Fleet management for maintenance of offshore wind farms: a simulation model

by

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Preface

This report has been written for the research assignment of the Multi-Machine Engineering track of the Master of Science in Mechanical Engineering at the Delft University of Technology.

Despite some setbacks with the server that were encountered during the assignment and were a bit frustrating at times, I have really enjoyed the assignment. The assignment greatly improved my Python and programming skills. It was satisfactory to develop the simulation model from scratch and see the progress week by week. I am excited to see whether the developed methodology can be used as a complement to other models in the field of offshore wind farm maintenance or be applied in practice to validate the model and evaluate its commercial value.

I would like to thank my supervisors Dr. ir. Xiaoli Jiang and MSc. Mingxin Li for their support and feedback throughout the last few months. Due to various server issues, finalizing the report has been delayed for a total of approximately six weeks. I would like to give special thanks to Breno Alves Beirigo for the support on the server and for fixing the server issues.

Bas Bijvoet
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Abstract

During the lifetime of an offshore wind farm, the operation and maintenance (O&M) costs account for a large portion of the total expenses. This is mainly caused by the high cost of vessels. In order to increase the competitiveness of offshore wind compared to onshore wind and other renewable energy sources, it is essential to decrease the cost of power generation of offshore wind. In this context, the scope of this research is the optimization of fleet management decisions, often referred to as the fleet size and mix problem, for the maintenance of offshore wind farms. Therefore, the literature on available solution methods and existing models have been reviewed first. Based on a comparison of the existing models, a simulation model is developed and presented in this report. The developed methodology is illustrated with a case study example. The model is verified by comparing the expected and actual results of various verification experiments. Moreover, several sensitivity analyses are performed. In the last section of this report, recommendations for features that can be added to the model are given. The developed methodology can be used to optimize fleet management decisions for a given maintenance strategy and, in addition, the consequences of various decisions can be evaluated since the model predicts the O&M costs and wind farm power production.

Contents

1 Introduction

Global warming and changing climate trends have raised more attention for a transition to renewable energy sources in the last decades. In a response to this and to tackle climate challenges, the European Green Deal has set targets for the European Union to become climate neutral in 2050, meaning no net emissions of greenhouse gases. To achieve this, the intermediate target for 2030 is a greenhouse gas emission reduction of 55% compared to 1990 levels. The greenhouse gas emission in 2018 was only reduced by 23% compared to 1990 levels (European Commission, 2019). Therefore, an acceleration in the transition to renewable energy sources is needed to achieve the targets. One strategy of the European Union is to increase offshore wind energy production. The total installed capacity of offshore wind energy in the European Union by the end of 2020 was 25 GW (WindEurope, 2020) and the targets are to increase this to at least 60 GW by 2030 and to 300 GW by 2050 (European Commission and Directorate-General for Energy, 2020).

Despite the growth in the total installed capacity of offshore wind turbines (OWTs) in the European Union, illustrated in Figure 1, the high operating costs of OWTs remain a major challenge. The levelized cost of energy (LCOE), which is a measure of the price of the electricity generated by a power source averaged over its entire life-cycle, of onshore and offshore wind power was about €60/MWh and €85/MWh in 2018, respectively (European Commission et al., 2020). This difference in LCOE of onshore and offshore wind power is for a large part due to the difference in O&M costs, which account for 5% and 23% of the total investment costs of onshore and offshore wind farms, respectively (Ren et al., 2021). The high O&M costs of offshore wind farms are mainly caused by high maintenance expenses, which are generally two to three times higher for offshore wind farms compared to onshore wind farms (Stehly et al., 2020). Therefore, reducing the maintenance costs of OWTs is important to reduce the LCOE of offshore wind energy, which will make offshore wind more competitive with other renewable energy sources and likely lead to the European Green Deal targets being reached more quickly.

