deployed, which significantly reduces the vessels' charter costs. Conversely, extending the charter length of the vessels causes more of them to remain idle during the charter period, increasing the vessel charter cost.

5.3.3. Changing age consumption threshold

The age consumption threshold is directly linked to the generation of maintenance tasks during the simulation. In this simulation, the age consumption threshold of the monitoring system will be changed to observe how the age consumption threshold of the maintenance strategy affects the maintenance. In this sensitivity analysis, the age threshold of defining the component wearing zone will be increased and decreased to observe how the age consumption threshold affects the optimization results. The results are shown in table5.13 and figure 5.3. Table 5.9 shows the modified age consumption threshold.
As can be observed from the table 5.13 and figure 5.3. When the age consumption threshold is decreased, the age consumption threshold of replacement is easier to reach, making the maintenance cycles more likely to be triggered. More major and minor maintenance will be added to the maintenance

Maintenance type	Baseline age consumption (%)	Increased age consumption (%)	Decreased age consumption (%)	Zone	Age reduction
No maintenance	[0,50)	[0,55)	[0,45)	Zone1	-
Minor maintenance	[50,80)	[55,85)	[45,75)	Zone2	30%
Major maintenance	[80,95)	[85,99)	[75,90)	Zone3	50%
Preventive replacement	[95,100)	[99,100)	[90,100)	Zone4	100%

Table 5.9: Age consumption with modified value

cycle due to the decrease in the age consumption threshold. More maintenance tasks require more vessels to be involved in the maintenance execution. Therefore, the vessel charter cost will increase.
The maintenance cycle will be harder to trigger when increasing the age consumption threshold. Therefore, fewer vessels are required to be involved in the maintenance execution, and the vessel charter cost will decrease. However, the vessel charter cost increases contrary to expectations. As a result, an in-depth survey of the charter cost of each type of vessel is conducted and shown in table 5.10.

	Vessel charter cost (keur/year)		
	CTV	FSV	HLV
Baseline age consumption	115.8	2784.9	36206.7
Age consumption threshold increase	113.9	2676.8	38016.9
Age consumption threshold decrease	134.9	3004.5	41263.8

Table 5.10: Vessel charter cost of modifying age consumption threshold

When the age consumption threshold is decreased, more maintenance tasks will be generated throughout the simulation, resulting in more vessels being involved in executing the maintenance tasks. Therefore, all three types of vessels' charter costs increase when the age consumption threshold decreases.
In the case that the age consumption threshold increases. As mentioned in the equation 4.73, the maintenance of the component must be initiated before the component runs into the next wearing stage. Therefore, for the replacement maintenance tasks, when the age consumption threshold increases, when the replacement task is generated, the remaining days of starting the maintenance is only 1% of the component's remaining useful life, which is far less than the baseline condition of 5% . The replacement must be executed as soon as possible. For multiple replacement tasks that are not far away from each other. In the baseline condition, these replacement tasks can be arranged on the same vessel. However, in the age consumption threshold increase case, these replacement tasks must start as quickly as possible, which requires chartering more HLVs to execute the replacement tasks. This results in an increase in the HLV charter cost while the CTV and FSV charter costs decrease.

5.3.4. Changing wind turbine amount

The amount of offshore wind farm turbines influences the number of components that need to be maintained and directly affects the number of maintenance tasks at each maintenance cycle. Therefore, the amount of wind turbines will affect the vessel charter strategy. In this sensitivity analysis, we will change the offshore wind farm's turbine amount by 50%, increase the number of wind turbines to 30, and then decrease the number of wind turbines to 10 to observe how the wind turbine amount affects the maintenance cost.
As is shown in table 5.13 and figure 5.4, increasing the number of wind turbines will significantly increase the vessel charter cost. The increment on the vessel charter cost corresponds to the increment of the offshore wind turbines of 53%. Conversely, as the number of wind turbines decreases, the vessel charter cost of the offshore wind farm decreases by 43% correspondingly. The significant change shows that the number of wind turbines is the most significant sensitivity factor.

5.3.5. Changing repair duration

The repair duration directly affects the days spent on each maintenance task. To minimize the downtime cost, the task & vessel arrangement module will choose different days for executing the maintenance tasks, affecting the vessel requirement each day and the vessel charter cost. In this sensitivity analysis, the repair duration of the maintenance tasks will be increased and decreased by 50%, observing how the repair duration of the components affects the maintenance execution. The modified repair duration is shown in table 5.11.

Maintenance type	Component	Duration(h)	Increased duration (h)	Decreased duration (h)
Replacement	Blades	288	432	144
	Bearing	36	54	18
	Gearbox	231	347	116
	Generator	81	122	41
	Shaft	144	216	72
Major maintenance	Blades	18	27	9
	Bearing	12	18	6
	Gearbox	16	24	8
	Generator	14	21	7
	Shaft	42	63	21
Minor maintenance	Blades	9	14	5
	Bearing	6	9	3
	Gearbox	8	12	4
	Generator	7	11	4
	Shaft	18	27	9

Table 5.11: Parameters of repair time with modified value

As a result, shown in table 5.13 and figure 5.4, the duration of the maintenance tasks significantly affects the charter cost by affecting the vessel deployed days and travel cost of the vessels by affecting the deployment days of the vessels. A longer maintenance duration means the vessel needs to be deployed for more days to complete the maintenance tasks, which increases the downtime cost. The increment in the vessel deployment times also brings more vessels involved in the maintenance execution, resulting in an increment in the vessel charter cost.

5.3.6. Changing maintenance period length

The maintenance period restricts the maintenance execution duration of each maintenance cycle. After the maintenance cycle is generated, the optimization model dispatches the vessels by maximizing the usage of the maintenance period, making the maintenance execution of the tasks scattered. As a result, the maintenance period affects the vessel deploying day, resulting in different vessel charter strategies. In this sensitivity analysis, the maintenance period length of executing the maintenance tasks will be increased to 120 days and decreased to 60 days to observe how the maintenance period length affects the operation and maintenance cost.

The results are shown in table 5.13 and 5.4. The travel cost of the vessels and the repair cost of the maintenance tasks remain unaffected by the length of the maintenance period, as the creation of maintenance tasks is not contingent on the duration of the period. The length of the maintenance period affects the charter cost of the vessel, as a shorter maintenance period aligns the execution days of maintenance tasks closer together, resulting in more compact vessel deployments. Conversely, a more extended charter period decentralizes the execution days of maintenance tasks, leading to a higher vessel charter cost.

5.3.7. Vessel arrangement closeness coefficient

The vessel arrangement closeness is included in the cost function of the task & vessel arrangement module, which is used to make the vessel rental arrangements more compact. Changing the coefficient of vessel arrangement closeness in the cost function can change the compactness of the vessel arrangement. A low vessel arrangement closeness value refers to the vessel rental arrangements being closer and the vessel rental amount of each day being closer. In this sensitivity analysis, the coefficient of the vessel arrangement closeness is changed to observe whether the total cost is sensitive to the vessel arrangement closeness. The initial coefficient of vessel arrangement closeness in the cost function is 1. The sensitivity analysis is done by increasing the coefficient to 10 and decreasing it to 0.1.

As shown in table 5.13 and figure 5.4, the charter cost of the vessels is sensitive to the coefficient of the vessel arrangement closeness. A higher coefficient makes the vessel rental arrangements more compact, leading to a lower vessel charter cost and a smaller scale of the initial vessel purchase fleet. While a small coefficient makes the rental arrangement less compact, resulting in a higher vessel charter cost.

5.3.8. Vessel charter cost

The vessel charter cost is critical in the decision-making process for chartering the vessels. Therefore, observing how the model reacts to the changing vessel charter cost is essential. The charter cost also affects the decision to purchase a vessel initially. The modified vessel charter cost is shown in table 5.12

Vessel	Baseline condition (eur/day)	Vessel charter cost decrease (eur/day)	Vessel charter cost increase (eur/day)
CTV	2,000	1,000	3,000
FSV	33,000	16,500	49,500
HLV	290,000	145,000	435,000

Table 5.12: Parameters of repair time with modified value

As it can be observed from the table 5.13, the annual vessel charter cost is sensitive to the daily vessel charter cost. The annual vessel charter changes correspondingly to the daily vessel charter cost. Daily vessel charter cost changes also affect the optimal initial purchase fleet, as is shown in figure 5.5. When the charter cost increases by 50%, The optimal initial purchase fleet has one additional CTV and FSV.

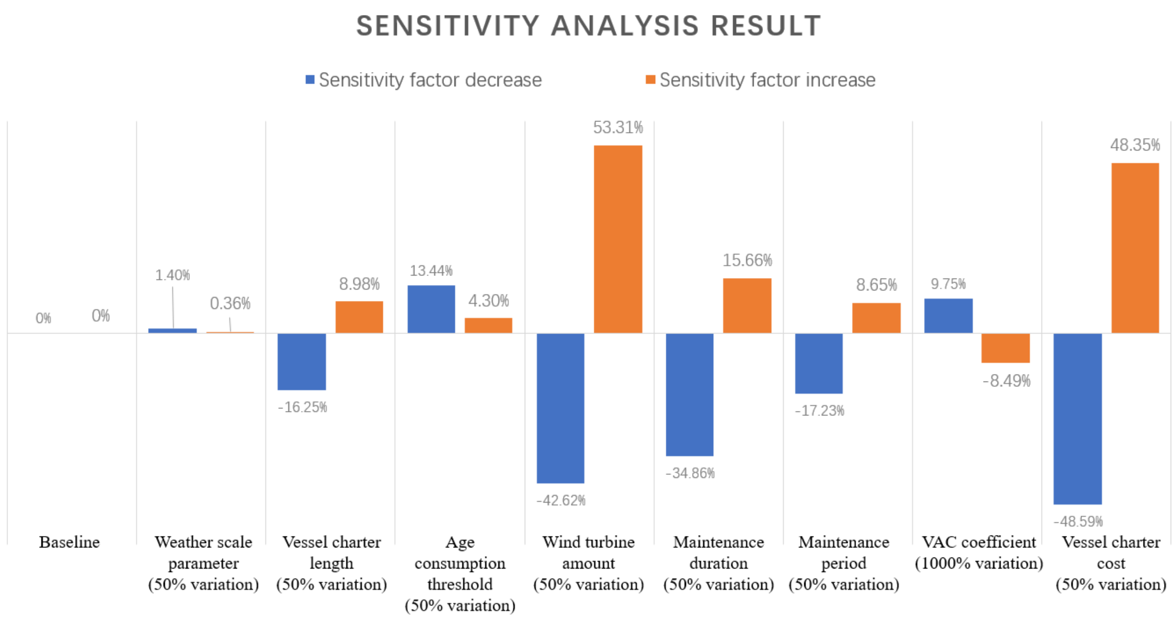
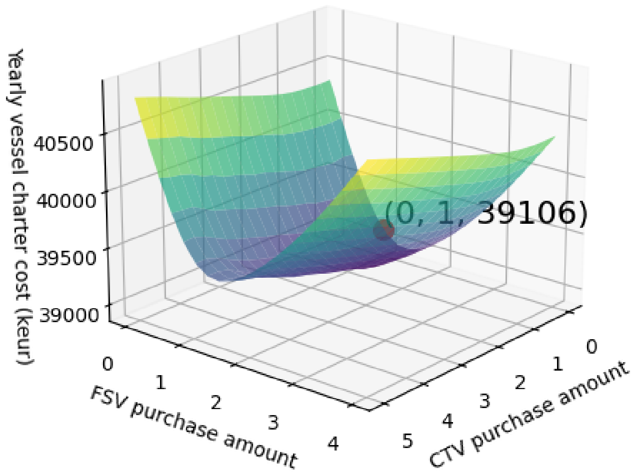
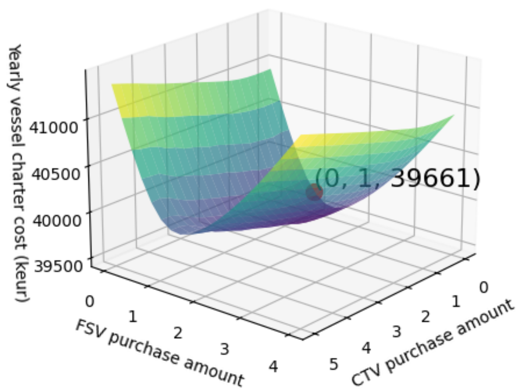


Figure 5.2: Sensitivity analysis result

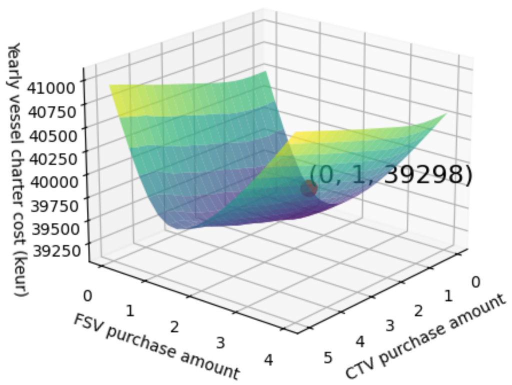
The result of the sensitivity analysis is shown in figure 5.2. The sensitivity analysis shows that the vessel charter cost with no initial purchases of the vessel fleet is sensitive to the maintenance duration of the components, maintenance period length and daily vessel charter cost. The full table with the every single cost of the sensitivity analysis also shown in the appendix table A.1



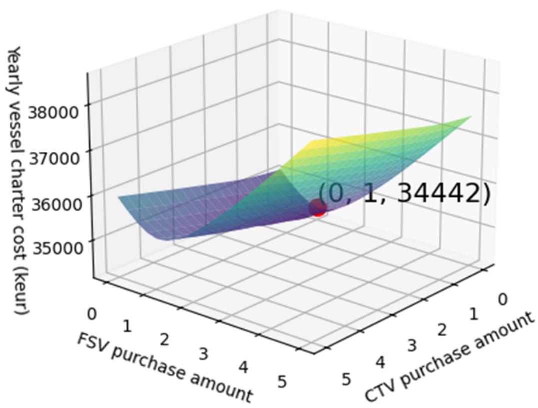
(a) Baseline condition



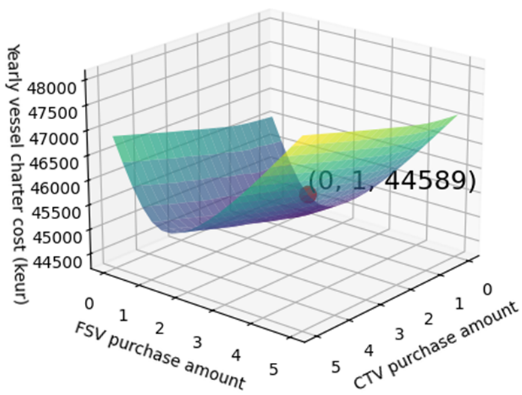
(b) Weather scale parameter *0.5



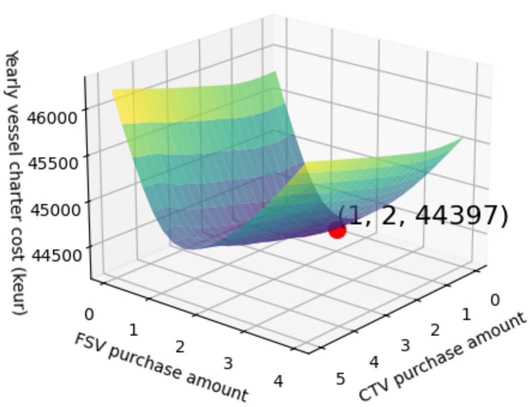
(c) Weather scale parameter *1.5



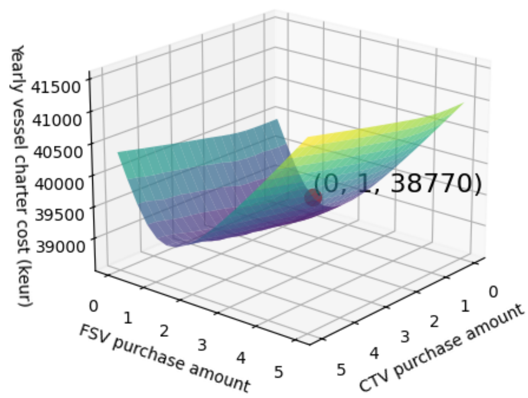
(d) Charter length *0.5



(e) Charter length *1.5

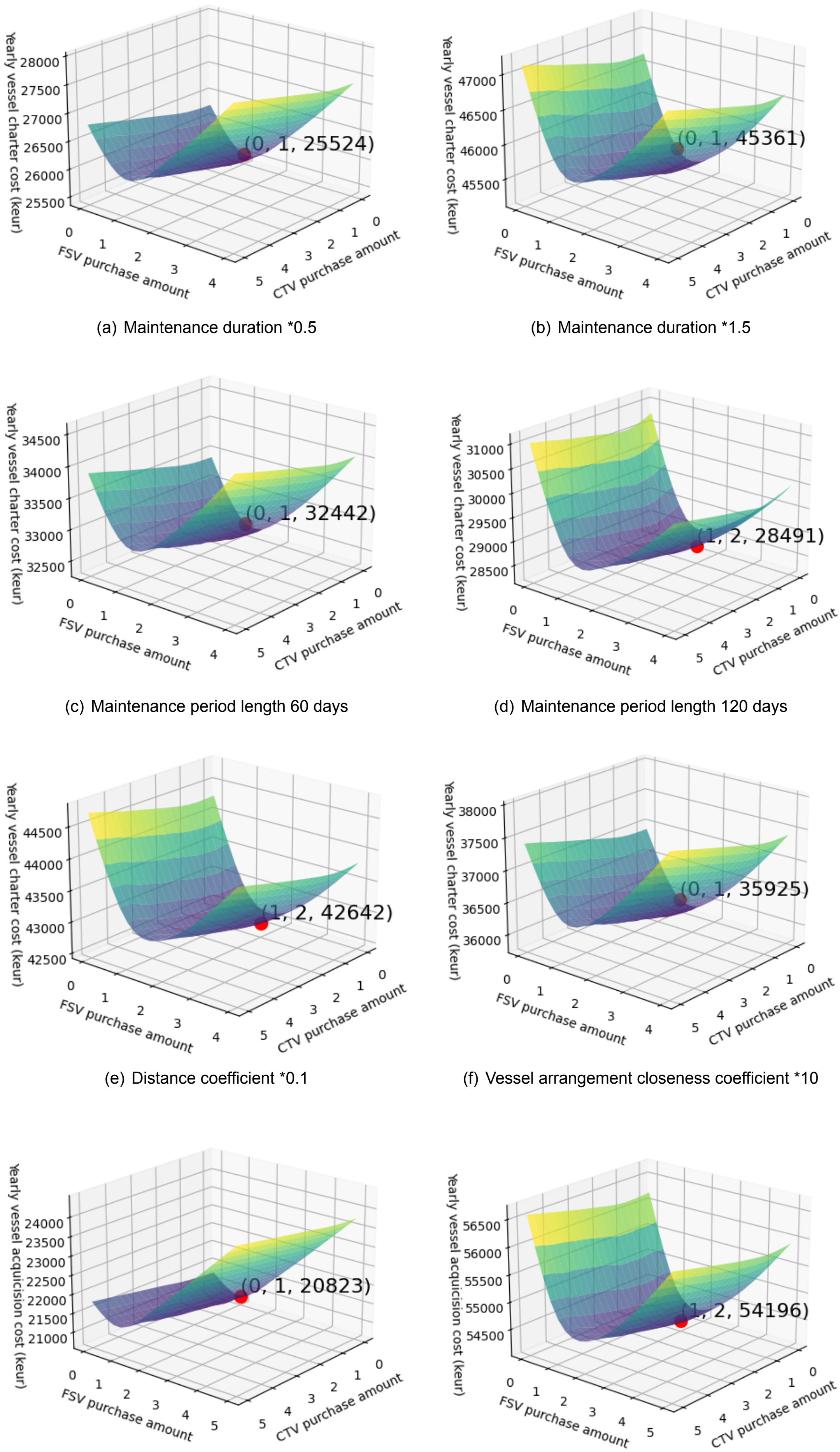


(f) Component's age consumption threshold decrease



(g) Component's age consumption threshold increase

Figure 5.3: Yearly vessel cost under different initial purchase amount



(a) Maintenance duration *0.5

(b) Maintenance duration *1.5

(c) Maintenance period length 60 days

(d) Maintenance period length 120 days

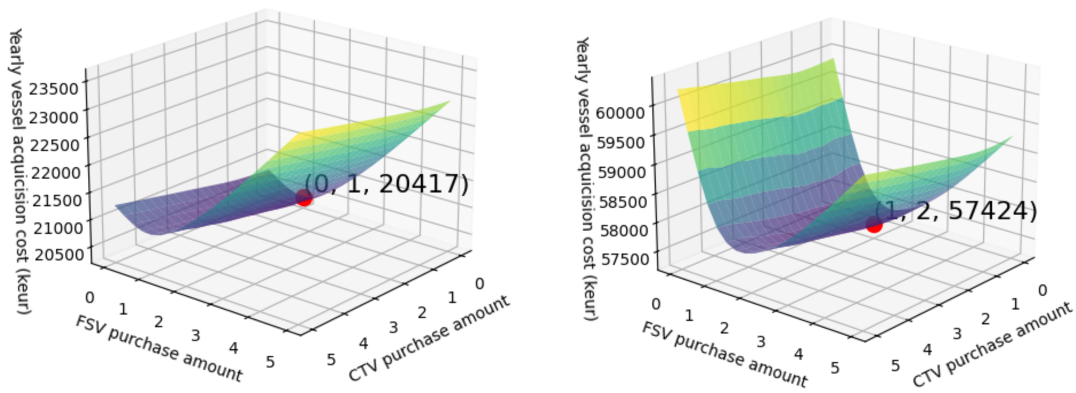
(e) Distance coefficient *0.1

(f) Vessel arrangement closeness coefficient *10

(g) Wind turbine amount decrease to 10

(h) Wind turbine amount increase to 30

Figure 5.4: Continued: Yearly vessel cost under different initial purchase amount