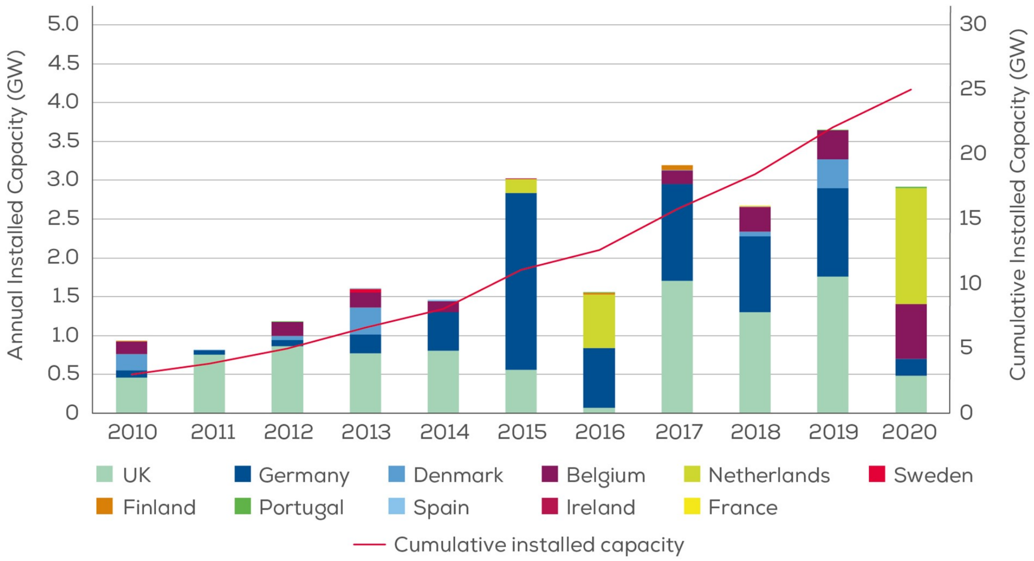


Figure 1: Annual offshore wind installations by country (left axis) and cumulative capacity (right axis). Image retrieved from WindEurope (2020).

1.1 Problem description

The cost of vessels accounts for more than 70% of the total O&M costs and the cost of vessels required for lifting operations constitutes over 50% of the total O&M costs of OWTs (Dalgic et al., 2015d). Therefore, minimizing the costs associated with the vessel fleet is essential to reduce the LCOE of offshore wind power, which is required to make offshore wind power commercially more attractive and boost the installed capacity of this renewable energy source.

Different types of vessels are needed to support maintenance activities. For example, crew transfer vessels (CTVs) can transport technicians to the site to conduct minor repair activities. When lifting activities are required, a heavy lifting vessel (HLV) is needed to lift the heavy components to the height of the cabin. The wind farm operator (or maintenance service provider) usually owns some vessels to conduct maintenance tasks, but these vessels may not be sufficient when a high number of maintenance tasks must be completed. In that case, vessels must be chartered which can be fairly expensive. Therefore, the determination of the optimal fleet size and mix to support maintenance activities at an offshore wind farm is crucial. This involves optimizing a vessel chartering strategy.

1.2 Scope of this research

In this research, the fleet size and mix problem that arises from O&M activities at offshore wind farms is considered. The goal is to develop a tool that can be used to optimize fleet management decisions such that O&M costs for an offshore wind farm can be minimized. These decisions involve determining the number of vessels of each type to be chartered at various moments throughout the wind farm's lifetime, given an available number of owned vessels. The objective is to minimize chartering costs, production losses, technician costs, penalty cost, and operational costs. Uncertainties related to turbine component failures and weather conditions are considered in this research. The model should be flexible to changes in the inputs and the outputs of the model should be easy to analyse in order for the model to be a valuable decision support tool.

Throughout this report, the following research questions will be answered. What are the available methods and models in the field of fleet optimization for O&M of offshore wind farms? What type of method is preferred for this research assignment and why? How can the developed model be verified?

1.3 Outline

The remainder of this report is organized as follows. In section 2, a literature review on the influencing factors of O&M for offshore wind farms and the existing solution models for the fleet size and mix problem are reviewed. The developed modeling methodology is explained in section 3. A case study is presented in section 4 to illustrate the developed methodology. Experiments for model verification and sensitivity analysis are discussed in section 5 and section 6, respectively. Some concluding remarks are given in section 7. Final recommendations for features that can be added to the methodology are provided in section 8.

2 Literature review

This section contains a literature review of relevant theory and solution methods for the studied problem in this research. First, an overview of influencing factors of offshore wind farm O&M in general is presented in section 2.1, which provides some background information about offshore wind farms that is necessary to comprehend the studied problem. In section 2.2 the literature on solution methods of the fleet size and mix problem for offshore wind farms is reviewed.

2.1 Offshore wind O&M framework

Shafiee (2015) classified the challenges associated with the maintenance logistics organization for offshore wind energy into three decision-making echelons based on the length of the planning period: (1) the strategic (long-term) echelon, (2) the tactical (medium-term) echelon, and (3) the operational (short-term) echelon, which are briefly introduced in section 2.1.1, section 2.1.2, and section 2.1.3, respectively. The echelons constitute a framework by which the influencing factors of O&M for offshore wind energy can be identified. Many categories within each echelon are subject to optimization. The reader is referred to Shafiee (2015) for more details on these echelons and references to literature on specific categories of each echelon.

2.1.1 Strategic (long-term) echelon

The strategic (long-term) echelon is characterized by decisions affect the O&M of the offshore wind farm over its entire life cycle (20-40 years). Shafiee (2015) identified four categories within this echelon. First, the decisions regarding wind farm design. Second, the location and capacity of maintenance locations at which (sub-)assemblies of OWTs can be revised. Third, the selection of the maintenance strategy. Fourth, the decisions regarding the outsourcing of repair services to external service providers.

Wind farm design
The decisions within this category include the geographical placement and layout of OWTs within the wind farm. The geographical placement refers to the distance of the wind farm from the shore and the water depth at the site, which both affect the expenditures of maintenance due to logistics and marine environments. The arrangement of OWTs within the wind farm has implications for, e.g., airflow disturbance and turbine accessibility.

Location and capacity of maintenance accommodations
In some cases, (sub-)assemblies cannot be revised on-site and need to be transported to a maintenance accommodation (onshore or offshore) to be revised. The decisions within this category affect the time-to-transport (sub-)assemblies from the site to a maintenance accommodation, which influences the downtime of OWTs.

Selection of the maintenance strategy
The choice of a maintenance strategy is an important decision for the owners and/or stakeholders of the offshore wind farm. The optimization of the maintenance strategy is a well-studied research topic for which Shafiee (2015) presents an overview. There are three main categories of maintenance strategies: corrective maintenance, proactive maintenance, and opportunistic maintenance (Ren et al., 2021). Corrective maintenance is a failure-based strategy, i.e., maintenance is carried out after a failure. Proactive maintenance is a strategy in which maintenance is carried out before a failure, which includes, i.a., preventive maintenance and condition-based maintenance. Preventive maintenance can be (i) periodically or (ii) usage-based. In the former (i), maintenance is performed at predetermined periods, which requires the determination of a visit frequency. The visit frequency is a trade-off between different costs since a high visit frequency leads to high fleet and personnel costs but lower downtime costs and vice-versa for a lower visit frequency. In the latter (ii), maintenance is performed based on the power generated by an OWT. In a condition-based maintenance strategy, condition monitoring systems (sensors) evaluate the condition of a system and maintenance is applied once a threshold value for the system is reached. Opportunistic maintenance is often a combination of other maintenance strategies and is characterized by taking the advantage of personnel (and parts, etc.) being at a location to perform a certain maintenance task by additionally performing other (unplanned) maintenance.

Outsourcing the repair services
The wind farm owner may choose to outsource the maintenance activities to an external service provider as it can be very expensive to keep the maintenance activities in-house and it requires a fleet of vessels and trained technicians. In case the maintenance tasks are outsourced, the wind farm owner pays an external service provider to perform the maintenance tasks.

2.1.2 Tactical (medium-term) echelon

The tactical (medium-term) echelon deals with decisions with a planning period from several months to several years. Shafiee (2015) identified three categories within this echelon. First, the decisions regarding spare parts inventory management. Second, the decisions regarding the maintenance support organization. Third, the purchasing and leasing decisions of transportation equipment.

Spare parts inventory management
The inventory management of spare parts is a trade-off between reordering costs, holding costs, and shortage costs. Maintaining a high level of spare parts leads to high holding costs but low shortage costs (such as downtime costs). On the other hand, a low level of spare parts results in low holding costs but high shortage costs.

Maintenance support organization
The decisions of the maintenance support organization require the allocation of transportation means and teams of technicians to perform certain types of maintenance activities. The vessel type and the number of technicians per type of maintenance activity should therefore be specified.

Purchasing and leasing decisions
Purchasing vessels for maintenance activities of OWTs is very expensive and, therefore, leasing vessels can be more cost-efficient. The vessel chartering strategy is identified as a critical issue since the vessel costs can constitute over two-thirds of total O&M costs.

2.1.3 Operational (short-term) echelon

The operational (short-term) echelon concerns the decisions of day-to-day operations. Shafiee (2015) identified three categories within this echelon. First, the decisions on the scheduling of maintenance tasks, taking into account the availability of resources. Second, the decisions regarding the routing of vessels within the offshore wind farm. Third, measuring the maintenance performance to evaluate the quality of services.