(a) Vessel charter cost decrease by 50%

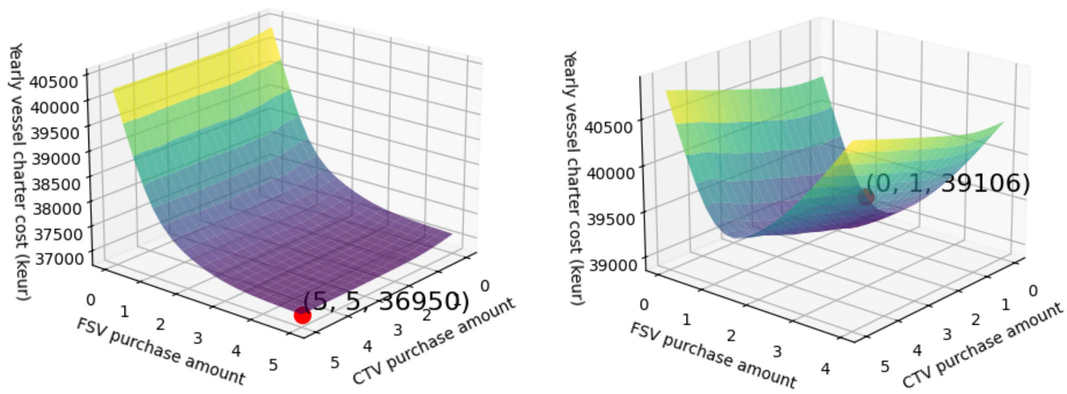
(b) Vessel charter cost increase by 50%

Figure 5.5: Continued: Yearly vessel cost under different initial purchase amount

5.4. Case study of different size of offshore wind farm

5.4.1. Result of small size offshore wind farm

In this case study, the wind turbine amount in the offshore wind farm is 20, which refers to the small size of the offshore wind farm. The yearly vessel charter cost under different initial vessel purchase amounts of the small-size offshore wind farm is shown in figure 5.6. As shown in the figure, an increase in the initial vessel purchase amount will significantly reduce the vessel's yearly pure charter cost. When it reaches the maximum value of 5 CTV and 5 FSV, the vessel's annual charter cost reaches the minimum of 36950 keur. Adding up the vessel purchase cost. When there's one FSV purchased in advance, the annual vessel acquisition cost reaches a minimum of 39106 keur.



(a) Yearly vessel charter cost under different initial vessel purchase amount of 20 turbines

(b) Yearly vessel acquisition cost under different initial vessel purchase amount of 20 turbines

Figure 5.6: Yearly vessel cost under different initial purchase amount of 20 turbines

Sensitivity factor	Charter cost when no initial purchase (keur/year)	Tendency	Charter cost change rate	Optimal initial purchase	Vessel acquisition cost (keur/year)
Baseline	40356.3	-	-	(0,1)	39106
Weather scale parameter *0.5	40922.7	↑	1.4%	(0,1)	39661
Weather scale parameter *1.5	40501.1	↑	0.4%	(0,1)	39298
Vessel charter length *0.5	33797.8	↓	-16.3%	(0,1)	34442
Vessel charter length *1.5	43980.5	↑	9.0%	(0,1)	44589
Component's age consumption threshold -0.05	45780.1	↑	13.4%	(1,2)	44397
Component's age consumption threshold +0.05	42092.6	↑	4.3%	(0,1)	38770
Wind turbine amount decrease to 10	23157.1	↓	-42.6%	(0,1)	20823
Wind turbine amount increase to 30	61870.3	↑	53.3%	(1,2)	20823
Maintenance duration * 0.5	26287.7	↓	-34.9%	(0,1)	54196
Maintenance duration * 1.5	46676.4	↑	15.7%	(0,1)	45361
Maintenance period length decrease to 60 days	33404.6	↓	-17.2%	(0,1)	32442
Maintenance period length increase to 120 days	43847.5	↑	8.7%	(1,2)	28491
Coefficient of vessel arrangement closeness decrease to 0.1	44290.1	↑	9.7%	(1,2)	42642
Coefficient of vessel arrangement closeness increase to 10	36930.9	↓	-8.5%	(0,1)	35925
Vessel daily charter cost decrease by 50%	20747.9	↓	-48.6%	(0,1)	20417
Vessel daily charter cost increase by 50%	59867.1	↑	48.3%	(1,2)	57424

Table 5.13: Sensitivity analysis result

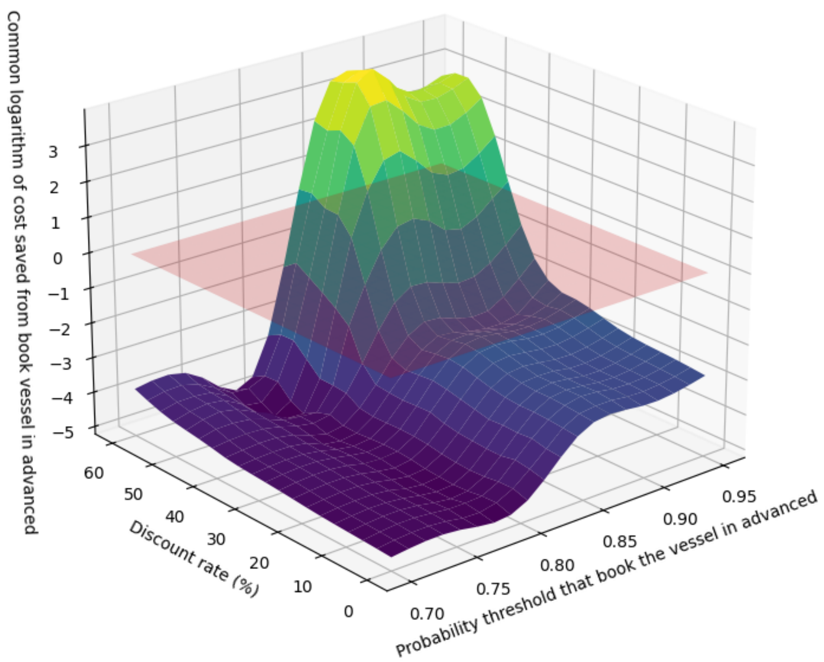


Figure 5.7: Cost saved from booking the vessel in advance of 20 wind turbines

The charter probability heat map for executing the maintenance tasks of the small size offshore wind farm is shown in figure A.2. For the offshore wind farm operator. Providing the data of vessel charter strategy from every simulation result as the charter recommendation is unrealistic. Instead, the operators would like to have a vessel charter strategy for each month, which is more helpful for the operators to arrange or charter the vessels each month. Therefore, the vessel charter probability heat map for executing the maintenance tasks of the small size offshore wind farm is shown in figure A.2. The heat map counts the probability of each vessel being chartered each month of each year throughout 200 simulations of 5 years. The elements in the heat map represent the probability that a vessel will be chartered that month in 200 simulations. For example, in September 2003, the vessel FSV1 had a charter probability 0.96. This means in the past 200 simulations, the vessel FSV1 was chartered 192 times in September 2003. A higher charter probability in the heat map represents that the vessel will be more likely to be chartered in other simulations. Therefore, the operator can book the vessel in advance, like early in the year. Ensure that the vessel is available when the maintenance cycle is generated.

For the shipowner that provides the vessel to the operator, their main goal is to reduce the idle time of the vessels, which reduces the operation cost of the vessel and increases the income created by the vessel. An early locked-in charter contract can help shipowners ensure a stable charter period, thus reducing the risk of idleness.

For the operator that charter the vessels. Booking the vessel in advance brings the advantage of being available in the selected time slot. In contrast, deciding to reserve the vessels in advance brings the disadvantage that if the vessel is chartered in advance but there's no maintenance needed to be done in the charter period, it will make the selected vessel idle in the operator's port. Resulting in vessels staying idle, wasting large amounts of rental costs.

Therefore, the shipowners are willing to provide a discount on the contract for the vessels that have been early booked. Figure 5.7 presents how much booking the vessel in advance saves from vessel charter costs under different charter probability thresholds and discount rates. The X-axis refers to the probability threshold, which means when the elements that represent the vessel charter probability in the heat map are higher than the threshold, the vessel will be reserved in advance, a fixed contract that covers the whole month will be given, reducing the vessel charter cost in the corresponding month. The Y-axis represents the discount rate, which means compared with the regular vessel rental contract, how much of a discount will the fixed contract that reserves the vessel in advance have.

Due to the vast difference among the cost data points of reserving the vessel in advance under different probability thresholds and discount rates (from -60000 to 600). It's not clear to present the cost data with the initial data. Therefore, a common logarithm of the saving cost is given in figure 5.7 to clarify the result. The equation 5.4 shows the calculation of taking the common logarithm of the saving cost that reserves the vessel in advance. If reserving the vessel in advance reduces the total vessel charter cost of 5 years, the saving cost $Cost^{save}$ will be positive. Conversely, if reserving the vessel in advance increases the total vessel charter cost, the $Cost^{save}$ will be negative.

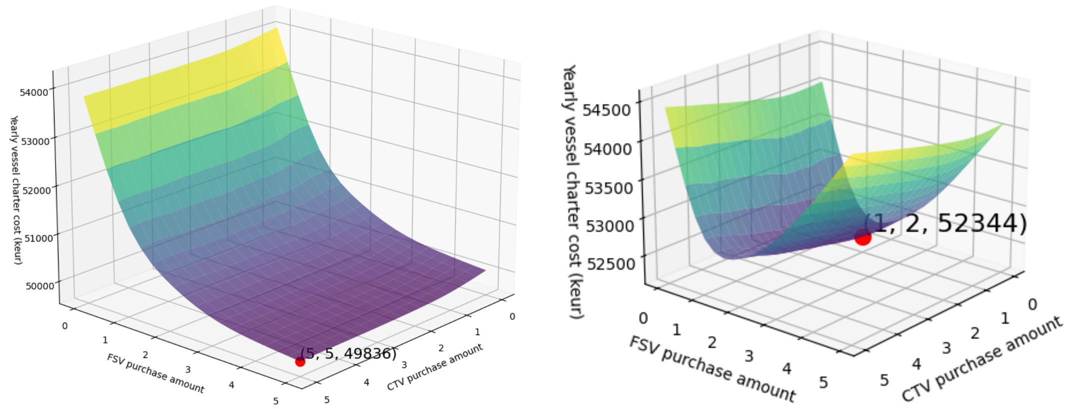
$$\text{Cost saving logarithm} = \begin{cases} log_{10}(Cost^{save}), Cost^{save} > 0 \\ 0, Cost^{save} = 0 \\ -log_{10}(Cost^{save}), Cost^{save} < 0 \end{cases} \quad (5.4)$$

As shown in figure 5.7, when the probability threshold reaches 0.85, and the discount of reserving the vessel in advance reaches 40%, reserving the vessel in advance is cost-effective. As a result, when the discount rate of reserving the vessel in advance is higher than 40%, reserving the vessel FSV 1 in October 2002, September, and October of the years 2003, 2004, and 2005. And HLV 1 in October 2004. It can be considered cost-effective when there's no initial purchase fleet. Figure 5.6 shows 1 FSV for the initial purchase. It can be concluded that under the initial purchase fleet mix of 1 FSV, when the discount rate of reserving a vessel in advance reaches 40%, reserving 1 HLV for October 2004 is cost-effective.

5.4.2. Medium size offshore wind farm

In this case study, the wind turbine amount in the offshore wind farm is 50, which refers to the medium size of the offshore wind farm. The yearly vessel charter and acquisition costs are shown in figure 5.8. As shown in the figure, the vessel charter cost increases with the increment in wind turbines. When considering only the vessel charter cost. The maximum initial purchase value of 5 CTV and 5

FSV makes the yearly charter cost reach 49836 keur. Consider the vessel's annual acquisition cost, increasing the purchase cost. The optimal initial purchase fleet is 1 CTV and 2 FSV, with a yearly vessel acquisition cost of 52344 keur. With the increase in the wind turbine amount from 20 to 50, an additional CTV and an FSV need to be purchased for the initial purchase fleet mix.



(a) Yearly vessel charter cost under different initial vessel purchase amount of 50 turbines

(b) Yearly vessel acquisition cost under different initial vessel purchase amount of 50 turbines

Figure 5.8: Yearly vessel cost under different initial purchase amount of 50 turbines

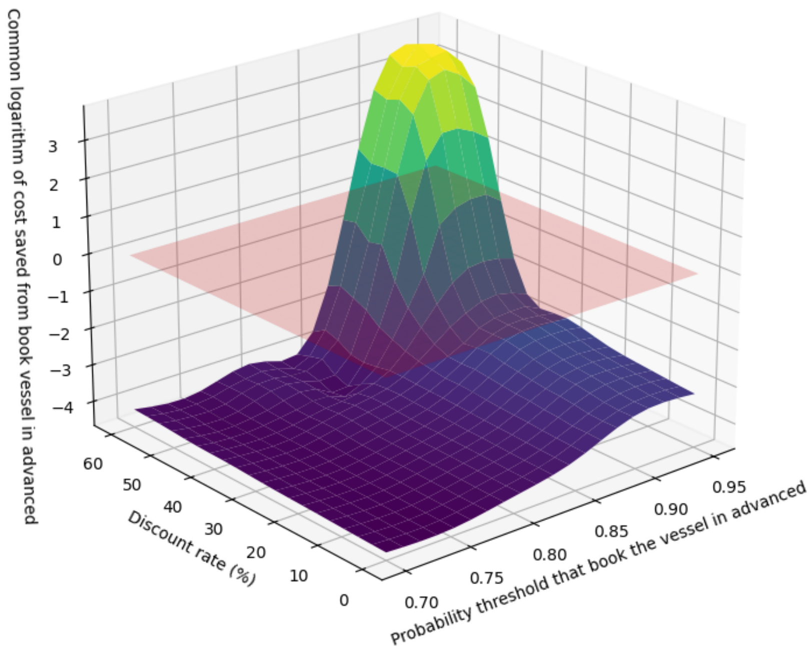
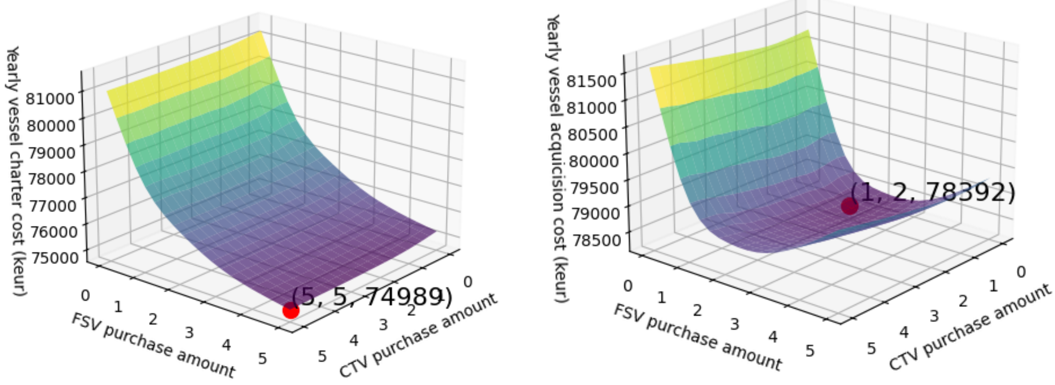


Figure 5.9: Cost saved from booking the vessel in advance of 50 wind turbines

The charter probability heat map for executing the maintenance tasks of the medium size offshore wind farm is shown in figure A.3. Compare with the charter probability heat map of small size offshore wind farm. The medium size offshore wind farm has more maintenance tasks. Therefore, the charter probability of the vessels increases when there's no initial purchase fleet. Figure 5.9 shows that when the probability threshold reaches 0.85 or 0.9, with the discount rate of 40%. Reserving the vessel in advance is cost-effective. Therefore, It can be concluded that when the discount rate is over 40%. Reserving the CTV 1 in September of 2004. FSV 1 in September and October of 2002,2004, and 2005, and September of 2003. HLV 1 in September of 2002 is cost-effective when there's no initial vessel purchase amount. Figure 5.8 shows 1 CTV and 2 FSV for the initial purchase. When the discount rate of reserving the vessel in advance reaches 40%, reserving 1 HLV in September of 2004 is cost-effective.

5.4.3. Large size offshore wind farm

In this case study, the wind turbine amount in the offshore wind farm is 100, which refers to the large size of the offshore wind farm. The yearly vessel charter and acquisition costs are shown in figure 5.10. As shown in the figure, the vessel charter cost increases with the increment in wind turbines. When considering only the vessel charter cost. The maximum initial purchase value of 5 CTV and 5 FSV makes the yearly charter cost reach 74989 keur. Consider the vessel's annual acquisition cost, which adds up the purchase cost. The optimal initial purchase fleet is 1 CTV and 2 FSV, with a yearly vessel acquisition cost of 78392 keur.



(a) Yearly vessel charter cost under different initial vessel purchase amount of 100 turbines (b) Yearly vessel acquisition cost under different initial vessel purchase amount of 100 turbines

Figure 5.10: Yearly vessel cost under different initial purchase amount of 100 turbines

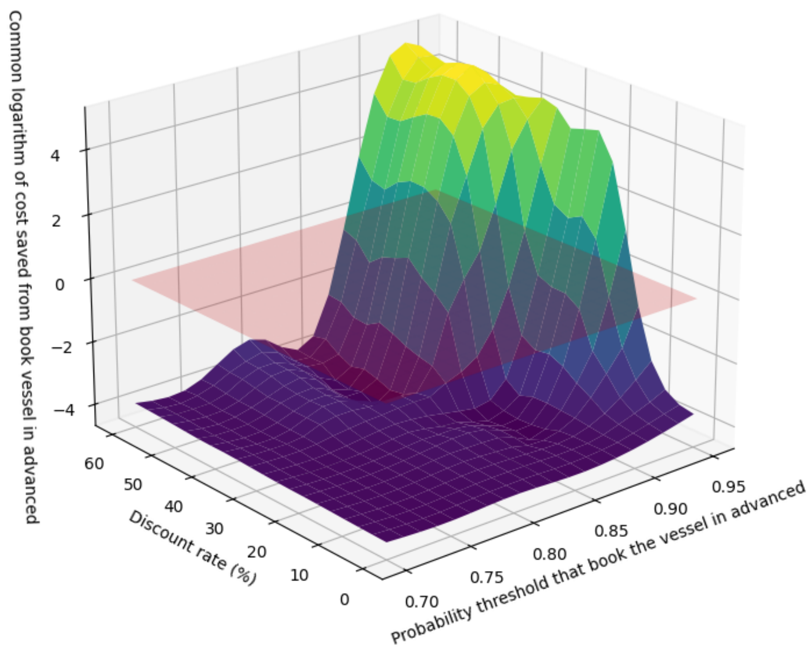


Figure 5.11: Cost saved from booking the vessel in advance of 100 wind turbines

The optimal initial vessel purchase fleet of the large-size offshore wind farm remains the same as that of the medium-sized offshore wind farm. But compared with the yearly vessel acquisition cost. The annual vessel acquisition cost of a medium sized offshore wind farm decreases significantly when there are 2 FSVs purchased. Then, the annual vessel acquisition cost increases significantly if the FSV's initial purchase amount increases. However, compared with large offshore wind farms, Having more than 2 FSVs as the initial purchase would not significantly increase the yearly vessel acquisition cost. This represents that as the wind turbine amount increases, the usage of third and fourth FSV also increases, which can also be concluded when comparing the vessel charter probability of medium size offshore wind farm in figure A.3 and large size offshore wind farm A.4. However, purchasing the vessel in advance is still not cost-effective.
The charter probability heat map for executing the maintenance tasks of the large size offshore wind farm is shown in figure A.4. Compare with the charter probability heat map of medium size offshore wind farm. The large size offshore wind farm has more maintenance tasks. Therefore, the charter probability of the vessels, especially the third and fourth FSV increases when there's no initial purchase fleet. Figure 5.11 shows that when the probability threshold reaches 0.85, the shipowner is willing to provide a discount over 20%. Reserving the vessel in advance is cost-effective. Therefore, when the discount rate is over 20%, Reserve the CTV 1 in September 2003, 2004, 2005, and August 2004. FSV 1 in September and October from 2001 to 2005. HLV 1 in September and October of 2001 is cost-effective when there's no initial vessel purchase amount. Figure 5.10 shows 1 CTV and 2 FSV for the initial purchase. When the discount rate of reserving the vessel in advance reaches 20%, reserving 1 HLV in September and October 2001 is cost-effective.