Scheduling of maintenance tasks
The maintenance tasks to be executed must be scheduled with a rolling time horizon to be able to react to changing conditions of weather, availability of vessels, spare parts, and technicians. Furthermore, the scheduling process is affected by uncertainty in component failures and weather conditions.

Routing of maintenance vessels
In accordance with the maintenance task schedule, the vessels need to be routed between the OTWs within the wind farm. An optimal routing plan minimizes the inter-transit time of vessels between OTWs and may result in fewer vessels required to support the maintenance activities.

Measuring the maintenance performance
It is important to carefully select the maintenance performance indicators since they have a huge impact on the decisions one wants to optimize. For example, if one aims to optimize the chartering strategy of the vessels and the maintenance performance is only expressed in terms of wind farm availability, the decisions will tend towards chartering as many vessels as possible to minimize downtime (regardless of the associated charter costs). The maintenance performance can be expressed by key indicators such as wind farm availability, accessibility, mean time between failures (MTBF), mean lead-time (MLT) for spare parts and support vessels, mean time to repair (MTTR), annual downtime, and production loss ratio (Shafiee, 2015).

2.2 Available solution methods for the fleet size and mix problem

In this section, the literature on solution methods of the fleet size and mix problem for the maintenance of offshore wind farms is reviewed. There are two main solution methods, which are categorized as exact methods and simulation methods. In exact methods, a mathematical model is formulated and solved by minimizing an objective function subject to constraints. In simulation methods, for one specific realization of the decision variables, the outputs (e.g., total costs and wind farm availability) are determined after simulating the maintenance activities. By performing simulations for different fleet configurations, the most favorable fleet size and mix can be determined.

2.2.1 Exact methods

There are two types of exact methods for the fleet size and mix problem for offshore wind farms: deterministic optimization and stochastic programming. In deterministic optimization, all the parameters are assumed to be known. In case some parameters are stochastic, the mathematical model is solved with the expected value of the stochastic parameters. In stochastic programming (SP), the uncertainty of parameters is considered by solving a scenario tree node-based deterministic equivalent.

2.2.1.1 Deterministic optimization models

Halvorsen-Weare et al. (2013) developed a deterministic vessel fleet optimization model for offshore wind farms. They aimed to give offshore wind farm operators a tool to determine which types of vessels to buy, which and how many vessels to charter, and which vessel bases (onshore and offshore) to use. The weather conditions, electricity price, vessels' charter rates, and corrective maintenance (turbine failure) tasks are all treated as deterministic parameters. Halvorsen-Weare et al. (2013) assumed a combination of a preventive and corrective maintenance strategy, where preventive maintenance activities are defined by soft and hard time windows. They used a planning horizon of one year. The objective of their mixed integer programming (MIP) model was to minimize a combination of fixed costs for bases and vessels, variable operating costs, penalty cost for delayed preventive maintenance tasks, expected downtime costs, and transportation costs. The set of vessels (including helicopters) that is considered by Halvorsen-Weare et al. (2013) is somewhat limited, for example, it is assumed that crane vessels can only be purchased.

2.2.1.2 Stochastic programming models

Gundegjerde et al. (2015) proposed a three-stage stochastic programming model for the fleet size and mix problem for offshore wind farms. They extended the deterministic model of Halvorsen-Weare et al. (2013), introduced in section 2.2.1.1, by including uncertainty in charter rates of vessels and helicopters, weather conditions (wind speed and wave height), electricity prices, and failures. In stages 1 and 2, decisions on which vessels to buy and charter, and which vessel bases to use can be made. In stage 3, the maintenance activities are executed by the available fleet. The stochastic programming model is solved by transforming it into its scenario tree node-based deterministic equivalent. Therefore, all decision variables affected by the uncertain parameters are transferred into node-based equivalents, one scenario for each realization of the uncertain parameters. Each realization of the uncertain parameters is referred to as a scenario in which all the parameters are deterministic. Both in stages 1 and 2 it is possible to enter charter contracts for vessels. In stage 1, which refers to the current moment in time, there is no uncertainty in vessels' charter rates, resulting in one node in the scenario tree. In stage 2, the uncertainty in charter rates for vessels becomes deterministic and can be high, medium, or low (each with a certain probability), resulting in three nodes in the scenario tree. In stage 3, the uncertainty in weather conditions, electricity prices, and failures becomes deterministic by sampling from a probability distribution. Gundegjerde et al. (2015) experimented with the number of third-stage scenarios, ranging from 3 to 36. The main focus of the computational study in Gundegjerde et al. (2015) was to evaluate the added value of the stochastic programming model compared to a deterministic equivalent (where all uncertain parameters are replaced by their expected value). The added value of a stochastic approach was concluded to be significant as, for some problem instances, the solution of the deterministic equivalent underestimates the required vessel fleet, resulting in fewer maintenance tasks being completed in rougher weather conditions.

Stålhane et al. (2019) identified three limitations of the models of Halvorsen-Weare et al. (2013) and Gundegjerde et al. (2015), which they improved. First, Stålhane et al. (2019) did not limit the maximum allowable time between the occurrence of a failure and its repair. In case of rough weather conditions, this avoids chartering one specific (expensive) vessel type capable of operating in these rough weather conditions to complete the maintenance task before the end of the hard time window. Second, instead of assuming that vessels have a number of time units available each day that are assigned to maintenance tasks, they considered sets of maintenance tasks a vessel can support in a certain time window. They did not allow vessels to work on tasks in different shifts, which means that a task is started only if it can be completed in one turn. Third, to handle end-of-horizon effects, they used a circular timeline that avoids chartering expensive vessels to support all maintenance tasks before the end of the planning horizon. In contrast to Gundegjerde et al. (2015), Stålhane et al. (2019) did not consider uncertainty in the electricity price and vessels' charter rates, since, according to Sperstad et al. (2017b), the optimal vessel fleet is unaffected by stochasticity in these parameters. The SP model of Stålhane et al. (2019) consists of two stages. In the first stage, it is decided which ships will be chartered and which bases will be used. In the second stage, the available vessel fleet is deployed to perform maintenance tasks and the performance is evaluated by the operating and downtime costs. The routing of vessels is also considered in the second stage of their model. The SP model is solved is using a deterministic equivalent by considering multiple scenarios with a certain probability (each representing a realization of the stochastic parameters with a certain probability).

Stålhane et al. (2017) proposed a two-stage SP model to determine the optimal jack-up vessel chartering strategy for an offshore wind farm. Schrotenboer et al. (2020) took the perspective of a maintenance service provider, instead of that of the wind farm owner, and developed a two-stage SP model for the fleet size and mix problem for offshore wind farms. Therefore, the objective is to minimize costs while adhering to the minimum service requirements specified by a service contract without taking into account production losses due to downtime.

2.2.2 Simulation methods

Dalgic et al. (2015c) used Monte-Carlo simulations to evaluate 65 different fleet compositions, formed from 2 different CTVs. Their objective was to find the fleet composition resulting in the minimum total O&M costs. They considered uncertainty in weather conditions and failures. The maintenance strategy used by Dalgic et al. (2015c) is a combination of preventive and corrective maintenance, where the preventive maintenance tasks must be performed within the specified service interval. For each fleet composition, 100 scenarios (with realizations of the stochastic parameters) are simulated. Similar Monte-Carlo simulation studies were done in Dalgic et al. (2015d) and Dalgic et al. (2015b), where the former investigated the optimum jack-up vessel chartering strategy and the latter the optimum mothership concepts and chartering strategy. Another simulation model was proposed by Dalgic et al. (2015a) who evaluated the performance of fleet compositions (which may consist of a helicopter, CTVs, offshore access vessels, and jack-up vessels) to minimize total O&M costs. Additionally, they included decisions like the shift time start, charter length of vessels, and the preventive maintenance start month. The results of the simulations indicated that several fleet configurations lead to very similar objective values. This suggests that a simulation model may be more useful than an exact model, since a simulation model allows the results of multiple fleet configurations to be evaluated and compared, whereas with an exact model only the result of the optimal solution is obtained. For example, if the objective of a stochastic programming model is to minimize the average total cost of several scenarios, the model will give the optimal values of the decision variables that minimize this objective function. Even though the average cost is minimized, it is possible that there is a different combination of values of decision variables that results in just slightly higher average costs, but with lower maximum costs for any of the scenarios. In other words, the optimal values of the decision variables may have more risk than other solutions with slightly higher values of the objective function. However, this cannot be determined with exact methods, since only the optimal solution is obtained. Simulation models, on the other hand, can be used to evaluate the results of different solutions, which is useful for risk versus benefit analysis.