5.5. Summary

This chapter presents a case study based on the latest progress data. The Monte Carlo simulation iteration of 200 is determined by comparing the total vessel cost and root mean square error of vessel charter probability under different simulation amounts of the small offshore wind farm with 20 wind turbines. A sensitivity analysis is performed to find the sensitivity factors. The result shows that the model is sensitive to the number of wind turbines, vessel charter length, maintenance task duration, and maintenance period length. The sensitivity analysis also shows that the closeness of vessel arrangement in the objective function helps make the vessel arrangement more compact each day, resulting in a shorter charter contract that reduces the cost of the vessel charter. The coefficient of the vessel arrangement closeness affects the vessel arrangement compactness and further affects the vessel charter cost. The case study of 3 different sizes of offshore wind farms shows that having one FSV purchased in advance is cost-effective for a small offshore wind farm. Having 1 CTV and 2 FSV is cost-effective for the medium and large offshore wind farms. Meanwhile, for those months when the probability of chartering a vessel is greater than 0.85, booking the vessel in advance is cost-effective if the shipowner can offer a discount of not less than 40%.

6 Conclusion and recommendations

6.1. Conclusion

Compared to existing research, this thesis presents a decision support optimization model for the fleet mix problem, explicitly focusing on vessel chartering and initial purchasing by minimizing yearly vessel acquisition costs. The component wearing and vessel arrangement simulation model is developed based on Marco's model. The task & vessel arrangement module, one of the key modules in the component wearing and vessel arrangement simulation model, used MILP to solve the task and vessel arrangement for each maintenance cycle. The vessel charter strategy generation module, which uses agglomerative clustering to group each vessel arrangement and generate the vessel charter strategy, avoids the problem of excess ships being chartered due to overlapping maintenance cycles.

The main research question of finding the optimal initial purchased fleet is answered in Chapter 5, which states that having 1 FSV for the small offshore wind farm and 1 CTV plus 2 FSV for the medium and large offshore wind farm is cost-effective, unlike the available research that is having CTV as the initial fleet. This thesis shows that under age-based opportunistic and preventive maintenance, having FSV in the initial fleet can significantly reduce the vessel acquisition cost and, furthermore, save the offshore wind farm operation cost.

The latest progress of the fleet mix problem for O&M of the offshore wind farm is reviewed in the chapter, which answers sub-question 1. The component wearing and vessel arrangement simulation model developed based on the component wearing and vessel wearing simulation model from Marco Borsotti is presented in Chapter 3, which answers sub-question 2. By introducing the yearly vessel acquisition cost under different initial vessel purchase amounts for the offshore wind farm, sub-question 3 is answered. By presenting the vessel charter probability heat map and the saving cost under different vessel charter probability thresholds and discount rates, sub-question 4 is answered. The sensitivity analysis in Chapter 5 shows that the model is sensitive to the number of wind turbines, the vessel charter length, maintenance duration, and maintenance period length. The coefficient of vessel arrangement closeness affects the vessel arrangement compactness and furthermore affects the vessel charter cost. Therefore, the sub question 5 is answered.

6.2. Recommendation

The component wearing and vessel arrangement simulation model presents a solution to solve the fleet mix problem, and the results show the optimal fleet mix for chartering and purchasing. However, there are still some problems in the model. The problems and drawbacks of the model are listed as follows:

- **Computational requirements**: Compared with other available research that used heuristic methods, the component wearing and vessel arrangement simulation model used the MILP to solve the fleet optimization problem, which means the optimizer is aiming to find the exact solution for the optimization problem. However, the numerous maintenance tasks increase the number of constraints and variables in the optimization model, increasing its complexity. The optimizer cannot find an optimal solution in a fixed time. Additionally, the growing number of integer variables makes the space for feasible solutions to the problem discrete, complicating the optimizer's search for feasible solutions and making it difficult to converge. Although the mathematical model has been simplified, the problem still happens when the number of maintenance tasks in the maintenance cycle increases.

- **Downtime loss consideration**: The weather conditions of the offshore wind farm significantly influence the downtime loss of the wind turbines, which is directly related to the electricity generated. In the component wearing and vessel arrangement simulation model, to simplify the model and increase the computation speed, the downtime loss of the wind turbines is using an average calculation value based on the wind turbine's power, implying that the model does not accurately reflect reality.
- **Fixed start time**: The optimization and simulation model initiates the simulation on the day the offshore wind farm commences operations. At the start of the simulation, all the components are brand new, and a few maintenance tasks are generated. The results of the maintenance task execution are different between the first two years and the last two years.
- **Vessel charter start time irregular**: For the operator that needs an annual vessel charter strategy. Presenting the vessel charter strategy for each month is a more intuitive approach. By presenting the vessel charter probability each month, it's more apparent for the operator to decide which vessel should be chartered each month. However, the start time of the vessel charter contract is irregular, resulting in more difficult statistics, for example, for a 30-day vessel charter contract that crosses two months. It will be considered that the vessel will be chartered in both two months when calculating the vessel charter probability. However, reserving the vessels for two months is not cost-effective unless the shipowner provides a considerable discount rate on reserving the vessel in advance. Therefore, in the results presenting the cost saved from reserving the vessel in advance, it's cost-effective unless the discount rate reaches 40%

To solve the problems and drawbacks of the component wearing and vessel arrangement simulation model, the following improvements can be made:

- **Implement with heuristic methods**: The main challenges for MILP in solving large-scale optimization problems are the high computational requirements and complex convergence. Heuristic methods like genetic algorithms are recommended to solve the problem of no convergence.
- **Improved maintenance strategy**: The preventive maintenance check has already determined whether the components require maintenance during winter periods and has carried out the necessary repairs ahead of schedule. The maintenance tasks generated near the start of the winter maintenance period fall under the opportunistic maintenance strategy. The opportunistic maintenance strategy does not execute these tasks in advance, exposing them to significant penalty costs during the winter period. By improving the maintenance strategy, the opportunistic maintenance tasks generated at the end of the optimal maintenance period can be rescheduled to avoid huge penalty costs.
- **Combine the maintenance tasks on the same wind turbine**: In the closed-loop simulation model, the maintenance tasks are executed separately, and the downtime costs are calculated independently among the maintenance tasks. To further improve the model, combining the maintenance tasks on the same turbine can be considered, and the calculation of the downtime cost can be more relevant to reality.
- **Combine the weather condition with the downtime loss**: The offshore wind farm's downtime loss is directly related to the wind speed. Combining the weather conditions with the downtime loss can make the maintenance strategy closer to reality.
- **Giving bonus of renting the vessel in an entire month**: To avoid the vessel charter contract across months. Adding up a bonus for making the vessel charter start at the beginning of the month and terminate at the end of the month may lead to the vessel charter period tending to start at the beginning of the month and terminate at the end of the month, which helps to decide to charter the vessels on which months by observing the minimum cost.

- **Integrate overlapped maintenance cycle**: The maintenance cycle generated by the opportunistic maintenance strategy sometimes has a maintenance period overlapping with the maintenance cycle generated by the preventive maintenance strategy. Although the VAC has been introduced to make the same vessel, which can be used for both maintenance cycles generated by opportunistic and preventive maintenance, changes in vessel arrangement only happen on the maintenance cycle with a later generation time. Integrating the overlapped maintenance cycles and running the optimization together can better solve the fleet mix problem

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A

Appendix

A.1. Maintenance strategy logistics

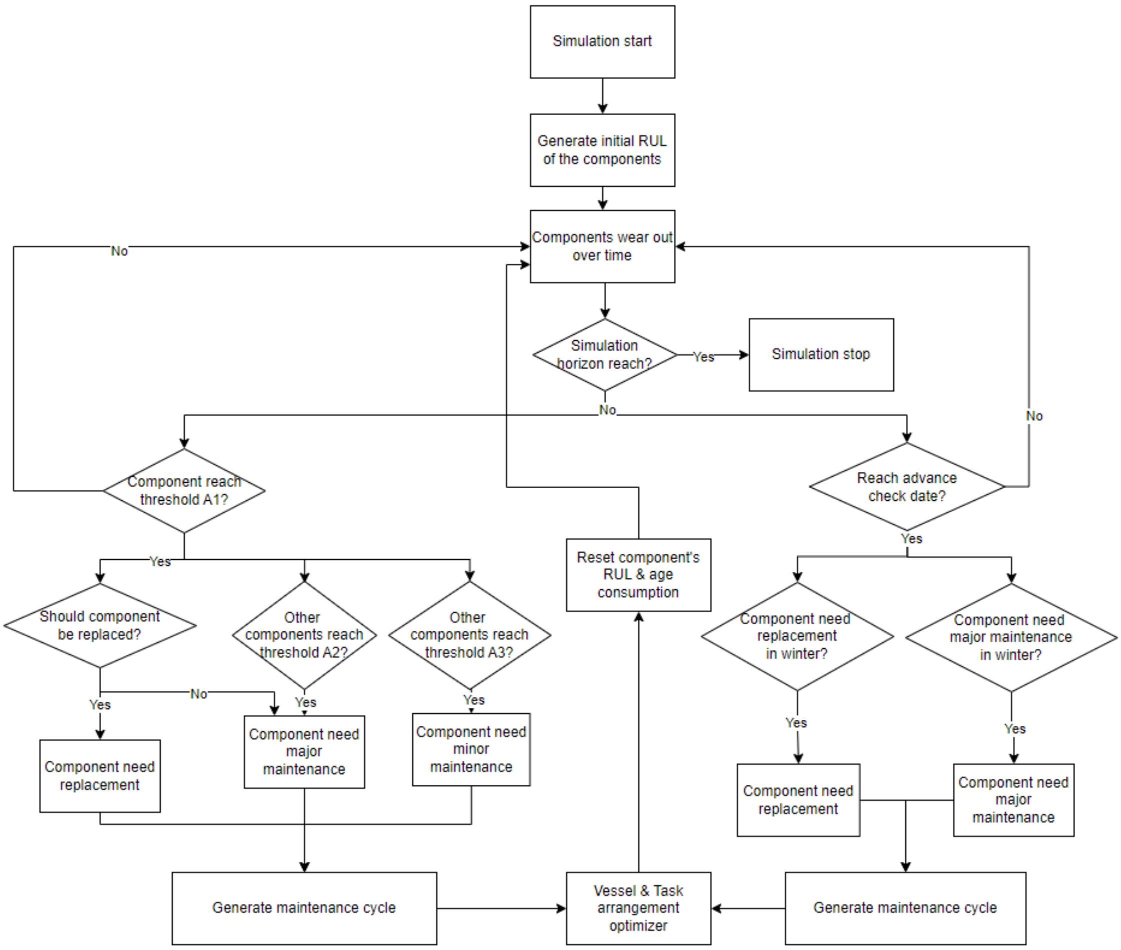

Figure A.1: Age-based opportunistic maintenance & preventive maintenance strategy logistics

A.2. Pseudo Code

Algorithm 1 Aged-based opportunistic maintenance simulation

```
Procedure Generate maintenance cycles
Input data Wind turbine set (N_t), Component set (C), Age consumption threshold (A1,A2,A3), start date, simulation time-span (n-days)
for day in 1 to n-days do
  day ← day + 1
  for turbine in 1 to N_t do
    for components in 1 to C do
      Age += 1/RUL
      if Age reach replacement threshold then
        Check whether component need replacement
        if Component need replacement then
          Need maintenance = True
          Component as trigger, generate maintenance requirement
        else if Component need major maintenance then
          Need maintenance = True
          Component as trigger, generate maintenance requirement
        else
          pass
        end if
      end if
    end for
  end for
  if Need maintenance = True then
    Check other components age
    for turbine in 1 to N_t do
      for components in 1 to C do
        if Component need major maintenance or minor maintenance then
          Generate maintenance requirement, combine with trigger
        else
          pass
        end if
      end for
    end for
  end if
  if Maintenance requirement generated then
    Requirement sent to optimizer for vessel arrange optimization
    Optimizer generate maintenance execution data, include maintenance finish day
  else
    pass
  end if
  for turbine in 1 to N_t do
    for components in 1 to C do
      if day = maintenance finish day then
        Maintenance finish
        if Maintenance task is replacement then
          Set new RUL for components
        else if Maintenance task is major or minor maintenance then
          Reduce age consumption
        else
          pass
        end if
      else
        pass
      end if
    end for
  end for
end for=0
```

Algorithm 2 Age-based preventive maintenance simulation

```
Procedure Generate maintenance cycles
Input data Wind turbine set ($N_t$), Component set (C), Age consumption threshold (A1,A2,A3), start
date, simulation time-span (n-days), winter period ($Month_{start}$ & $Month_{end}$)
for $day$ in 1 to n-days do
  $day \leftarrow day + 1$
  for $turbine$ in 1 to $N_t$ do
    for $components$ in 1 to $C$ do
      Age += $\frac{1}{RUL}$
      Estimate replacement day = (A1-Age)*RUL + day
      Estimate major maintenance day = (A2-Age)*RUL + day
    end for
  end for
  if Time reach $Month_{start} - 2$ then
    Check components estimate reach A1 and A2 date
    if Component estimate replacement date in winter period then
      Need maintenance = True
      Component as trigger, generate replacement maintenance requirement
    else if Component estimate major maintenance date in winter period then
      Need maintenance = True
      Component as trigger, generate major maintenance requirement
    else
      pass
    end if
  end if
  if Maintenance requirement generated then
    Requirement sent to optimizer for vessel arrange optimization
    Optimizer generates maintenance execution data, and includes maintenance finish day
  else
    pass
  end if
  for $turbine$ in 1 to $N_t$ do
    for $components$ in 1 to $C$ do
      if $day$ = maintenance finish day then
        Maintenance finish
        if Maintenance task is replacement then
          Set new RUL for components
        else if Maintenance task is major or minor maintenance then
          Reduce age consumption
        else
          pass
        end if
      else
        pass
      end if
    end for
  end for
end for=0
```

Algorithm 3 Aged-based opportunistic maintenance with time-based preventive maintenance

```
Procedure Generate maintenance cycles
Input data Wind turbine set (N_t), Component set (C), Age consumption threshold (A1,A2,A3), start
date, simulation time-span (n-days), optimal maintenance period (Month_start & Month_end), winter
period
for day in 1 to n-days do
    day ← day + 1
    for turbine in 1 to N_t do
        for components in 1 to C do
            Age += 1/RUL
            if Age reach replacement threshold then
                Check whether component need replacement, generate maintenance requirement
            end if
        end for
    end for
    if Need maintenance = True then
        Check other components age
        for turbine in 1 to N_t do
            for components in 1 to C do
                if Component need major maintenance or minor maintenance then
                    Generate minor or major maintenance requirements and combine with trigger
                end if
            end for
        end for
    end if
    if Time reach Month_start − 2 then
        Check components estimate replacement or major maintenance date
        if Component needs replacement or major maintenance in winter period then
            Generate maintenance requirements
        end if
    end if
    if Maintenance requirement generated then
        Requirement sent to optimizer for vessel arrange optimization
        Optimizer generate maintenance execution data, include maintenance finish day
    else
        pass
    end if
    for turbine in 1 to N_t do
        for components in 1 to C do
            if day = maintenance finish day then
                Maintenance finish
                Reset or reduce component's RUL
            end if
        end for
    end for
end for=0
```

A.3. Sensitivity analysis vessel cost distribution

Type	Charter cost (keur/year)	Travel cost (keur/year)	Repair cost (keur/year)	Downtime cost (keur/year)	Penalty cost (keur/year)	Stay overnight cost (keur/year)
Baseline condition	40356.3	44.1	351.6	1953.6	171.8	0.3
Weather scale parameter *0.5	40922.7	43.7	353.3	1953.9	202.5	0.3
Weather scale parameter *1.5	40501.1	43.9	352.4	1937.1	179.2	0.3
Vessel charter length *0.5	33797.8	44.1	351.1	2025.8	185.4	0.3
Vessel charter length *1.5	43980.5	44.1	351.1	2025.8	185.4	0.3
Component's age consumption threshold -0.05	45780.1	47.8	387.2	2188.4	198.6	0.5
Component's age consumption threshold +0.05	42092.6	46.8	363.5	2096.1	169.6	0.4
Wind turbine amount decrease to 10	20253	12.8	208	730.2	73	0.2
Wind turbine amount increase to 30	61702.3	30.7	477.5	2841.1	250	0
Maintenance duration * 0.5	26287.7	21.4	363.8	856.9	78.1	0.1
Maintenance duration * 1.5	46676.4	60.4	356.9	3258.8	419.7	0.6
Maintenance period length decrease to 60 days	33404.6	42.4	364.3	1552.7	126.5	0.3
Maintenance period length increase to 120 days	43847.5	22.1	346.4	2077.4	358.2	0.6
Coefficient of vessel arrangement closeness decrease to 0.1	44290.1	49.8	354.4	2423.4	160.3	0.1
Coefficient of vessel arrangement closeness increase to 10	36930.9	41.8	368.1	1685.5	152.7	0.2
Vessel charter cost *0.5	20747.9	44.1	351.7	1953.6	171.9	0.3
Vessel charter cost *1.5	59867.1	44.1	351.7	1953.6	171.9	0.3

Table A.1: Sensitivity analysis result on vessel cost

A.4. Vessel charter probability distribution

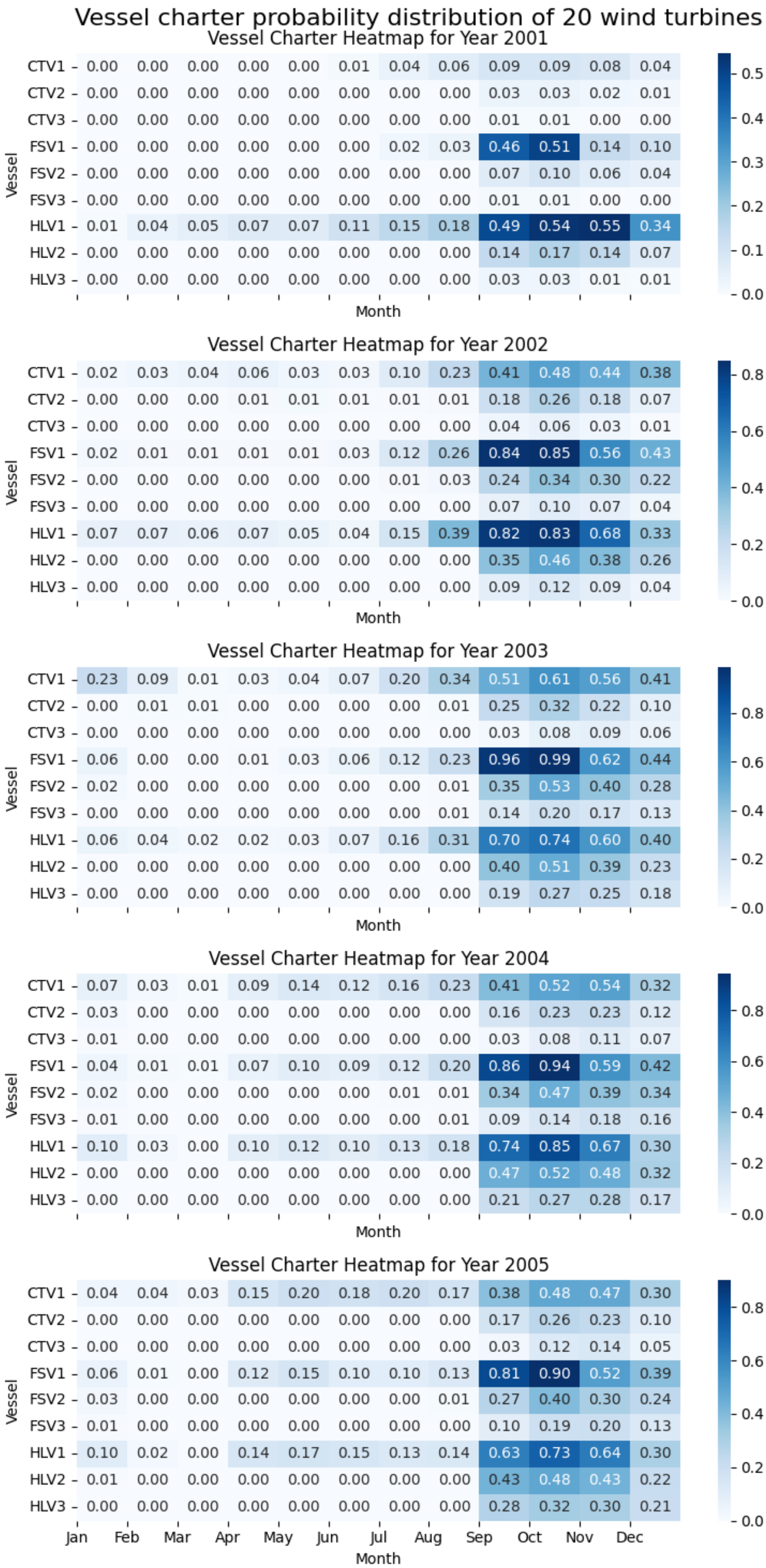

Figure A.2: Vessel charter probability of 20 wind turbines

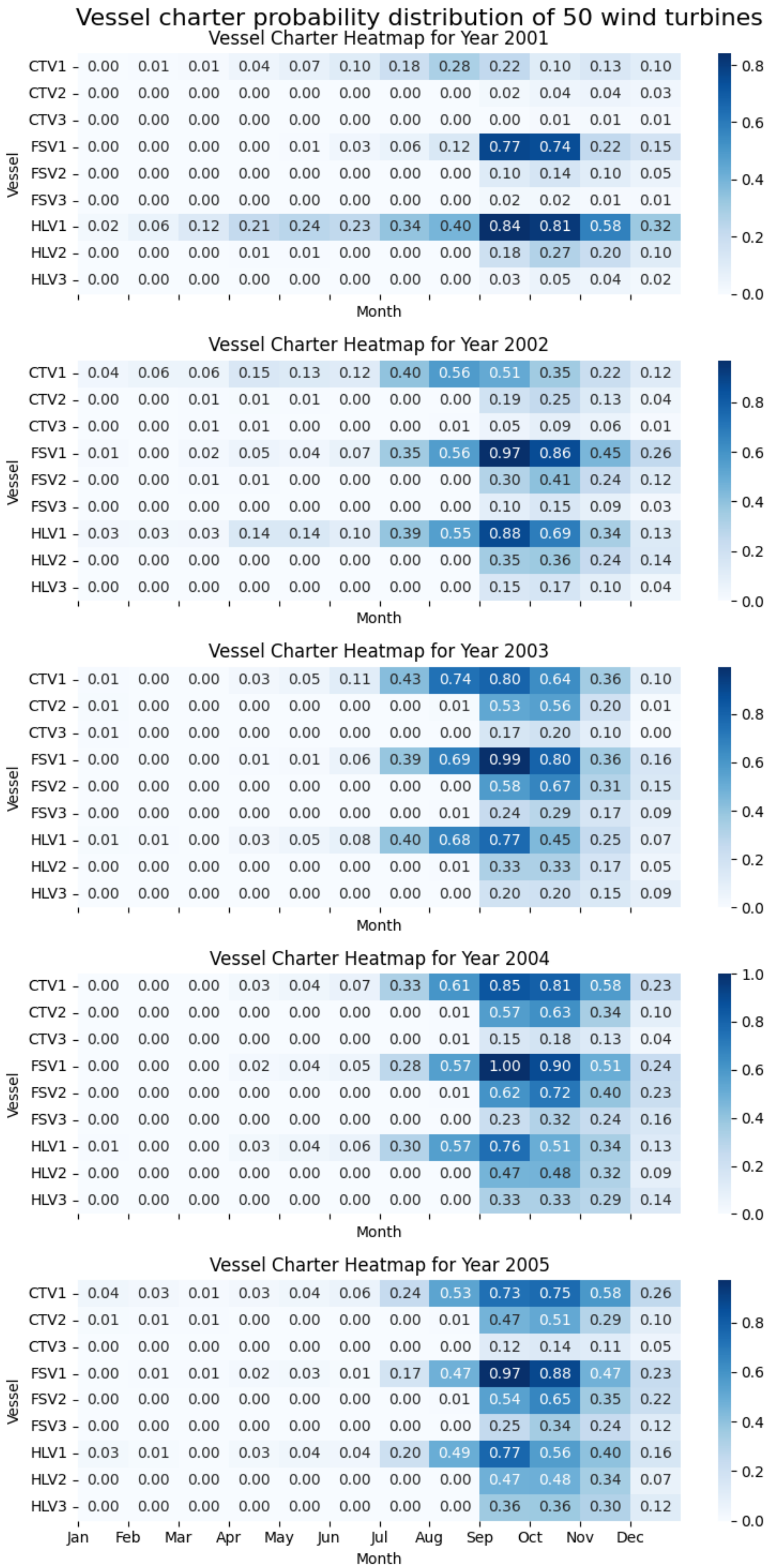

Figure A.3: Vessel charter probability distribution of 50 turbines

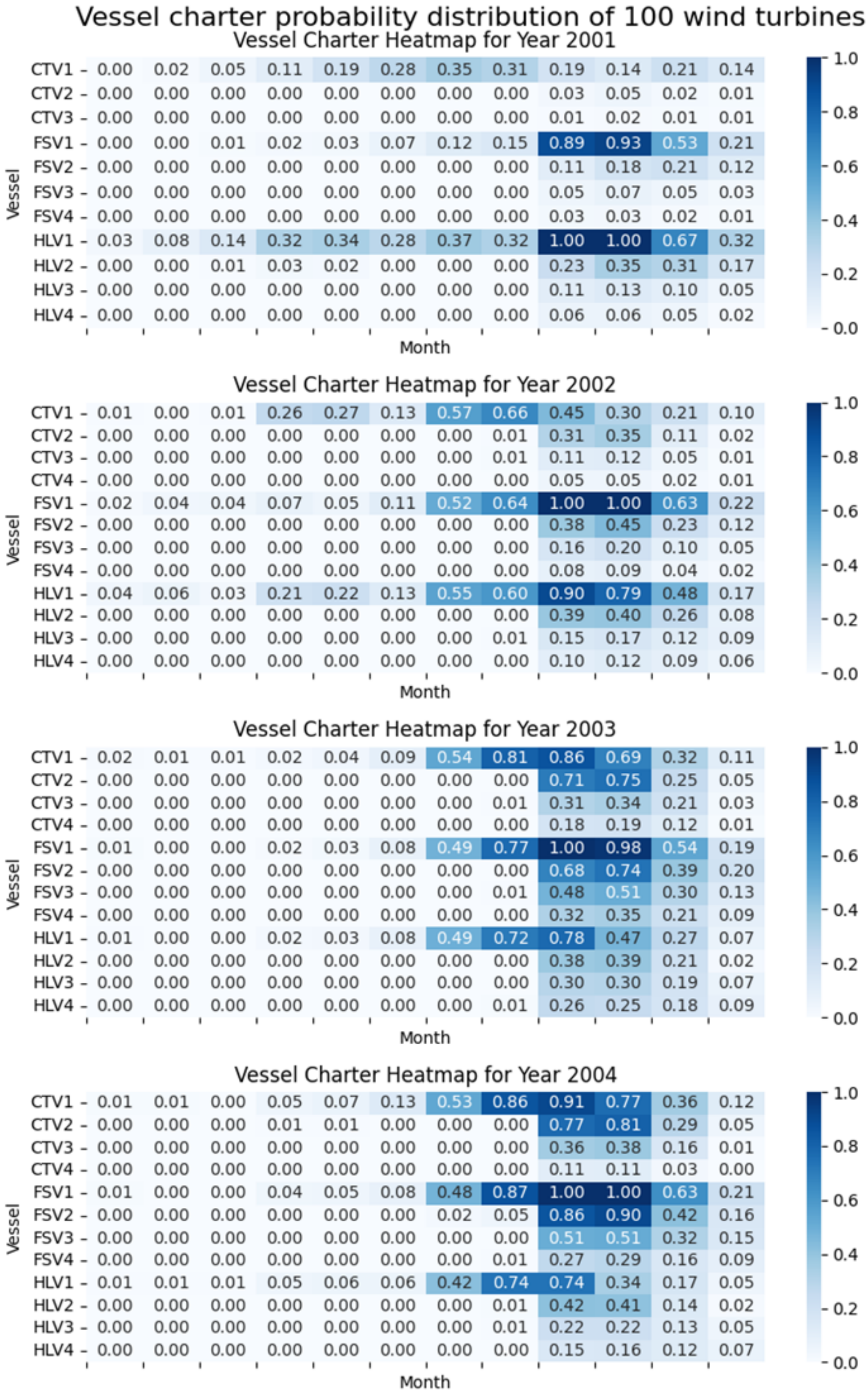

Figure A.4: Vessel charter probability distribution of 100 turbines

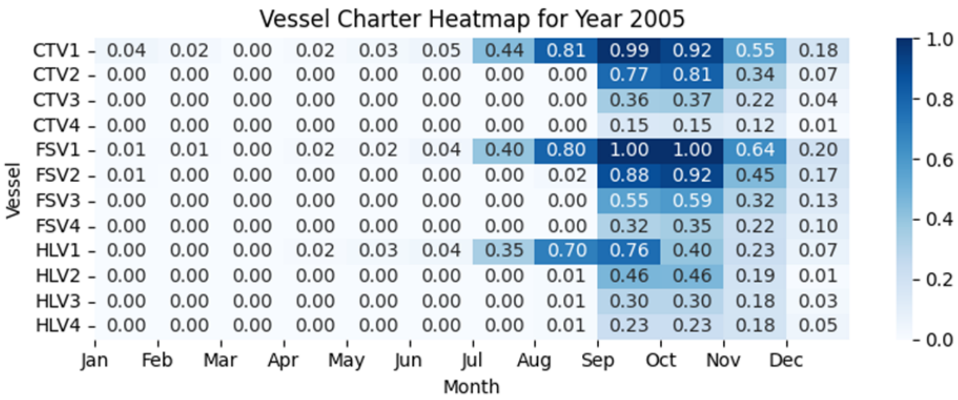

Figure A.5: Continue: Vessel charter probability distribution of 100 turbines

A.5. Scientific paper

Fleet selection for offshore wind farm operation and maintenance

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***Abstract*—The offshore wind farm plays an important role in generating electricity for society. The offshore wind farms are far from the shores, so the fleet needs to transport the technicians and equipment for maintenance. Therefore, the vessel acquisition cost is a huge proportion of the overall operation and maintenance cost. Optimizing the vessel fleet to minimize the vessel acquisition cost is a cost-effective way to reduce the overall O&M cost for the operators. This paper proposes a component wearing and vessel arrangement simulation model based on an age-based opportunistic and preventive maintenance strategy. The core module – task & vessel arrangement module is an optimizer based on linear programming, which is used to arrange the optimal fleet mix and task execution with the minimum vessel charter cost. The case study with the input data from the latest available research is executed, and the sensitivity analysis is performed to determine the simulation model's sensitivity factors. The 3D plot of different initial vessel purchase amounts is shown so the operators can decide the optimal initial vessel purchase amount for the offshore wind farm. The vessel charter probability distribution is presented with the figure showing how the vessel cost is saved from booking the vessel in advance, which helps the operator decide the vessels to be reserved for upcoming maintenance tasks.**

***Index Terms*—Offshore wind farm, Operation and maintenance, Optimization, Mixed integer linear programming, Task scheduling, Fleet size and mix problem**

I. Introduction

The goal of reducing greenhouse gas emissions has become imperative in society's development. Sustainable energy, particularly electricity, will be in high demand. The wind farm, among the various sources of sustainable energy, plays an important role in generating electricity with the power of the wind. Based on the location, the wind farm can be classified into onshore and offshore wind farms.

Unlike onshore wind farms, offshore wind farms (OWF) are located above the ocean, where the wind exhibits consistently outstanding power. The OWF's location allows the turbine to generate powerful electricity more efficiently. The offshore wind turbine has a larger scale to withstand harsher conditions, including stronger winds and severe weather conditions over the ocean. An offshore wind turbine in the North Sea has a rotor diameter of 222 m and a rated power of 15 MW [23]. In comparison, an onshore wind farm's turbine has a rotor diameter of 97–117 m and a rated power of around 1.5–3 MW [31]. A larger size of the wind turbine makes the wind turbine generate more electricity but also brings challenges for the operation and maintenance (O&M) of the offshore wind farm. The challenges of the O&M of the OWF come from the following aspects:

- **The OWFs are far away from the shore**: To acquire stable and strong wind energy, the OWFs are far from the shore, which increases the unavailability of the technicians and reduces their accessibility to the wind turbines. To execute the maintenance, the operators must hire a fleet to transport the technicians and equipment to the wind turbines.
- **The uncertainty of the weather**: Unlike the onshore wind farm that provides easier access to the wind turbines. The OWF requires technicians to travel to the wind farm by vessel. The vessel's accessibility to the wind turbines heavily depends on weather conditions [25]. The weather limits the maintenance's execution. If weather issues disrupt maintenance, the wind turbine will be offline for a long time, resulting in significant losses.
- **High maintenance costs**: Even after decades of development, the equipment for OWF operations is still relatively expensive. Advanced equipment, such as motion-compensated gangways, has been applied to the vessels to make maintenance much easier than before [11]. The maintenance costs of OWFs are higher than the equivalent work on onshore wind farms.
- **Lack of maintenance resources**: The number of OWFs is growing; by the end of 2018, around 712 offshore wind projects were planned and 53 were under construction [24]. The requirements for O&M will increase significantly in the future. The growing requirements lead to a shortage of experienced technicians for wind turbine maintenance. Training the new technicians for the wind farms requires a significant investment of resources. The technicians who have already been trained have to do the training repeatedly to ensure they can work safely and efficiently [5].
- **Fleet selection for the maintenance execution**: To inspect and maintain offshore wind turbines, technicians must travel to the turbines with spare parts and tools. In this case, vessels are required to transport technicians and equipment. Choosing appropriate vessels is critical for the operators to achieve their goal of minimizing the OWF's total operating expenses. Operators face challenges related to fleet size and mix when choosing which types and models of vessels to deploy for transportation. This

challenge includes determining the best fleet of vessels and infrastructure to support an OWF's operation and maintenance [32].

The current challenges faced by OWFs necessitate an urgent optimization of the O&M process for operators to achieve their goal of reducing the operation cost. Fleet selection is a significant consideration in the operator's decision-making process. O&M consists of a variety of vessels that transport equipment and technicians between wind turbines and operation centers. Different types of vessels provide varying job capacities, presenting unique advantages and challenges for O&M tasks. The vessel acquisition cost accounts for approximately 50% of the O&M cost [8]. In this case, optimizing the vessel chartering strategy and solving the fleet mix problem is essential to reducing the total O&M cost by reducing the vessel chartering cost.

To solve the problem of fleet mix optimization, a decision support system (DSS) was created for OWF maintenance planning. This system integrates data, optimizes resources, and analyzes risks. Its goal is to help decision-makers find the best maintenance schedule for offshore wind turbines. The table I concludes the literature that focuses on the fleet mix problem. The available studies are summarized as follows: (1) the modeling approach; (2) the vessels involved in the problem; (3) the simulation horizon of the model; and (4) the solvers that were used. The table II concludes the mathematical models based on the available research. The available research is summarized on the following aspects: The summary of available research is based on three key aspects: (1) cost function; (2) constraints; and (3) uncertainty.

The DSS fleet mix problem model can be classified into two categories: deterministic programming and stochastic programming. In both modeling approaches, the mathematical model with objective function and constraints is built to solve the problem. Deterministic programming is an optimization process based on the deterministic model, which assumes the parameters and variables are all predictable without uncertainties. The constraints and objective functions are all deterministic and do not take into account stochastic factors. Deterministic programming is usually used to solve the problem that parameters and variables can be measured and controlled exactly, providing a more accurate and stable solution [22]. The studies [13] and [37] used deterministic programming to optimize the fleet mix problem with known information about weather conditions and component failure in advance. Deterministic programming can also be divided into multiple stages to address different levels of problems. The study [14] used the 2-stage deterministic model to evaluate the optimal vessel fleet mix for offshore wind farm maintenance by determining which base and what kind of vessels should be involved. On the other hand, stochastic programming is an optimization method that relies on uncertainties, thereby allowing for the stochastic nature of variables and parameters. The stochastic programming can fully consider the uncertainties and risks in the system, providing a more reliable result [16]. However, stochastic programming needs to consider the complex probability distribution; the computation time and computation cost are significantly higher than those of deterministic programming. The studies [17], [32], [34], and [33] used a two-stage stochastic programming method to pick the ships for maintenance work and how to organize their tasks. The study [12] introduced a 3-stage stochastic model where the fleet mix problem is solved in 2 stages instead of one, which considers more parameters.

The OWF uses vessels for its operations and maintenance. The Crew Transfer Vessel (CTV) plays an important role in transferring the technicians between the operation center and offshore wind farm [4]. The Field Support Vessel (FSV) transfers large quantities of technicians and equipment for maintenance, as well as providing the capability of staying offshore [20]. For all the available research that mentioned the vessel deployment in table I, most of them include the arrangement of the CTVs and FSVs. The crane vessel (CV), like the heavy lift vessel (HLV) or jack-up vessel (JUV), is used to lift large equipment or spare parts during maintenance. The studies [16] and [34] involve the CVs in the optimization, considering the replacement activities of the maintenance that need the involvement of the CVs.

The available research simulation horizon is mainly focused on 1 year, which can be considered a short-term optimization. The DSS focuses on vessel arrangements and routing problems. This has the benefit of incorporating the entire year's seasons and weather into the modeling process, bringing the system closer to the real situation over time and making cost calculation easier. The long-term optimization has also been considered in the available research. The study [32] chose the 25-year simulation horizon to calculate the entire operation cost of the OWFs.

The mathematical models are solved using commercial solvers. The available research uses commercial solvers like FICO Xpress or CPLEX due to their extremely high performance and adaptability on different computation platforms, which help the operators make decisions efficiently.

The mathematical model of optimization consists of cost functions, constraints, and uncertainty factors. The cost function in the DSS that concentrates on the routing, scheduling, and fleet mix problems focuses on the costs associated with the OWF. The study [6] focuses on the routing, scheduling, and vessel arrangement problems and has the cost function that is related to the downtime cost and maintenance incomplete penalty of the wind turbines. For studies that concentrate on the fleet mix problem, it is necessary to consider the costs associated with both vessels and offshore wind farms. The studies [7], [16] and [22] consider the vessel charter cost, vessel mobilization cost, and travel cost of the vessels. The cost of wind turbine downtime is also taken into account. The studies [14] and [32] consider the vessel charter and technician cost, as well as the maintenance incomplete penalty from the OWFs. Additionally, vessel and port constraints are taken into account. The studies [6], [12], and [28] considered the offshore operation time and wind turbines visit amount limitation of the vessel. The studies [16], [32], and [34] considered the vessel capacity of the harbor and the initial available vessel amount in the port. The maintenance execution constraints have also been taken into consideration. The studies [14] and [36] take the personnel onboard for each vessel during the maintenance into

Ref	Modelling approach		Vessel				Simulation horizon	Solver
	Deterministic programming	Stochastic programming	CTV	FSV	CV	Other		
[16]	√	√	√	√	√	√	1 year	FICO Xpress
[17]		√	√	√			3 month	FICO Xpress
[12]		√	√	√			1 year	FICO Xpress
[14]	√						1 year	CPLEX
[13]	√						1 year	CPLEX
[32]		√					25 year	FICO Xpress
[34]		√	√	√	√		1 year	FICO Xpress
[33]		√					1 year	FICO Xpress
[37]	√		√	√			8 year	FICO Xpress

TABLE I
LITERATURE ON FLEET MIX PROBLEM

Ref	Cost		Constraint			Uncertainty		
	Vessel	Offshore wind farm	Vessel	Maintenance Execution	Port	Offshore wind farm	Vessel	Climate
[6]		√	√	√	√			
[7]	√	√	√		√		√	√
[16]	√	√	√	√	√	√		√
[9]			√	√	√			
[14]	√	√		√	√	√		√
[13]	√	√	√	√	√	√		
[12]	√	√	√		√	√	√	√
[22]	√	√	√	√	√			
[26]			√	√				
[28]			√		√			
[32]	√	√		√	√	√		√
[34]	√	√	√	√	√	√		√
[36]			√	√	√			
[40]			√		√			
[41]			√	√				
[42]			√	√	√			

TABLE II
LITERATURE ON FLEET MIX PROBLEM MATHEMATICAL MODEL

consideration. The studies [41] and [42] limit the maintenance accomplishment during the maintenance execution period.

The previous papers all focused on the optimal vessel fleet mix to be chartered during operations and maintenance. For some large-scale offshore wind farms, where the maintenance tasks are numerous and lengthy, chartering the vessels for a long time will increase the vessel acquisition cost. In this case, purchasing some vessels for maintenance in advance in the harbor at the beginning will reduce the vessel acquisition cost. In this research, the simulations with different initial purchase amounts of vessels are attempted to find the optimal initial vessel purchase combination and give the annual vessel charter cost and vessel acquisition cost under different initial purchase combinations.

II. MODEL STRUCTURE

A. Model Assumption

Due to the complexity of the offshore wind farm maintenance process, many real-life factors need to be considered. Therefore, specific assumptions need to be made when constructing the simulation model to ensure that the model can be simplified and, at the same time, close to the actual situation. At the same time, considering that different terms have different meanings in various studies, explaining some terms involved in the simulation model is necessary.

- **Time step**: The model simulates the offshore wind farm's operation and maintenance (O&M) process following the time. The simulation time step defines how the simulation model moves from one point in time to the next, referring the discrete interval between each calculation and update within the simulation. The model's simulation time step is one day and will be referred to as a time step in later content. In this thesis, the time step of the simulation model is one day
- **Maintenance cycle**: The maintenance cycle refers to a maintenance blog containing the maintenance tasks generated on the same day. When the age consumption of one of the components reaches the threshold for triggering maintenance, the system generates the maintenance cycle. It sends it to the optimizer for vessel and task arrangement.
- **Maintenance period**: The maintenance period is a start-to-finish time that is used to perform all maintenance tasks in the maintenance cycle. In this thesis, the maintenance period is assumed to be 90 days after the generated maintenance cycle.
- **Maintenance execution time**: The maintenance execution time refers to the time spent on the maintenance of the components during the optimization of the vessel and task arrangement. The maintenance execution time in the simulation model is calculated by hours, which refers to the hours spent on executing the maintenance task. The time spent executing maintenance tasks is considered constant and remains unaffected by weather conditions. Multiple vessels are required to execute maintenance tasks. The maintenance execution time solely accounts

for the hours all vessels are available to complete the task.

- **Maintenance execution**: Different kinds of maintenance are executed independently, even if the tasks are on the same wind turbine. A wind turbine with multiple components must be maintained in the maintenance cycle. The maintenance tasks are performed independently by different maintenance groups and can be considered to be executed simultaneously, unaffected by others. The maintenance execution time equals the component's maintenance duration. The maintenance task is considered finished.
- **Simulation horizon**: The simulation horizon of the model refers to the number of days between the simulation start time and end time. At the beginning of the simulation, a day number counter in the model is set to zero and plus one after each time step. When the day number counter reaches the simulation horizon, the simulation will stop. In this thesis, the simulation horizon is set to 5 years, which refers to 1825 days.
- **Weather condition**: The weather conditions, including wave height and wind speed, independently influence whether the vessels operate. The weather condition covers the whole day and is assumed to be constant for 1 hour (equal to 24 periods in one day).
- **Component**: The components' lifetimes are independent, and the wearing process is only related to the RUL (Remain Useful Life) and time. The component can only be maintained once during each maintenance cycle. The components in a maintenance cycle will not be considered in other maintenance cycles.
- **Technicians and spare parts**: It is assumed that spare parts are always available in the operation center, and each vessel can carry all the spare parts for executing the maintenance tasks. The number of technicians in the operation center is unlimited, and they can be deployed to the vessels for maintenance at any time.
- **Vessel charter length**: The vessel charter period represents the period from the day the vessel starts to be chartered until the day the vessel charter contract terminates. Each kind of vessel has a minimum charter period and an extended charter period. If the vessel requires fewer days than the minimum charter period, it must still be chartered for the entire minimum period. The operator can extend the vessel's charter period at the end of the minimum charter period. The vessel that has been chartered during the extended charter period must be chartered till the end of the extended charter period.
- **Vessel mobilization time**: The mobilization is an action that transfers the vessel from the ship owner to the operator, and it takes a few days for the vessel to travel between the ship owner and operator, which is called the mobilization period. To show the impact of mobilization on vessel chartering, when the vessel's charter contract ends, the ship owner will move the vessel back from the operator, and the operator needs to move the vessel from the operator for the next charter period. In this case, the same vessel would not be available for at least two mobilization periods between two charter contracts.
- **Vessel travel distance**: The simulation model considers the vessel deployment and chartering for the maintenance execution of the wind turbines. Therefore, vessel routing and travelling on wind farms are not part of the scope of the research. The travelling distance of the vessel in the simulation model refers to the distance that the vessel travels from the port to the offshore wind farm. Travelling within the wind farm is not considered.
- **Vessel travelling time**: The travelling speed of the vessels between the operation centre and the offshore wind farm is assumed to be constant, and the travel time is calculated by the distance divided by the average travel speed. The simulation model is focused on the vessel and task arrangement. In this case, the inter-transit times between each wind turbine are assumed to be ignored.

B. Component wearing simulation model

The component wearing simulation model is developed by Marco Borsotti (will be referred to as Marco's model later in this paper). Marco's model simulates the component wearing, maintenance generation, and execution of the wind turbines on the offshore wind farm. Marco's model includes data input, component wearing and monitoring module, maintenance cycle generation & execution module, and the data output module. Figure 1 shows the flow chart of the initial model.

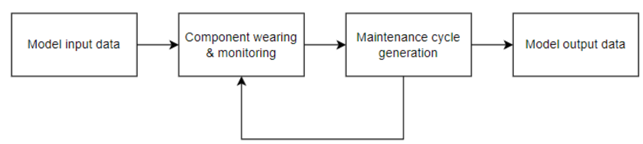

Fig. 1. Component wearing simulation model

1) Model input data: Marco's model assumes the lifetime of the components follows the Weibull distribution. Therefore, the Weibull shape parameter and Weibull scale parameter of the components serve as the input data of the components. The table III shows the component information inputs of the component wearing & monitoring module.

No	Item	Unit
1	Number of wind turbines	turbines
2	Simulation horizon	day
3	Component name	-
4	Component shape	-
5	Component scale	-
6	Component replacement cost	keur
7	Component major repair cost	keur
8	Component minor repair cost	keur
9	Component replacement time	hour
10	Component major repair time	hour
11	Component minor repair time	hour
12	Component replacement probability	-

TABLE III
INPUT DATA OF MARCO'S MODEL

The input [1] shows the number of wind turbines in the OWF, which is related to the size of the components' RUL matrix generation in this module. The input [2] refers to the simulation horizon of the simulation model. The inputs [3-5] are the components' names and the shape and scale parameters of the components. The component's RUL is generated using the input [3, 4], following a Weibull distribution. The inputs [6-11] show the cost and time of maintaining the components. The input [12] represents the probability of replacing the component after it reaches the replacement life threshold. The RUL and age consumption of the components are estimated and converted into output and updated daily to the maintenance requirement generation part.

2) Component wearing and monitoring: The component wearing and monitoring module simulates the wearing and degradation of the components during the operation of the offshore wind farm and establishes the age consumption of the components. At the beginning of the simulation, the matrices that refer to the components' remaining useful life (RUL) and age consumption and the corresponding wind turbine number are established. The equation 1 shows how the RUL of the components is calculated using the Weibull distribution [3]. The age consumption of the components is 0 at the beginning of the simulation. However, when the day number increases, the age consumption of the components adds up to the inverse of the RUL. The equation 2 shows how the age consumption of the component increases by the day.

$$\text{RUL}_{\text{true}} = \lambda \left(-\ln(U)\right)^{\frac{1}{\alpha}}, \quad U \sim \text{Unif}(0,1) \tag{1}$$

$$\text{Age consumption}_{\text{d+1}} = \text{Age consumption}_{\text{d}} + \frac{1}{\text{RUL}} \tag{2}$$

The component wearing and monitoring module simulates the RUL, and the age consumption of the components increases over time. Sending the age consumption of the components to the next module, the maintenance cycle generation module. When the maintenance tasks are finished, the RUL and age consumption of the components are changed; the table IV shows the age consumption reduction of the components when the corresponding maintenance is executed. When the component has been replaced, the RUL of the components will be regenerated.

At each simulation time step, the component wearing and monitoring module sends the matrix containing the components' age consumption to the next module, the maintenance cycle generation module. In the following module, the age consumption of the components is monitored and used to generate the maintenance cycle.

3) Maintenance cycle generation: Marco's model generates the maintenance maintenance cycles following the age-based opportunistic maintenance strategy. The maintenance cycle generation module monitors the age consumption of the components. When the age consumption of the components reaches the threshold of replacement (Zone 4), the maintenance cycle is triggered, and the age consumption of the rest of the components is checked to see whether they reach the threshold of major maintenance (Zone 3) or minor maintenance (Zone 2) [20]. If so, the components needing major or minor maintenance will be added to the maintenance cycle. When the maintenance cycle is generated, the components are assumed to be repaired immediately. The maintenance execution data will be stored as model output data and sent back to the component wearing and monitoring module. The table IV shows the age consumption threshold for different types of maintenance.

Maintenance type	Component age consumption (%)	Zone	Maintenance age reduction	Component's RUL	Vessel type
No maintenance	[0,50)	Zone 1	-	-	-
Minor maintenance	[50,80)	Zone 2	30%	Keep remain	CTV
Major maintenance	[80,95)	Zone 3	50%	Keep remain	FSV
Replacement	[95,100)	Zone 4	New component	Regenerate	HLV

TABLE IV
MAINTENANCE STRATEGY [20]

The maintenance cycle generation module assumes that all the maintenance tasks in the maintenance cycle can be executed and finished immediately. The maintenance cycle containing the maintenance tasks and finish time is generated and sent back to the component wearing and monitoring module, where the age consumption and RUL of the corresponding components will be reset.

4) Model output data: Marco's model generates the maintenance blog of the components in the wind turbines during the whole simulation horizon. The table V shows the output data contained in the maintenance blog of Marco's model.

No	Item	Unit
1	Maintenance cycle	-
2	Turbine number	-
3	Component name	-
4	Maintenance type	-
5	Age consumption	-
6	Maintenance date	YYYY-MM-DD
7	Maintenance duration	hour

TABLE V
OUTPUT DATA OF MARCO'S MODEL

The output [1] indicates the maintenance cycle number during the simulation horizon. The output [2,3] shows the component name and its corresponding wind turbine that needs maintenance. The output [4,5] shows the component's maintenance type and the age consumption value when the maintenance cycle is generated. The output [6] indicates the date the maintenance cycle is generated. The output [7] represents the maintenance duration for executing the maintenance of the component.

C. Component wearing and vessel arrangement simulation model

Marco's model presents the components wearing, maintenance cycle generation, and maintenance execution, which simulates the components' degradation and maintenance of the offshore wind farm. However, there are still some disadvantages in Marco's model:

- **Maintenance complete immediately**: Marco's model assumes that the components will be repaired immediately when the maintenance cycle is triggered. However, technicians and equipment are required to transfer to the wind turbines to execute maintenance tasks, resulting in the maintenance tasks not being finished immediately. The finish time for the maintenance tasks will be delayed by a couple of days, which will affect the age consumption reduction of the components and further affect the generation of the following maintenance cycles. In this case, choosing the appropriate fleet and arranging the maintenance tasks for each maintenance cycle is necessary.
- **Maintenance cycle generation time**: The age-based maintenance strategy generates the maintenance cycle when one of the components reaches the age-consumption threshold of replacement. Therefore, the maintenance cycle generation time is related to the components' RUL and age consumption value, which are random numbers following the Weibull distribution. Thus, the maintenance cycles can be generated at any time of the year. However, during certain times of the year, such as winter, performing maintenance tasks is unsuitable for vessels traveling. The maintenance cycle generated in the winter period might lead to the maintenance tasks being unable to be performed, resulting in the wind turbines turning off and producing downtime costs. In this case, avoiding the maintenance tasks generated in the winter period is necessary.

Based on Marco's model's drawbacks, a component wearing and vessel arrangement simulation model was developed (which will be referred to as the current model later in this paper). Compared with Marco's model, the current model has the following improvements.

- **Maintenance tasks arrangement**: In contrast to assuming the immediate component repair. The current model incorporates the task and vessel arrangement module in the feedback loop between the maintenance cycle generation module and the component wearing & monitoring module. The maintenance cycle is generated and sent to the task and vessel arrangement module, where the maintenance task execution date and corresponding vessels for executing the maintenance will be arranged. The maintenance tasks' finish days are returned to the component wearing & monitoring module to reset the components' age consumption and RUL.
- **Introduce preventive maintenance**: An age-based preventive maintenance strategy is introduced to avoid the maintenance cycle being initiated in the winter period. The maintenance cycle containing replacement and major maintenance is created and executed before the winter period of every year. Avoiding the maintenance cycle triggered by age-based opportunistic maintenance in the winter period.
- **Generate vessel charter strategy after simulation**: Introducing the preventive maintenance strategy makes both opportunistic and preventive maintenance strategies can trigger the maintenance cycles. For the two maintenance cycles with the generation date close to each other, the two maintenance periods might overlap. To solve the overlapping problem, the vessel chartering strategy will not be created for each maintenance cycle. Instead, the vessel requirements for executing the maintenance every day are stored and sent to the vessel charter strategy generation module after the simulation stop, in which the vessel charter strategy is generated based on the initial vessel purchase amount and vessel requirement.

Figure 2 shows the flow chart of the current model. The two additional modules that arrange the vessel and generate vessel charter strategy based on Marco's model are highlighted.

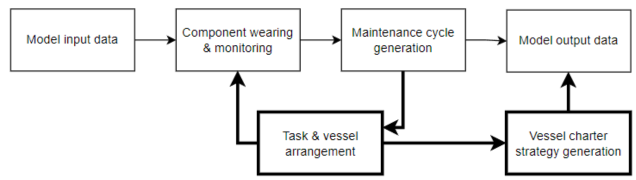

Fig. 2. Component wearing and vessel arrangement model

1) Input data: The component wearing and vessel arrangement model involves the task scheduling for the maintenance execution and vessel arrangement for transporting the technicians to the offshore wind farm. Therefore, apart from the wind turbine data already shown in table III. The extra information related to the vessel chartering, vessel deployment and vessel arrangement is also considered.

- **Vessel inputs**
  The input data that is related to the vessel chartering is shown in table VI

No	Item	Unit
1	Travel cost	keur
2	Fuel cost	keur/ton
3	Fuel consumption	ton/h
4	Travel speed	km/h
5	Rental cost	keur/day
6	Mobilize cost	keur
7	Overnight cost	keur/night
8	Operation cost	keur
9	Limit wave height	m/s
10	Limit wind speed	m/s
11	Maximum parallel teams	team/vessel
12	Technician capacity	person
13	Mobilize time	day
14	Initial charter length	day/period
15	Extended charter length	day/period

TABLE VI
INPUT DATA OF VESSEL

The inputs [1] show the one-way travel cost of the vessel from the operator center to the offshore windfarm, which is calculated by the inputs [2-4], the fuel consumption of the vessel per hour, the travel speed of the vessel, fuel price, and the input [1] from table VII, the distance between the operation center and the wind farm. The inputs [5, 6] are the rental and mobilization costs of the vessel. When a vessel is chartered, the mobilization cost is calculated once, while the rental cost varies based on the number of days the vessel is chartered. The input [7] represents the vessel's overnight stay cost. When the vessel needs to be deployed for many days, it can stay overnight at the offshore wind farm to reduce travel costs between the wind farm and the operation center. The input [8] is the operation cost of the vessel; when the vessel is deployed to execute the maintenance, the operation cost is calculated. The inputs [9, 10] are the vessel's weather restrictions. When the weather condition of the specific hour is higher than the vessel's wind speed and wave height, the vessel is considered non-operational at that hour, and the maintenance execution will be suspended and continue until the next operational hour. The input [11, 12] shows the maximum parallel team the vessel can carry and the vessel's capacity to carry technicians between the operation center and the offshore wind farm. The input [13–15] shows the vessel's mobilization time and day limit for each charter period. The vessel must return to the ship owner after the charter period ends and move from the ship owner when the next charter period starts. In this case, the time gap between the two charter periods must be greater than the vessel's mobilization time. The vessel charter begins with an initial charter length and can be extended after the initial charter period.

- **Wind farm inputs**
  The inputs that are related to the maintenance execution of the wind farm are shown in table VII

No	Item	Unit
1	OWF distance	km
2	WT downtime cost	keur / day
3	Shift start	hh
4	Shift end	hh
5	Technician requirement	person
6	Minor maintenance team requirement	team
7	Major maintenance team requirement	team
8	Replacement team requirement	team

TABLE VII
INPUT DATA OF WIND FARM

The input [1] shows the distance between the OWF and the operation center. The input [2] shows the wind turbine's maintenance downtime cost. The inputs [3, 4] indicate the working period of the day for the maintenance shift. The inputs [5-8] show the technician requirements and the repair team needed for component maintenance.

2) Component wearing & monitoring: Compare with the component wearing & monitoring module in Marco's model. In the component wearing and vessel arrangement simulation. The matrices represent the estimated failure, replacement, major maintenance, and minor maintenance days for the components established. The estimated maintenance days of the components are calculated by the age consumption threshold and the RUL of the components. The equation 3 to 6 shows the computations for the estimated. The estimated maintenance days refer to the day numbers that components run into the corresponding zone shown in table IV.

$$EFD_{component} = day + (1 - Age_{component}) * RUL_{component} \tag{3}$$

$$ERD_{component} = day + (A1 - Age_{component}) * RUL_{component} \tag{4}$$

$$EMD_{component} = day + (A2 - Age_{component}) * RUL_{component} \tag{5}$$

$$EMIND_{component} = day + (A3 - Age_{component}) * RUL_{component} \tag{6}$$

3) Maintenance cycle generation: The maintenance cycle generation module generates the maintenance cycles that must be sent into the task & vessel arrangement module, apart from the aged-based opportunistic maintenance strategy used in Marco's model. The aged-based preventive maintenance strategy is combined with the age-based opportunistic maintenance strategy.

The O&M of the offshore wind farm is highly related to the area's weather conditions. Weather conditions such as wave heights and wind speed significantly affect maintenance execution by limiting the accessibility of vessels transporting the technician and equipment from the operation center [29]. Maintenance on offshore wind farms cannot occur throughout the year. The severe winter weather may make it impossible for the technicians to perform the necessary maintenance [35]. Suppose the failure happens during the winter season. In that case, it is possible that technicians will not be able to access the wind turbines for repairs, leading to a prolonged period of downtime and significant revenue losses.

To prevent failure during the winter season, A preventive maintenance strategy is introduced to combine with the age-based opportunistic maintenance strategy. The 12 months of the year are divided into the winter period and the non-winter period based on the suitability of the season. During the winter period, the vessels are difficult to travel, and a penalty will be applied if the vessels are still deployed. Under this maintenance strategy, a preventive component inspection is executed before the start of the winter period, which is a couple of months before. The monitoring system checks the RUL and estimates the components' failure dates. Suppose the components fail during the winter when maintenance is hard to execute. If possible, the maintenance requirement is generated, and maintenance tasks will be carried out before the winter. The winter period starts in November and ends in March of next year, the components' preventive inspection will take place in September since its monthly production is the lowest [1].

4) Task & vessel arrangement: The maintenance cycle generation module generates the maintenance cycle, which is then sent to the task & vessel arrangement module for arranging the vessel and maintenance tasks execution time. The task & vessel arrangement module arranges the maintenance task execution and vessel deployment based on the vessel's capacity, sea-keeping ability, weather conditions, task requirements, and maintenance cost. Each maintenance task's start and finish times are arranged and transferred to the component wearing and monitoring module as the feedback loop. The maintenance task execution and vessel deployment data are stored as the model output data.

The combination of the age-based opportunistic maintenance strategy and the age-based preventive maintenance strategy overlaps the problem of two maintenance cycles. The preventive check of the components takes place in September, which means the maintenance period of the maintenance cycle triggered by the age-based preventive maintenance strategy covers the time until November, while the rest time of September and October. There is still a chance that the age-based opportunistic maintenance strategy will trigger the maintenance cycle. In this case, the two maintenance cycles are overlapped with each other. Since the vessel arrangement is for a single maintenance cycle, when two maintenance cycles overlap, a situation occurs in which a vessel in one of the maintenance cycles parks in the harbour when it is idle and does not perform the tasks in the other maintenance cycle. More vessels are hired to perform the maintenance tasks.

To prevent the situation in which maintenance cycles overlap, many vessels are chartered for a short period and then rapidly become empty again. At each maintenance, the vessel charter strategy would not be determined. The task & vessel arrangement module generates the vessel requirement each day, giving the vessel requirement to the vessel charter strategy generation module, where the vessel charter strategy will be generated based on the vessel requirement. To prevent significant variations in the daily vessel requirement, resulting in an excessive number of vessels being chartered. The vessel arrangement closeness based on the Euclidean distance calculation method from the FLP (Facility Location Problem) is introduced to evaluate the closeness of the vessel arrangement.

According to this concept, the optimizer arranges the vessels and tasks for the current maintenance period. The vessels arranged during the previous maintenance cycle are considered the demanding points. The term facility refers to the vessels that must be arranged during this maintenance period. The optimizer arranges the vessels as close to the existing vessel arrangement. Figure 3 shows a small example of a 2-dimensional area. This figure presents the process of finding facilities for existing demand points, converting the facilities into demand points, and then finding new facilities. The locations of the facilities are chosen based on minimizing the total Euclidean distance of the facilities and demanding points. The equation 7 shows the calculation of Euclidean distance between each point [39].

$$\text{Distance} = \sum d_{ij} = \sum \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2} \quad (7)$$

d_{ij} : Euclidean distance between point i and j

X_i, X_j : Coordinates of point i and j on the x-axis

Y_i, Y_j : Coordinates of point i and j on the Y-axis

As shown in figure 3, the demand points are generated and shown in step 1, while in step 2, the facilities that fulfil the requirement of minimizing the distance towards the demand points are generated and presented. In step 3, the facilities generated in step 2 are transferred into new demand points and combined with the previous demand points generated in step 1. The new facilities are then generated in step 4.

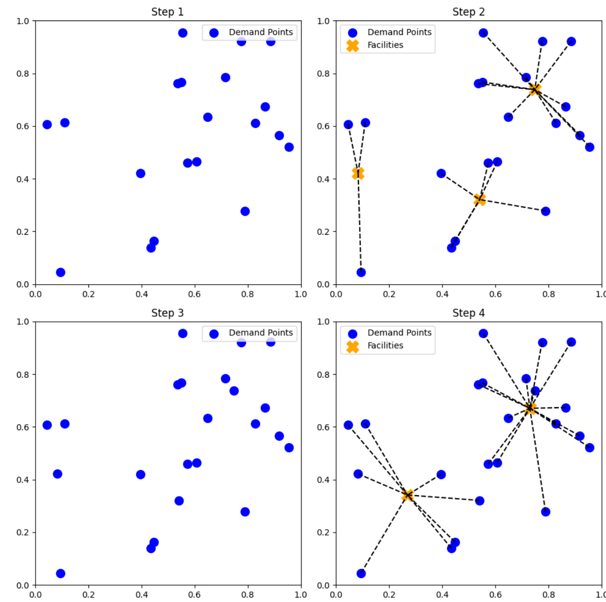

Fig. 3. 2-D Facility location problem example

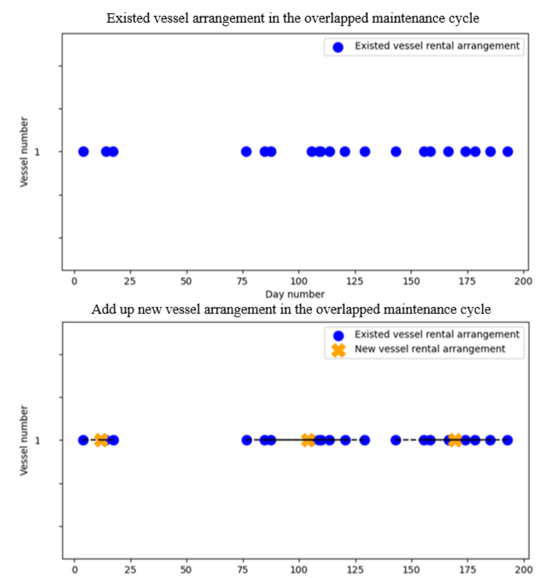

Fig. 4. Arrange new vessel in overlapped maintenance cycle

Convert the 2-D plane to a 1-D line. As shown in figure 4. The demand points are the existing vessel rental requirement, and the facilities are the new vessel rental arrangement. The X-axis in the original FLP problems is considered the day number during the simulation. The Y axis in original FLP problems is the vessel and its corresponding number. When arranging the new vessels at each maintenance cycle, the closeness of the vessel arrangement is considered in the objective function, minimizing the closeness of the vessel arrangement. Therefore, the vessel arrangements are more compact with each other, resulting in increased utilization of the vessels and reduced charter and mobilization costs brought by unnecessary additional vessel charter contracts. The calculation of the vessel arrangement closeness (VAC) is shown in equation 8:

$$\text{VAC} = \sum_{d \in D_g} \sqrt{(d * U_{ijd} - d * R_{ijd})^2} \tag{8}$$

d : Day number during the simulation

D_g : Day numbers of the maintenance period

U_{ijd} : Existed vessel arrangement, a binary value that represent whether the vessel i number j is hired on specific day d

R_{ijd} : New vessel arrangement, a binary value that represent whether the vessel i number j is hired on specific day d

5) Vessel charter strategy generation: The task & vessel arrangement module arranges the vessels individually to prevent overlap or proximity to each maintenance cycle, which could result in unnecessary mobilization costs for vessel chartering. After arranging all the vessels for maintenance, the vessel charter strategy generation module will generate the vessel charter strategy. For the overlapping and close maintenance cycles, the vessel charter strategy generation module extends the individual vessel charter period to cover these maintenance cycles, reducing unnecessary costs.

After generating the vessel arrangement for each maintenance cycle and deducting the initial purchase amount, chartering fulfils the remaining vessel requirements. In this case, the matrix of vessel rental requirements throughout the whole simulation horizon is generated. Agglomerative clustering will be used to group the vessel rental arrangement into different clusters based on the day number of the vessel rental requirement. After the classification, each cluster will become a rental period for the vessel.

Agglomerative clustering is a hierarchical clustering method that builds nested clusters from the bottom. Agglomerative clustering involves merging the most similar clusters at each step until a specific number of clusters is achieved. Agglomerative clustering involves different linkage methods, which determine how the distance between the clusters is calculated during the process. Among various linkage methods, the ward linkage method is particularly effective for producing compact and spherical clusters [2]. The vessel rental strategy, which does not have a specific number of clusters, aims to minimize the total vessel charter cost. In this scenario, the ward linkage method is appropriate.

Using the data from figure 4, the vessel rental arrangements are turned into data points that indicate the days the vessels must be chartered. The vessel charter requirement is turned into different charter periods by implementing the clustering algorithm. The process of dividing the demand for chartering into clusters is based on minimizing the total charter cost. The result of the example is shown in figure 5.

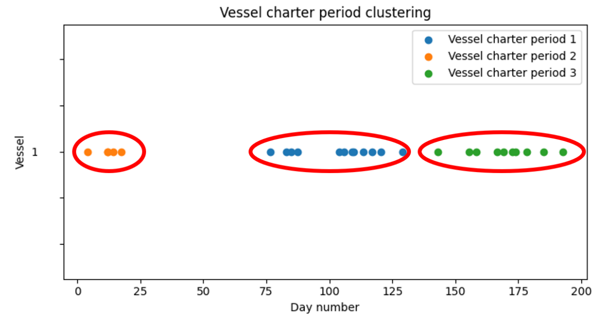

Fig. 5. Clustering the vessel charter periods

6) Output data: The output data of the current model considers the maintenance blog of the whole simulation horizon, the maintenance cycle distribution, and the vessel charter strategy under different initial purchase amounts. Table VIII shows the output data from the current model.

Maintenance blog		
No	Item	Unit
1	maintenance cycle	-
2	First day	-
3	Last day	-
4	turbine	-
5	component	-
6	type	-
7	age consumption	-
8	maintenance require time	YYYY-MM-DD
9	duration	hour
10	maintenance strategy	-
11	repair cost	keur
12	maintenance start day	YYYY-MM-DD
13	maintenance finish day	YYYY-MM-DD
Vessel charter strategy		
No	Item	Unit
14	Vessel type	-
15	Vessel number	-
16	Charter start time	YYYY-MM-DD
17	Charter end time	YYYY-MM-DD
18	Charter period	day
19	Rental cost	keur
20	Mobilize cost	keur
21	Vessel cost	keur
22	Initial CTV purchase amount	-
23	Initial FSV purchase amount	-

TABLE VIII
OUTPUT DATA OF CURRENT MODEL

The output [1] refers to the maintenance cycle number during the whole simulation, which is the same as the output [1] in table V. The output [2,3] indicates the day number of the beginning and end of the maintenance cycle. The output [4-9] shows the turbine number, component name, maintenance type, and age consumption when the maintenance cycle is generated; the maintenance cycle generates time and maintenance duration for each maintenance task. The output [4-9] corresponds to the output [2-7] in table V. The output [10] indicates that the maintenance cycle is triggered under the age-based opportunistic or age-based preventive maintenance strategy. The output [11] refers to the repair cost of the component, a fixed cost related to the component's name and maintenance type. The output [12,13] is the maintenance start day and maintenance finish day of the maintenance tasks.

In the vessel charter strategy part, the output [14,15] refers to the vessel type and its corresponding number that needs to be chartered. The output [16-18] represents the charter start date and termination date of the vessel and the length of the charter period of the vessel. The output [19,20] shows the vessel rental and mobilization costs when chartering the vessel. Moreover, the output [21] vessel cost refers to the sum of vessel charter and mobilization costs. The output [22.23] shows the initial purchase amount of the vessels.

III. Mathematical model

The mathematical model of the task & vessel arrangement module focuses on the number of vessels that have been deployed and maintenance tasks that have been scheduled for execution on each day. The task and vessel arrangement model is divided into three distinct parts. The first part is identifying the vessels that are purchased or chartered and deciding whether the vessel needs a charter or not during the maintenance period. The second part is the vessel arrangement, which specifies the vessels that are dispatched to the wind farm to carry out the maintenance. The third part is dedicated to task scheduling. This part arranges the days on which maintenance tasks will be executed. The mathematical model of the task & vessel arrangement module is shown below:

A. Sets

I: Vessel Types
K: Work types
C: Turbine's components set
L: Load type for maintenance
T_{kc}: Set of maintenance tasks of component c and work type k, $c \in C, k \in K$
G: Groups of maintenance requirements
D: Simulation horizon of the program
D_g: Maintenance window of each group, $g \in G$
H: Hours of a day

B. Parameters

$Cost_i^{Rent}$: Charter cost for vessel type i , $i \in I$
$Cost_i^{Travel}$: Travel cost of vessel type i, $i \in I$
$Cost_t^{Downtime}$: Downtime cost of maintenance task t, $t \in T_{kc}$
$Cost_i^{Mobilized}$: Mobilization cost of vessel type i, $i \in I$
$Cost_{td}^{Pe}$: Penalty cost of task t out of optimal maintenance period on day d, $t \in T_{kc}, d \in D$
$Duration_t$: Duration of maintenance task t, $t \in T_{kc}$
$Capa_{tl}^{Require}$: Capacity requirement for maintenance task t and load type l, $t \in T_{kc}, l \in L$
$Capa_{il}^{Provide}$: Capacity that vessel type i can provide for load type l, $i \in I, l \in L$
$VA_i^{limitation}$: Vessel amount limitation for type i, $i \in I$
VP_i: Vessel type i amount limitation in the port $i \in I$
$D_g^{Initial}$: Maintenance require day of group g, $g \in G$
D_t^{next}: Next stage remain days of component A_h:Available working hours of the day, $h \in H$
U_{id}: Existing vessel rental arrangement, how many vessels are already used on that day $i \in I, d \in D$
D_i^{stay}: Maximum stay offshore time of the vessel, $i \in I$
VA_i^{buy}: Vessel type i initial purchase amount $i \in I$

C. Decision variables

β_{td}: 1 if maintenance activity t is scheduled on day d, 0 otherwise,$t \in T_{kc}, d \in D_g$
R_{id}: Amount of vessel type i rented on day d $i \in I, j \in J, d \in D_g$,
h_{td}: Hours spent on executing task t on day d, $t \in T_{kc}, d \in D_g$
F_t: First day of the maintenance $t \in T_{kc}$
L_t: Last day of the maintenance $t \in T_{kc}$

D. Auxiliary variables

α_{itd}: Amount of vessel type i deployed for task t on day d, $i \in I, t \in T_{kc}, d \in D_g$
λ_{id}: Amount of vessel type i deployed to execute the maintenance on day d $i \in I, d \in D_g$
PF_{id}: Amount of vessel type i travel from port to wind farm on day d $i \in I, d \in D_g$
FP_{id}: Amount of vessel type i travel from wind farm to port on day d $i \in I, d \in D_g$
S_{id}: Amount of vessel stay overnight on day d, $i \in I, d \in D_g$
$Rent_i$: Amount of vessel rented in this maintenance cycle $i \in I$
VAC_i: Vessel arrangement closeness of vessel type i $i \in I$

E. Objective function

$$\min Z = \sum_{i \in I} Cost_i^{Rent} * (\sum_{d \in D_g} R_{id}) \tag{9}$$
$$+ \sum_{i \in I} Cost_i^{Travel} * (\sum_{d \in D_g} PF_{id} + FP_{id}) \tag{10}$$
$$+ \sum_{i \in I} (Cost_i^{night} * \sum_{d \in D_g} S_{id}) \tag{11}$$
$$+ \sum_{i \in I} (Cost_i^{Mobilized} * Rent_i) \tag{12}$$
$$+ \sum_{t \in T_{kc}} (L_t - F_t) * Cost_t^{downtime} \tag{13}$$
$$+ \sum_{t \in T_{kc}} \sum_{d \in D_g} Cost_{td}^{Pe} * \beta_{td} \tag{14}$$
$$+ \sum_{i \in I} VAC_i \tag{15}$$

The objective function of the improved vessel and task arrangement model is to reduce the overall cost of executing the maintenance tasks. The vessel charter costs are indicated by 9. The equation 10 represents the travel cost of the vessels that transport the technicians and maintenance teams between the offshore wind farm and the operation center. The equation 11 indicates the cost of having the vessels stay overnight at the offshore wind farm. The equation 12 refers to the mobilization cost of the vessel. The equation 13 indicates the downtime cost of maintaining the wind turbines. The equation 14 indicates the penalty cost that the maintenance tasks are executed in the winter period, which will penalize the operator. The equation 15 refers to the Vessel arrangement closeness between the vessel rental arrangement of the current maintenance period and previous maintenance periods. Its purpose is to prevent the scenario where a large number of vessels are rented simultaneously and then quickly become idle.

F. Auxiliary equation

$$Rent_i = max(R_{id}) \tag{16}$$

$$S_{id} = \sum_{d=0}^{d} (PF_{id} - FP_{id}) \tag{17}$$

$$\lambda_{i(d+1)} = S_{id} + PF_{i(d+1)} \tag{18}$$

$$VAC_i = \sum_{i \in I} \sqrt{(\sum_{d \in D_g} [(d * R_{id}) - (d * U_{id})]^2)} \tag{19}$$

The objective function of the improved vessel and task arrangement model is to reduce the overall cost of executing the maintenance tasks. The vessel charter costs are indicated by 9. The equation 10 represents the travel cost of the vessels transporting the technicians and maintenance teams between the offshore wind farm and the operation center. The equation 11 indicates the cost of having the vessels stay overnight at the offshore wind farm. The equation 12 refers to the mobilization cost of the vessel. The equation 13 indicates the downtime cost of maintaining the wind turbines. The equation 14 indicates the penalty cost that the maintenance tasks are executed in the winter period, which will penalize the operator. The equation 15 refers to the Vessel arrangement closeness between the vessel rental arrangement of the current maintenance period and previous maintenance periods. Its purpose is to prevent the scenario where many vessels are rented simultaneously and quickly become idle.

G. Constraints

1) *Vessel acquire amount constraint:*

$$R_{id} + U_{id} \leq VA_i^{limitation}, i \in I, d \in D_g \tag{20}$$

$$VA_i \geq 0 \tag{21}$$

$$R_{id} \geq 0 \tag{22}$$

$$Rent_i \geq 0 \tag{23}$$

The constraint 20 restricts the number of vessels hired each day and should not exceed the limitation of the port. The constraints 21 to 23 indicates the bounds for the decision variables VA_i, R_{id} and $Rent_i$.

2) *Task arrangement constraint:*

$$\sum_{d \in D_g} \beta_{td} \geq \frac{Duration_t}{(T^{end} - T^{start})}, t \in T_{kc} \tag{24}$$

$$\sum_{i \in I} \lambda_{id} * Capa_{il}^{Provide} \geq \sum_{t \in T_{kc}} \beta_{td} * Capa_{tl}, , d \in D_g, l \in L \tag{25}$$

$$\lambda_{id} \leq VA_i + R_{id} \tag{26}$$

$$\lambda_{id} \geq S_{id} \tag{27}$$

$$\lambda_{i(d+1)} \geq S_{id} \tag{28}$$

$$\beta_{td} \in \{0, 1\} \, t \in T_{kc}, d \in D_g \tag{29}$$

$$\lambda_{id} \geq 0, i \in I, d \in D_g, t \in T_{kc} \tag{30}$$

The constraint 24 restricts the minimum days spent on each maintenance task. The constraint 25 shows that the capacity of the vessel that has been deployed on each day should provide more capacity than the requirements from the maintenance tasks. The constraint 26 shows that the number of vessels deployed should not exceed the number of vessels already purchased and chartered. The constraints 27 and 28 indicate that the number of vessels that stay overnight in the offshore wind farm should be less or equal to the number of vessels deployed to the offshore wind farm on that day and the following day. The last two constraints, 29 and 30, specify the bounds for the decision variables β_{td} and λ_{id}.

3) *Task schedule constraint:*

$$\sum_{d \in D_g} h_{td} \geq Duration_t, t \in T_{kc} \tag{31}$$

$$h_{td} \leq \sum_{h \in H} \left\lfloor \sum_{i \in I} \alpha_{itd} * W_{idh} * A_h \right\rfloor, t \in T_{kc}, d \in D_g, h \in H \tag{32}$$

$$m * \lambda_{id} \geq \sum_{t \in T_{kc}} \alpha_{itd}, i \in I, d \in D_g \tag{33}$$

$$m * \beta_{td} \geq h_{td}, t \in T_{kc}, d \in D_g \tag{34}$$

$$\lambda_{id} + U_{id} \leq VA_i^{buy} + R_{id} \tag{35}$$

$$L_t \geq D_g^{Initial} \tag{36}$$

$$L_t \geq d * \beta_{td} \tag{37}$$

$$F_t \leq d * \beta_{td} + m * (1 - \beta_{td}) \tag{38}$$

$$F_t \leq D_t^{next} \tag{39}$$

$$\alpha_{ijt} \in \{0, 1\}, i \in I, j \in J_b \cup J_r \tag{40}$$

$$h_{td} \geq 0, t \in T_{kc}, d \in D_g \tag{41}$$

The constraint 31 indicates that the total hours spent on the tasks should be more than the duration of the maintenance task. The following constraint 32 limits the hours spent on each maintenance task on each day, which is less than the weather permit operational hours of the vessel that was arranged to execute the maintenance task. The following constraint, 33 indicates that the vessels sent for executing the maintenance task each day should not exceed the vessel operating at the offshore wind farm. The constraint 34 restricts that once a maintenance task has maintenance hours on a given day, the maintenance task is considered as arranged on that day. The constraint 35 restricts that considering the maintenance periods of different maintenance cycles overlap with each other, the number of vessels that deployed on each day should not exceed the number of vessels that have been purchased and chartered. The constraints 36 and 37 indicate that the maintenance finish day of each task should be after any days that execute the maintenance and the day that the maintenance request is generated. The constraints 38 and 39 indicate that the first maintenance day of the tasks should be before any maintenance execution day and before the components run into the next stage of wearing. The constraints 40 and 41 illustrate the boundary of the decision variables α_{itd} and h_{td}.

H. Solver for optimization

The vessel & task arrangement module is an optimization model based on mixed integer linear programming. As the maintenance tasks amount in each maintenance cycle increase, the scale of the problem also increases, resulting in the computation time increase and huge demand on the computation resource. To solve the problem quickly and accurately, choosing a suitable solver is crucial. Many potential solvers, such as CPLEX or Gurobi, can be used to solve the MILP problems since the Monte Carlo simulations need to execute multiple simulations to obtain the final result. Computational speed is the priority factor when choosing a solver.

Compared with other commercial solvers, Gurobi performs better at computation speed. When solving the same linear programming problem, Gurobi has 33% less computation time compared with commercial solver CPLEX and 57% less computation time compared with commercial solver FICO Xpress [18]. As a result, Gurobi is chosen as the solver of the mathematical model.

IV. Case Study

The previous chapter presents the mathematical model of the optimizer. This chapter will perform a case study based on the current model with the corresponding data. Firstly, the input data of the case study will be shown. Secondly, a Monte Carlo simulation is implemented to determine the minimum number of iteration amount. Next, the sensitivity study based on a small-sized offshore wind farm is presented, aiming to find the sensitivity factors that affect the vessel charter cost. Finally, the case study of 3 different size offshore wind farms is presented, giving the result of the optimal initial purchase fleet and vessel charter recommendation for each month.

A. Simulation input data

During the model simulation, the maintenance strategy of age-based opportunistic and time-based preventive maintenance is implemented. The input data of the opportunistic maintenance strategy is shown in table IV. The winter period is from November to April next year, with the preventive maintenance check in September [1]. The input data related to the offshore wind farm is shown in table IX

No	Input	Value	Unit
1	Number of wind turbines of the small size offshore wind farm	20	turbine
2	Number of wind turbines of the medium size offshore wind farm	50	turbine
3	Number of wind turbines of the large size offshore wind farm	100	turbine
4	Distance from shore	25	km
5	Simulation horizon	5	year
6	Shift 1 start	1:00	hh:mm
7	Shift 1 end	11:00	hh:mm
8	Shift 2 start	13:00	hh:mm
9	Shift 2 end	23:00	hh:mm
10	Maintenance period	90	day
11	Wind turbine power	3	MW
12	Electricity price	150	Eur/kwh
13	Downtime cost	10,800	Eur/day

TABLE IX
PARAMETERS OF THE OFFSHORE WIND FARM AND TURBINES [3] [20] [27]

The downtime cost calculation of the wind turbine is based on its rated power and electricity price, which is shown in equation 42

$$\text{Downtime cost} = P_{electric} * P_{wind} * 24 \tag{42}$$

$P_{electric}$: Electricity price (Eur)
P_{wind} : Wind turbine power (W)

Component	Weibull shape parameter (days)	Weibull scale parameter
Blades	3	3,000
Bearing	2	3,750
Gearbox	3	2,400
Generator	2	3,300
Shaft	1.5	7,500

TABLE X
LIFETIME PARAMETERS FOR THE COMPONENT [3]

Maintenance type	Component	Duration(h)	Cost (Eur)	Technician (person)
Replacement	Blades	288	90,000	8
	Bearing	36	10,000	
	Gearbox	231	230,000	
	Generator	81	60,000	
	Shaft	144	232,000	
Major maintenance	Blades	18	25,000	6
	Bearing	12	3,750	
	Gearbox	16	18,750	
	Generator	14	5,000	
	Shaft	42	14,000	
Minor maintenance	Blades	9	4,000	3
	Bearing	6	1,000	
	Gearbox	8	5,000	
	Generator	7	1,500	
	Shaft	18	1,000	

TABLE XI
PARAMETERS OF REPAIR TIME, REPAIR COST AND TECHNICIAN AMOUNT ON COMPONENTS [19] [21] [3] [30]

The parameters related to the components' lifetime are shown in table X, with their maintenance duration and maintenance cost in table XI. The parameters related to the vessels are concluded in table XII. The vessel travel cost of each type of vessel transfer between the offshore wind farm and the operation center is calculated by the travel speed, fuel consumption, and fuel cost from table XII and the distance between the offshore and the operation center in table IX. The travel cost is calculated by equation 43.

No	Input	Value			Unit
		CTV	FSV	HLV	
1	Travel speed	44	25	20	km/h
2	Technician on board	12	12	24	person
3	Maximum parallel team	4	1	1	team
4	Limit wave height	1.7	2	2.8	m
5	Limit wind speed at sea	25	25	36.1	m/s
6	Limit wind speed at hub	-	-	15.3	m/s
7	Mobilization time	7	21	30	day
8	Minimum charter length	30	30	30	day
9	Extend charter length	15	15	15	day
10	Fuel consumption	0.24	0.2	0.55	mt/h
11	Charter price	2,000	33,000	290,000	Eur/day
12	Purchase cost	3,000,000	20,250,000	-	Eur
13	Mobilization cost	50,000	200,000	800,000	Eur/ mobilization
14	Fuel cost	300	300	450	Eur/ton
15	Travel cost	100	100	600	Eur/travel

TABLE XII
VESSEL RELATED PARAMETERS [7] [30] [10] [15]

The travel cost calculation of the vessel is based on the vessel travel speed, the distance between the port and the offshore wind farm, hourly fuel consumption of the vessel, and the fuel cost of the vessel in table XII, which is shown in equation 43

$$C_{travel} = \frac{D}{V_t} * HC_{fuel} * C_{fuel} \tag{43}$$

C_{travel} : Vessel travel cost
D : Distance between the port and the offshore wind farm
V_t : Vessel travel speed
HC_{fuel} : Hourly fuel consumption of the vessel
C_{fuel} : Cost of the fuel

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

TABLE XIII
TABLE OF PARAMETERS RELATED TO WIND AND WAVE CHARACTERISTICS [38] [7]

The weather limits the vessels' ability to perform maintenance tasks. The met-ocean wind speed and wave height significantly influence the vessel's operation. The synthetic climate data is generated by using Weibull distribution. For different heights of wind speed, the equation 44 shows the calculation of wind speed at different heights [7]. The data that generates the synthetic weather data is shown in table XIII:

$$\frac{v_2}{v_1} = (\frac{h_2}{h_1})^a \tag{44}$$

v_1 : wind speed at height h_1
v_2 : wind speed at height h_2
a : constant of wind power law equation

B. Monte Carlo simulation convergence analysis

The uncertainties come from the Components' RUL and weather conditions at the offshore wind farm. The former uncertainties make the maintenance tasks in the maintenance cycle and the maintenance cycle generation date uncertain. The latter uncertainty decides whether the vessel can execute the maintenance task at the offshore wind farm. These uncertainties affect the maintenance cycle generation, task and vessel scheduling in the task & vessel arrangement module, and the vessel charter strategy generation. To eliminate the uncertainties, the Monte Carlo simulation is applied. The convergence analysis of the Monte Carlo simulation is necessary to estimate how many iterations are needed. In the convergence analysis, the Monte Carlo simulation iteration amount is increased, presenting the average vessel total charter cost under different iteration amounts. The charter probability heat map will be given when the iteration amount reaches 50,100, 200, 500, and 1000.

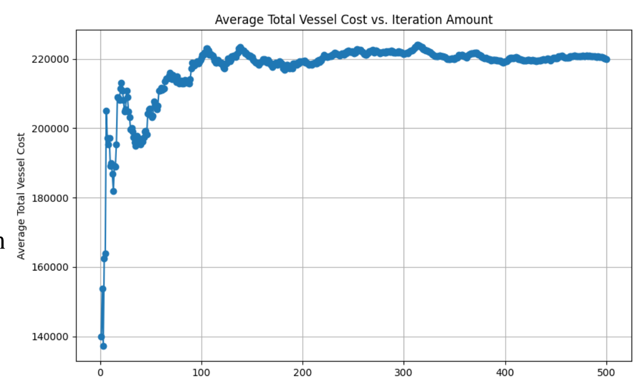

Fig. 6. Average vessel total charter cost under different iteration amount

According to the implementation results above, the average total vessel cost becomes stable after the iteration amount reaches a certain number of times. As shown in figure 6, after the iteration amount reaches 200, the average total cost of each scenario stabilizes at 220,000 keur. Stabilized average total cost represents the number of vessels and the charter period for the vessels to become stable. To reduce the computation amount to carry out the subsequent implementation, the 200-times iteration will be chosen for subsequent implementation.

C. Sensitivity analysis

Sensitivity analysis is essential for model verification. The simulation model is designed with many input parameters, and the sensitivity analysis can determine the sensitive factors affecting the model output. At the same time, the sensitivity analysis can verify the reasonableness and credibility of the model and improve the model's accuracy by observing the simulation model's response to the changes of inputs and judging whether the model changes according to the expectation.

The sensitivity analysis uses the small size offshore wind farm with 20 wind turbines for the simulation. The simulation horizon is five years. The input data will be changed to analyze the sensitivity factors that affect the vessels' chartering strategies. To observe how the sensitivity factors affect the vessel acquisition cost. The following sensitivity factors are chosen for the sensitivity analysis, which will be further illustrate in each subsection.

- Weather scale parameter
- Vessel charter length
- Age consumption threshold
- Wind turbine amount
- Maintenance duration
- Maintenance period length
- Vessel arrangement closeness (VAC) coefficient
- Vessel charter cost

1) Changing weather scale parameters: The weather influences maintenance execution by limiting whether the vessel is operational during specific hours, directly affecting the available maintenance execution hours of each day. The available maintenance execution hours of the day further affect the maintenance task execution and vessel deployment of each day. Therefore, weather conditions can be considered a sensitivity factor for analysis. The synthetic weather data follows the Weibull distribution and is generated at the beginning of the simulation. In this sensitivity analysis, the scale parameter of the weather will increase and decrease by 50% to observe the changes in the maintenance execution. The modified weather parameters are shown in table XIV

No	Item	Baseline value	Modified value (increase)	Modified value (decrease)	Unit
1	Weibull shape parameter of wind speed (at 21 m)	2.43	2.43	2.43	-
2	Weibull scale parameter of wind speed (at 21 m)	8.58	12.87	4.29	m/s
3	Weibull shape parameter of wave height	1.58	1.58	1.58	-
4	Weibull scale parameter of wave height	1.1	1.65	0.55	m
5	Relevant height above sea	5	5	5	m
6	Wind speed coefficient	0.1	0.1	0.1	-

TABLE XIV
WEATHER PARAMETERS WITH MODIFIED VALUE [38] [7]

The simulation results of changing weather scale parameters are shown in table XXI. Increasing the weather scale parameter gives weather data a higher value when generated. Representing the weather is more severe. In contrast, decreasing the weather scale parameter provides the weather with data with a lower value when generated. Representing the weather is more gentle. However, the task & vessel arrangement module aims to arrange all the tasks execution in a fixed maintenance period by minimizing the downtime cost and making the vessel arrangement on each day more stable. Therefore, the maintenance period will be fully used in the task & vessel arrangement. The changing weather data can only affect the vessel arrangement each day but cannot affect how many days the maintenance tasks are executed. As shown in table XV, changing the weather scale parameter increases the average maintenance period length by 1.56% and 2.39%, leading to the vessel charter cost slightly increase.

	Average maintenance period length (day/period)	Variation
Baseline	53.55	-
Weather scale parameter *0.5	54.39	1.56%
Weather scale parameter *1.5	54.83	2.39%

TABLE XV
AVERAGE MAINTENANCE PERIOD LENGTH UNDER DIFFERENT

2) Changing charter length of the vessels: The vessel charter starts with a fixed charter length and then decides whether the charter length needs to be extended. In the closed-loop simulation model, The clustering algorithm clusters the vessel chartering requirement together with the fixed length of the chartering period. Finding the optimal chartering strategy based on the vessel's total cost. For those vessels that only need to be chartered for a few days, the minimum charter length still needs to be obtained, as well as the vessel charter contract, resulting in the vessels staying idle in the port.

By changing the vessel charter length, the charter period of the vessel can be terminated earlier or later. This affects the vessel charter cost. In this sensitivity analysis, the minimum charter length of the vessels will increase and decrease by 50% to observe how the chartering length affects the total cost. The modified vessel charter length is shown in table XVI

Vessel		CTV	FSV	HLV
Baseline	Charter length (days)	30	30	30
	Extend charter length (days)	15	15	15
Increase by 50%	Charter length (days)	45	45	45
	Extend charter length (days)	22	22	22
Decrease by 50%	Charter length (days)	15	15	15
	Extend charter length (days)	7	7	7

TABLE XVI
VESSEL CHARTER LENGTH WITH MODIFIED VALUE [7]

As shown in table XXI , the charter cost of the vessels decreased with the decrease in charter length. The reason is that the number of days the vessels are deployed is far lower than the vessel charter length, which leads to a low utilization of the vessels. In this case, reducing the charter length of the vessels can reduce the charter cost when the vessels are not being deployed, which significantly reduces the vessels' charter costs. Conversely, extending the charter length of the vessels causes more of them to remain idle during the charter period, increasing the vessel charter cost.

3) Changing age consumption threshold: The age consumption threshold is directly linked to the generation of maintenance tasks during the simulation. In this simulation, the age consumption threshold of the monitoring system will be changed to observe how the age consumption threshold of the maintenance strategy affects the maintenance. In this sensitivity analysis, the age threshold of defining the component wearing zone will be increased and decreased to observe how the age consumption threshold affects the optimization results. The results are shown in tableXXI. Table XVII shows the modified age consumption threshold.

Maintenance type	Baseline age consumption (%)	Increased age consumption (%)	Decreased age consumption (%)	Zone	Age reduction
No maintenance	[0,50)	[0,55)	[0,45)	Zone1	-
Minor maintenance	[50,80)	[55,85)	[45,75)	Zone2	30%
Major maintenance	[80,95)	[85,99)	[75,90)	Zone3	50%
Preventive replacement	[95,100)	[99,100)	[90,100)	Zone4	100%

TABLE XVII
AGE CONSUMPTION WITH MODIFIED VALUE [20]

As can be observed from the table XXI . When the age consumption threshold is decreased, the age consumption threshold of replacement is easier to reach, making the maintenance cycles more likely to be triggered. More major and minor maintenance will be added to the maintenance cycle due to the decrease in the age consumption threshold. More maintenance tasks require more vessels to be involved in the maintenance execution. Therefore, the vessel charter cost will increase.

The maintenance cycle will be harder to trigger when increasing the age consumption threshold. Therefore, fewer vessels are required to be involved in the maintenance execution, and the vessel charter cost will decrease. However, the vessel charter cost increases contrary to expectations. As a result, an in-depth survey of the charter cost of each type of vessel is conducted and shown in table XVIII.

	Vessel charter cost (keur/year)		
	CTV	FSV	HLV
Baseline age consumption	115.8	2784.9	36206.7
Age consumption threshold increase	113.9	2676.8	38016.9
Age consumption threshold decrease	134.9	3004.5	41263.8

TABLE XVIII
VESSEL CHARTER COST OF MODIFYING AGE CONSUMPTION THRESHOLD

When the age consumption threshold is decreased, more maintenance tasks will be generated throughout the simulation, resulting in more vessels being involved in executing the maintenance tasks. Therefore, all three types of vessels' charter costs increase when the age consumption threshold decreases.

In the case that the age consumption threshold increases. As mentioned in the equation 39, the maintenance of the component must be initiated before the component runs into the next wearing stage. Therefore, for the replacement maintenance tasks, when the age consumption threshold increases, when the replacement task is generated, the remaining days of starting the maintenance is only 1% of the component's remaining useful life, which is far less than the baseline condition of 5% . The replacement must be executed as soon as possible. For multiple replacement tasks that are not far away from each other. In the baseline condition, these replacement tasks can be arranged on the same vessel. However, in the age consumption threshold increase case, these replacement tasks must start as quickly as possible, which requires chartering more HLVs to execute the replacement tasks. This results in an increase in the HLV charter cost while the CTV and FSV charter costs decrease.

4) Changing wind turbine amount: The amount of offshore wind farm turbines influences the number of components that need to be maintained and directly affects the number of maintenance tasks at each maintenance cycle. Therefore, the amount of wind turbines will affect the vessel charter strategy. In this sensitivity analysis, we will change the offshore wind farm's turbine amount by 50%, increase the number of wind turbines to 30, and then decrease the number of wind turbines to 10 to observe how the wind turbine amount affects the maintenance cost.

As is shown in table XXI, increasing the number of wind turbines will significantly increase the vessel charter cost. The increment on the vessel charter cost corresponds to the increment of the offshore wind turbines of 53%. Conversely, as the number of wind turbines decreases, the vessel charter cost of the offshore wind farm decreases by 43% correspondingly. The significant change shows that the number of wind turbines is the most significant sensitivity factor.

5) Changing repair duration: The repair duration directly affects the days spent on each maintenance task. To minimize the downtime cost, the task & vessel arrangement module will choose different days for executing the maintenance tasks, affecting the vessel requirement each day and the vessel charter cost. In this sensitivity analysis, the repair duration of the maintenance tasks will be increased and decreased by 50%, observing how the repair duration of the components affects the maintenance execution. The modified repair duration is shown in table XIX.

Maintenance type	Component	Duration(h)	Increased duration (h)	Decreased duration (h)
Replacement	Blades	288	432	144
	Bearing	36	54	18
	Gearbox	231	347	116
	Generator	81	122	41
	Shaft	144	216	72
Major maintenance	Blades	18	27	9
	Bearing	12	18	6
	Gearbox	16	24	8
	Generator	14	21	7
	Shaft	42	63	21
Major maintenance	Blades	9	14	5
	Bearing	6	9	3
	Gearbox	8	12	4
	Generator	7	11	4
	Shaft	18	27	9

TABLE XIX
PARAMETERS OF REPAIR TIME WITH MODIFIED VALUE [19] [21] [3] [30]

As the result shown in table XXI, the duration of the maintenance tasks significantly affects the charter cost by affecting the vessel deployed days and travel cost of the vessels by affecting the deployment days of the vessels. A longer maintenance duration means the vessel needs to be deployed for more days to complete the maintenance tasks, which increases the downtime cost. The increment in the vessel deployment times also brings more vessels involved in the maintenance execution, resulting in an increment in the vessel charter cost.

6) Changing maintenance period length: The maintenance period restricts the maintenance execution duration of each maintenance cycle. After the maintenance cycle is generated, the optimization model dispatches the vessels by maximizing the usage of the maintenance period, making the maintenance execution of the tasks scattered. As a result, the maintenance period affects the vessel deploying day, resulting in different vessel charter strategies. In this sensitivity analysis, the maintenance period length of executing the maintenance tasks will be increased to 120 days and decreased to 60 days to observe how the maintenance period length affects the operation and maintenance cost.

The results are shown in table XXI . The travel cost of the vessels and the repair cost of the maintenance tasks remain unaffected by the length of the maintenance period, as the creation of maintenance tasks is not contingent on the duration of the period. The length of the maintenance period affects the charter cost of the vessel, as a shorter maintenance period aligns the execution days of maintenance tasks closer together, resulting in more compact vessel deployments. Conversely, a more extended charter period decentralizes the execution days of maintenance tasks, leading to a higher vessel charter cost.

7) Vessel arrangement closeness coefficient: The vessel arrangement closeness is included in the cost function of the task & vessel arrangement module, which is used to make the vessel rental arrangements more compact. Changing the coefficient of vessel arrangement closeness in the cost function can change the compactness of the vessel arrangement. A low vessel arrangement closeness value refers to the vessel rental arrangements being closer and the vessel rental amount of each day being closer. In this sensitivity analysis, the coefficient of the vessel arrangement closeness is changed to observe whether the total cost is sensitive to the vessel arrangement closeness. The initial coefficient of vessel arrangement closeness in the cost function is 1. The sensitivity analysis is done by increasing the coefficient to 10 and decreasing it to 0.1.

As shown in table XXI, the vessel acquisition cost is sensitive to the coefficient of the vessel arrangement closeness. A higher coefficient makes the vessel rental arrangements more compact, leading to a lower vessel charter cost and a smaller scale of the initial vessel purchase fleet. While a small coefficient makes the rental arrangement less compact, resulting in a higher vessel charter cost.

8) Vessel charter cost: The vessel charter cost is critical in the decision-making process for chartering the vessels. Therefore, observing how the model reacts to the changing vessel charter cost is essential. The charter cost also affects the decision to purchase a vessel initially. The modified vessel charter cost is shown in table XX

As it can be observed from the table XXI, the annual vessel charter cost is sensitive to the daily vessel charter cost. The annual vessel charter changes correspondingly to the daily vessel charter cost. Daily vessel charter cost changes also affect the optimal initial purchase fleet. When the charter cost increases by 50%, The optimal initial purchase fleet has one additional CTV and FSV.

Vessel	Baseline condition (eur/day)	Vessel charter cost decrease (eur/day)	Vessel charter cost increase (eur/day)
CTV	2,000	1,000	3,000
FSV	33,000	16,500	49,500
HLV	290,000	145,000	435,000

TABLE XX
PARAMETERS OF REPAIR TIME WITH MODIFIED VALUE [15] [30]

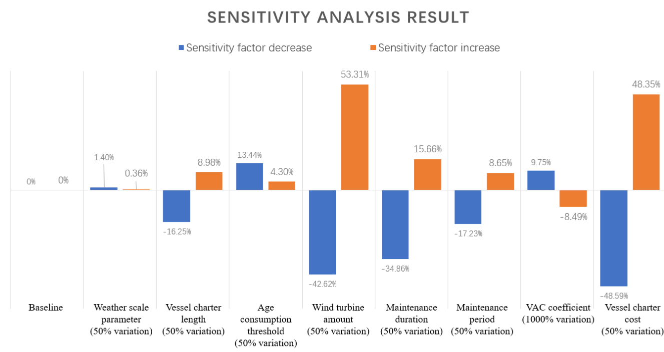

Fig. 7. Sensitivity analysis result

The sensitivity analysis shows that the vessel charter cost with no initial purchases of the vessel fleet is sensitive to the maintenance duration of the components, maintenance period length and daily vessel charter cost. The full table with the every single cost of the sensitivity analysis also shown in the appendix table

D. Case study of different size of offshore wind farm

1) Result of small size offshore wind farm: In this case study, the wind turbine amount in the offshore wind farm is 20, which refers to the small size of the offshore wind farm.

As shown in figure 8, an increase in the initial vessel purchase amount will significantly reduce the vessel's yearly pure charter cost. When it reaches the maximum value of 5 CTV and 5 FSV, the vessel's annual charter cost reaches the minimum of 36950 keur. Adding up the vessel purchase cost. As shown in figure 9, when one FSV is purchased in advance, the annual vessel acquisition cost reaches a minimum of 39106 keur.

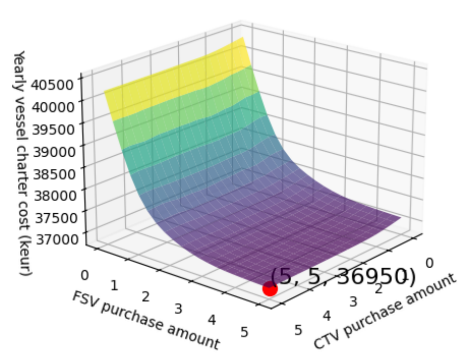

Fig. 8. Yearly vessel charter cost under different initial vessel purchase amount of 20 turbines

Sensitivity factor	Charter cost when no initial purchase (keur/year)	Tendency	Charter cost change rate	Optimal initial purchase	Vessel acquisition cost (keur/year)
Baseline	40356.3	-	-	(0,1)	39106
Weather scale parameter *0.5	40922.7	↑	1.4%	(0,1)	39661
Weather scale parameter *1.5	40501.1	↑	0.4%	(0,1)	39298
Vessel charter length *0.5	33797.8	↓	-16.3%	(0,1)	34442
Vessel charter length *1.5	43980.5	↑	9.0%	(0,1)	44589
Component's age consumption threshold -0.05	45780.1	↑	13.4%	(1,2)	44397
Component's age consumption threshold +0.05	42092.6	↑	4.3%	(0,1)	38770
Wind turbine amount decrease to 10	23157.1	↓	-42.6%	(0,1)	20823
Wind turbine amount increase to 30	61870.3	↑	53.3%	(1,2)	20823
Maintenance duration * 0.5	26287.7	↓	-34.9%	(0,1)	54196
Maintenance duration * 1.5	46676.4	↑	15.7%	(0,1)	45361
Maintenance period length decrease to 60 days	33404.6	↓	-17.2%	(0,1)	32442
Maintenance period length increase to 120 days	43847.5	↑	8.7%	(1,2)	28491
Coefficient of vessel arrangement closeness decrease to 0.1	44290.1	↑	9.7%	(1,2)	42642
Coefficient of vessel arrangement closeness increase to 10	36930.9	↓	-8.5%	(0,1)	35925
Vessel daily charter cost decrease by 50%	20747.9	↓	-48.6%	(0,1)	20417
Vessel daily charter cost increase by 50%	59867.1	↑	48.3%	(1,2)	57424

TABLE XXI
SENSITIVITY ANALYSIS RESULT

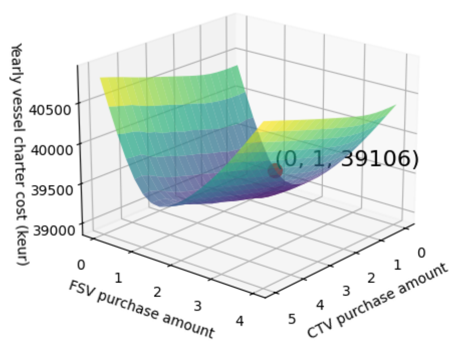

Fig. 9. Yearly vessel cost under different initial purchase amount of 20 turbines

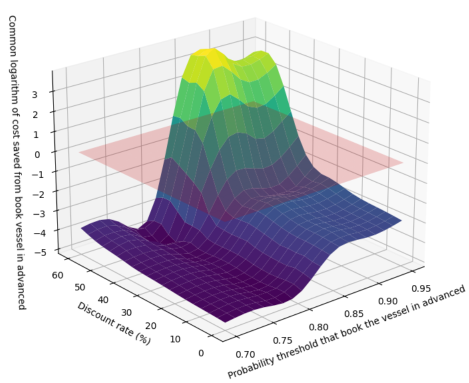

Fig. 10. Cost saved from booking the vessel in advance of 20 wind turbines

The charter probability heat map for executing the maintenance tasks of the small size offshore wind farm is shown in figure 11. For the offshore wind farm operator. Providing the data of vessel charter strategy from every simulation result as the charter recommendation is unrealistic. Instead, the operators would like to have a vessel charter strategy for each month, which is more helpful for the operators to arrange or charter the vessels each month. Therefore, the vessel charter probability heat map for executing the maintenance tasks of the small size offshore wind farm is shown in figure 11. The heat map counts the probability of each vessel being chartered each month of each year throughout 200 simulations of 5 years. A higher charter probability in the heat map represents that the vessel will be more likely to be chartered in other simulations. Therefore, the operator can book the vessel in advance, like early in the year. Ensure that the vessel is available when the maintenance cycle is generated.

For the shipowner that provides the vessel to the operator, their main goal is to reduce the idle time of the vessels, which reduces the operation cost of the vessel and increases the income created by the vessel. An early locked-in charter contract can help shipowners ensure a stable charter period, thus reducing the risk of idleness.

For the operator that charter the vessels. Booking the vessel in advance brings the advantage of being available in the selected time slot. In contrast, deciding to reserve the vessels in advance brings the disadvantage that if the vessel is chartered in advance but there's no maintenance needed to be done in the charter period, it will make the selected vessel idle in the operator's port. Resulting in vessels staying idle, wasting large amounts of rental costs.

Therefore, the shipowners are willing to provide a discount on the contract for the vessels that have been early booked. Figure 10 presents how much booking the vessel in advance saves from vessel charter costs under different charter probability thresholds and discount rates. The X-axis refers to the probability threshold, which means when the elements that represent the vessel charter probability in the heat map are higher than the threshold, the vessel will be reserved in advance, a fixed contract that covers the whole month will be given, reducing the vessel charter cost in the corresponding month. The Y-axis represents the discount rate, which means compared with the regular vessel rental contract, how much of a discount will the fixed contract that reserves the vessel in advance have.

Due to the vast difference among the cost data points of

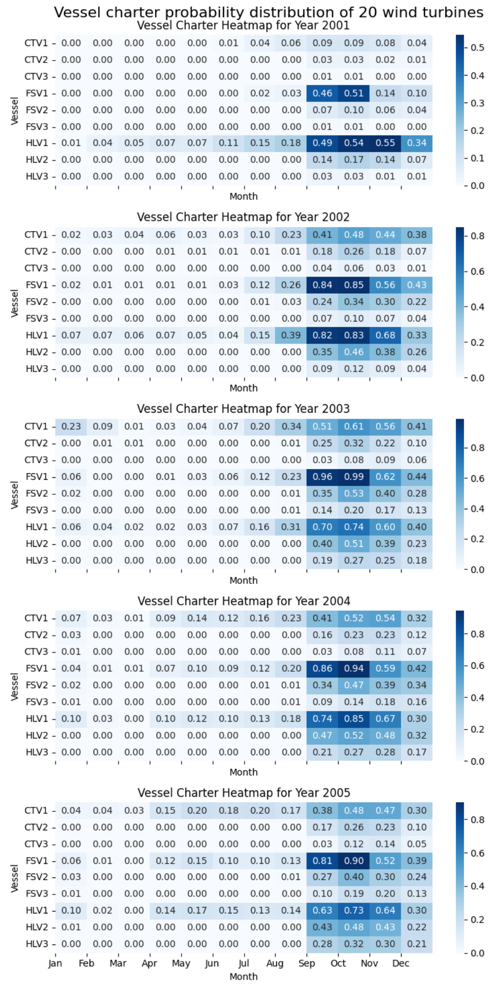

Fig. 11. Vessel charter probability of 20 wind turbines

reserving the vessel in advance under different probability thresholds and discount rates (from -60000 to 600). It's not clear to present the cost data with the initial data. Therefore, a common logarithm of the saving cost is given in figure 10 to clarify the result. The equation 45 shows the calculation of taking the common logarithm of the saving cost that reserves the vessel in advance. If reserving the vessel in advance reduces the total vessel charter cost of 5 years, the saving cost $Cost^{save}$ will be positive. Conversely, if reserving the vessel in advance increases the total vessel charter cost, the $Cost^{save}$ will be negative.

$$\text{Cost saving logarithm} = \begin{cases} log_{10}(Cost^{save}), Cost^{save} > 0 \\ 0, Cost^{save} = 0 \\ -log_{10}(Cost^{save}), Cost^{save} < 0 \end{cases} \tag{45}$$

As shown in figure 10, when the probability threshold reaches 0.85, and the discount of reserving the vessel in advance reaches 40%, reserving the vessel in advance is cost-effective. As a result, when the discount rate of reserving the vessel in advance is higher than 40%, reserving the vessel FSV 1 in October 2002, September, and October of the years 2003, 2004, and 2005. And HLV 1 in October 2004. It can be considered cost-effective when there's no initial purchase fleet. Figure 9 shows 1 FSV for the initial purchase. It can be concluded that under the initial purchase fleet mix of 1 FSV, when the discount rate of reserving a vessel in advance reaches 40%, reserving 1 HLV for October 2004 is cost-effective.

2) Medium size offshore wind farm: In this case study, the wind turbine amount in the offshore wind farm is 50, which refers to the medium size of the offshore wind farm. As shown in the figure 12, when considering only the vessel charter cost. The maximum initial purchase value of 5 CTV and 5 FSV makes the yearly charter cost reach 49836 keur, as shown in figure 13. Consider the vessel's annual acquisition cost, increasing the purchase cost. The optimal initial purchase fleet is 1 CTV and 2 FSV, with a yearly vessel acquisition cost of 52344 keur. With the increase in the wind turbine amount from 20 to 50, an additional CTV and an FSV need to be purchased for the initial purchase fleet mix.

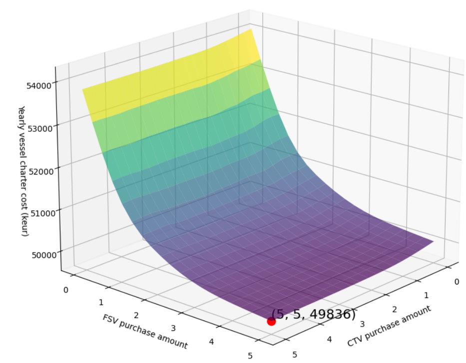

Fig. 12. Yearly vessel charter cost under different initial vessel purchase amount of 50 turbines

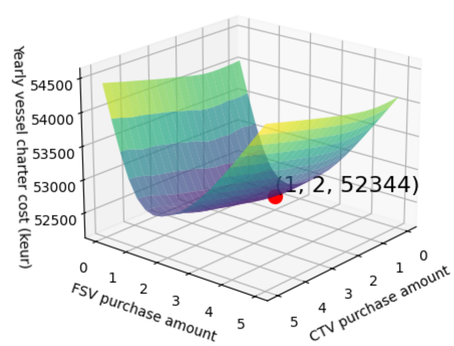

Fig. 13. Yearly vessel cost under different initial purchase amount of 50 turbines

The charter probability heat map for executing the maintenance tasks of the medium size offshore wind farm is shown in figure 15. Compare with the charter probability heat map of small size offshore wind farm. The medium size offshore wind farm has more maintenance tasks. Therefore, the charter probability of the vessels increases when there's no initial purchase fleet. Figure 14 shows that when the probability threshold reaches 0.85 or 0.9, with the discount rate of 40%. Reserving the vessel in advance is cost-effective. Therefore, It can be concluded that when the discount rate is over 40%. Reserving the CTV 1 in September of 2004.

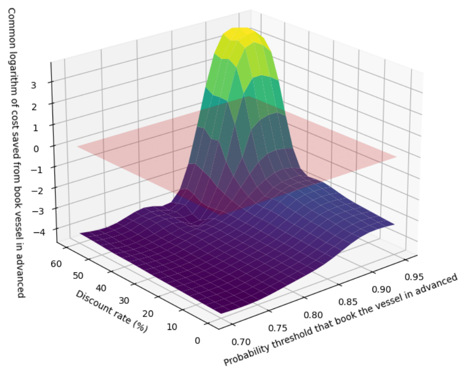

Fig. 14. Cost saved from booking the vessel in advance of 50 wind turbines

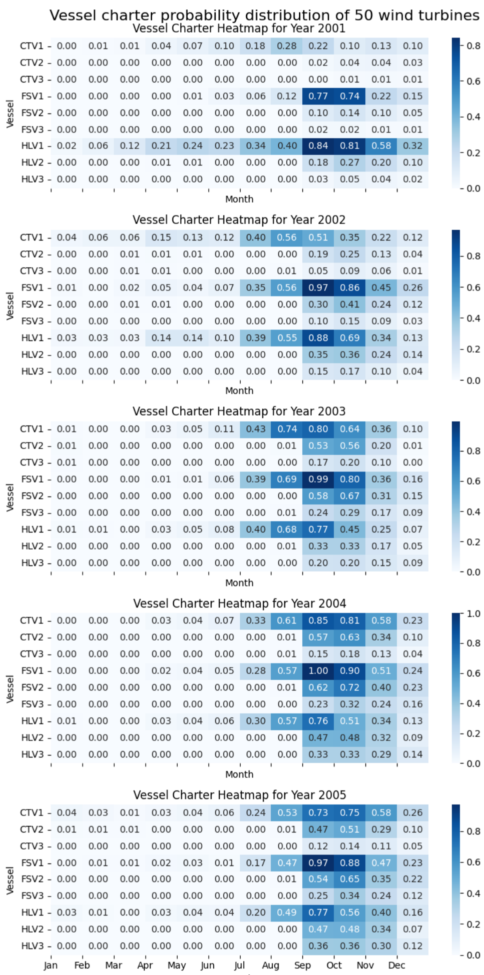

Fig. 15. Vessel charter probability of 50 wind turbines

FSV 1 in September and October of 2002,2004, and 2005, and September of 2003. HLV 1 in September of 2002 is cost-effective when there's no initial vessel purchase amount. Figure 13 shows 1 CTV and 2 FSV for the initial purchase. When the discount rate of reserving the vessel in advance reaches 40%, reserving 1 HLV in September of 2004 is cost-effective.

3) Large size offshore wind farm: In this case study, the wind turbine amount in the offshore wind farm is 100, which refers to the large size of the offshore wind farm. As shown in the figure 16, the vessel charter cost increases with the increment in wind turbines. When considering only the vessel charter cost. The maximum initial purchase value of 5 CTV and 5 FSV makes the yearly charter cost reach 74989 keur. Consider the vessel's annual acquisition cost, which adds up the purchase cost. As it shown in figure 17The optimal initial purchase fleet is 1 CTV and 2 FSV, with a yearly vessel acquisition cost of 78392 keur.

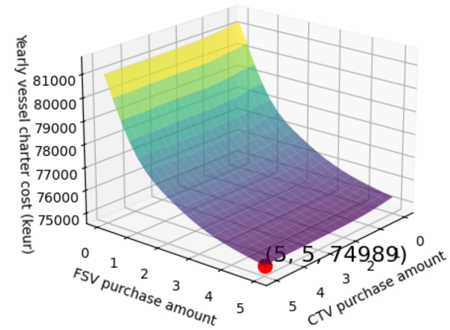

Fig. 16. Yearly vessel charter cost under different initial vessel purchase amount of 100 turbines

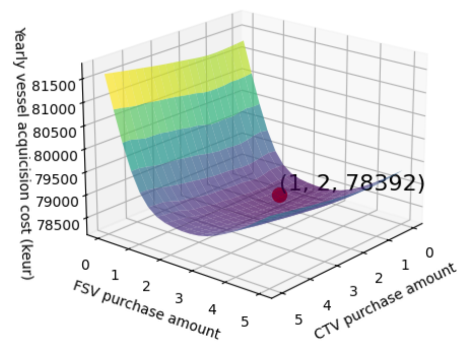

Fig. 17. Yearly vessel cost under different initial purchase amount of 100 turbines

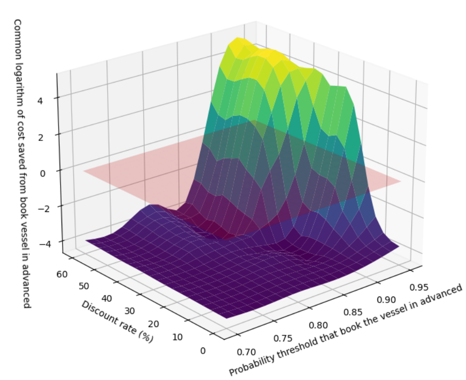

Fig. 18. Cost saved from booking the vessel in advance of 100 wind turbines

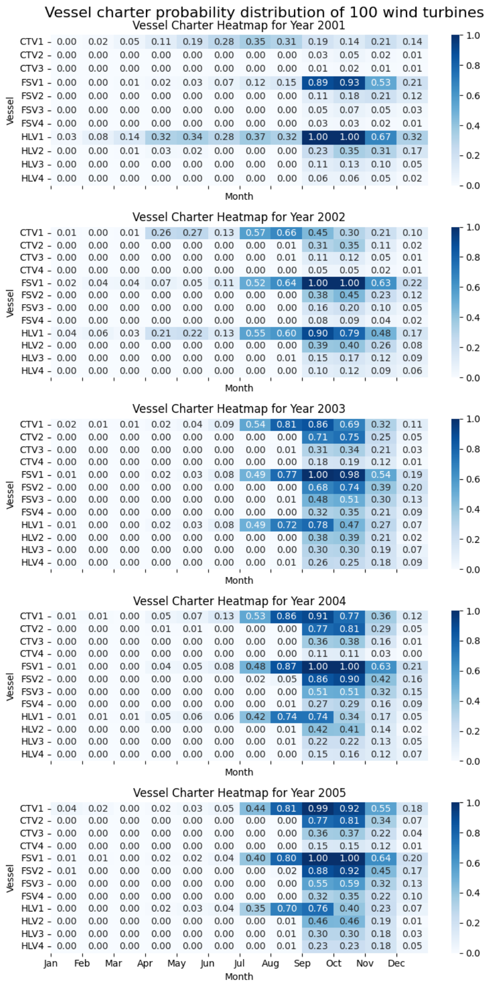

Fig. 19. Vessel charter probability of 100 wind turbines

The optimal initial vessel purchase fleet of the large-size offshore wind farm remains the same as that of the medium-sized offshore wind farm. But compared with the yearly vessel acquisition cost. The annual vessel acquisition cost of a medium sized offshore wind farm decreases significantly when there are 2 FSVs purchased. Then, the annual vessel acquisition cost increases significantly if the FSV's initial purchase amount increases. However, compared with large offshore wind farms, Having more than 2 FSVs as the initial purchase would not significantly increase the yearly vessel acquisition cost. This represents that as the wind turbine amount increases, the usage of third and fourth FSV also increases, which can also be concluded when comparing the vessel charter probability of medium size offshore wind farm in figure 15 and large size offshore wind farm 19. However, purchasing the vessel in advance is still not cost-effective.

The charter probability heat map for executing the maintenance tasks of the large size offshore wind farm is shown in figure 19. Compare with the charter probability heat map of medium size offshore wind farm. The large size offshore wind farm has more maintenance tasks. Therefore, the charter probability of the vessels, especially the third and fourth FSV increases when there's no initial purchase fleet. Figure 18 shows that when the probability threshold reaches 0.85, the shipowner is willing to provide a discount over 20%. Reserving the vessel in advance is cost-effective. Therefore, when the discount rate is over 20%, Reserve the CTV 1 in September 2003, 2004, 2005, and August 2004. FSV 1 in September and October from 2001 to 2005. HLV 1 in September and October of 2001 is cost-effective when there's no initial vessel purchase amount. Figure 17 shows 1 CTV and 2 FSV for the initial purchase. When the discount rate of reserving the vessel in advance reaches 20%, reserving 1 HLV in September and October 2001 is cost-effective.

V. Conclusion

The thesis aims to develop a decision support optimization model for the fleet mix problem, explicitly focusing on vessel chartering and the initial purchasing amount. The key module of the decision support model is the optimizer that arranges the vessel and maintenance tasks. The optimizer is based on mixed-integer linear programming. The Monte Carlo simulation method is applied to generate sufficient strategies for the initial vessel purchase amount. The results from the simulation show that for a medium- or large-scale offshore wind farm, having one FSV purchased in advance can significantly reduce the operator's yearly vessel charter cost.

The closed-loop simulation and optimization model offers a method for selecting the ideal fleet mix. There are still some limits to the model. For example, mixed integer linear programming can precisely arrange tasks and vessels, resulting in an optimal solution. However, as the number of wind turbines increases, the number of maintenance tasks in each cycle increases correspondingly. The solver cannot handle the large-scale model, and as a result, it cannot converge. To reduce the complexity of the model and improve its computation speed, the model calculates the downtime loss using an average value, which results in a solution that is not close to reality. Furthermore, the model has a fixed start time, corresponding to the day the wind farm begins operating. It is impossible to provide the components' current RUL and age consumption at any point during the wind farm's operation.

In the future, some directions can still be improved based on the model. Firstly, to solve the problem, MILP needs huge computational requirements and is difficult to converge when facing large-scale optimization problems. Heuristic methods, such as genetic algorithms, are recommended. Also, the maintenance strategy can be modified to move the maintenance tasks triggered under the opportunistic maintenance strategy forward to avoid the situation that the maintenance tasks are triggered at the end of the optimal maintenance period and need to face a huge penalty during the non-optimal maintenance period. Additionally, different maintenance tasks on the same wind turbine can be combined to save the downtime loss during the maintenance. What's more, optimize the maintenance strategy to avoid overlapping maintenance cycles. Lastly, introducing the dynamic downtime loss combined with the weather conditions at the offshore wind farm can make the model closer to reality.

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