In Dinwoodie et al. (2015), four different operation and maintenance simulation models for offshore wind farms were compared (the models of Hofmann and Sperstad (2013), Endrerud et al. (2014), Douard et al. (2012), and Dinwoodie et al. (2013)). The results indicated that the four simulation models produce significantly different results due to different modeling approaches and assumptions. They concluded that the following modeling assumptions have a large effect on the simulation results and, hence, should be paid high attention to: "(1) possibility to perform parallel maintenance tasks in a shift, (2) approach of modeling failures, (3) possibility to assign maintenance tasks to vessels when offshore, and (4) approach on modeling of charter options for heavy-lift vessels" (Dinwoodie et al., 2015). The modeling approach of chartering HLVs (4) refers to whether HLVs are chartered for a minimum length (e.g., one month) or for the minimum required period to complete the tasks.

2.2.3 Comparison of solution methods

In the study of Sperstad et al. (2017b), six different decision support tools for offshore wind farm O&M were applied to a reference wind farm to compare the decisions on the best vessel fleet. They compared four simulation models, one SP model, and one analytical spreadsheet-based tool. Sperstad et al. (2017b) performed a sensitivity analysis to determine how robust these models are for different input parameters. They concluded that the models generally agree on which vessel fleet is the best. However, the sensitivity analyses indicated that modeling assumptions cause discrepancies between the models. It was concluded that what determines the best fleet to perform maintenance at an offshore wind farm depends heavily on the assumptions made in developing a decision tool. Therefore, it is important that the modeling assumptions reflect the operational strategy of the wind farm owner.

From the literature review on the different solution methods for fleet management of offshore wind farms, four main differences (advantages and disadvantages) were identified. First, the exact models solve a static problem where all information is known a priori. For example, the corrective maintenance tasks (sudden failures) of OWTs and weather conditions are assumed to be known over the planning horizon. Thus, optimal routing and scheduling decisions can be determined by anticipating future events, while in practice the failures and weather conditions are not known a priori. Consequently, exact methods (both deterministic optimization and stochastic programming, see section 2.2.1) may underestimate the required fleet size and costs of O&M since in practice there is incomplete information. Contrasting to exact methods, simulation methods can deal with information to be revealed over time, i.e., simulation methods can be considered more dynamic. Consequently, the problem can be modeled more realistically in simulation methods compared to exact methods. Second, the results of using a specific fleet can be analysed in much greater detail with simulation methods compared to exact methods. This is because exact methods lead to one outcome, which is the fleet that minimizes the objective function, whereas with simulation methods the outcomes of several fleet configurations can be analysed. Such analyses can be very useful for assessing the risks versus the benefits of different fleets. For example, one specific fleet composition resulting in the lowest expected costs may have significantly more risks in extreme cases than another fleet composition with somewhat higher average costs. These considerations can be taken into account by analysing the results of a simulation model. Third, the obvious benefit of exact models is that the optimal solution is obtained automatically, whereas with simulation models the inputs (decision variable values) for each simulation have to be defined manually. Therefore, simulation methods basically require a trial-and-error procedure by defining the inputs, simulating the O&M activities for the inputs, evaluating the results, and then defining new inputs until one cannot find a set of inputs that leads to better results. Fourth, and last, it stands out that the models of exact methods are publicly available and described in detail in their papers, while the models of simulation methods are not publicly available. Thus, the mathematical formulation of an existing exact method can be implemented and tested very easily using a commercial mixed integer programming solver. In contrast, a simulation model cannot be easily tested since the code of these models is not publicly available. For example, a total of only 13 licenses have been granted to parties for the simulation model of Sperstad et al. (2017a), with these parties not having access to the code but only to an executable version of the model. The reason simulation models are not publicly available may be due to their value for commercial use.

3 Methodology

Based on the differences and advantages of simulation models compared to exact models (see section 2.2.3), a discrete-event simulation (DES) model is developed for this research assignment. First, the O&M activities can be modeled more realistically with a simulation model compared to an exact model, as a simulation model can better deal with information to be revealed over time (a rolling time horizon). Secondly, the performance of different fleets under different conditions can be analysed better with a simulation model as an exact model prescribes only one outcome. Third, although finding the best solution for the objective function is only guaranteed with an exact model, it is expected that the best solution with a simulation model can be found anyway as long as a sufficient number of simulations are performed. Fourth, simulation models are publicly not available while exact models are. Therefore, developing a simulation model fills a gap but can be more challenging since fewer examples are available compared to exact models.

Therefore, developing a simulation model can be more challenging since fewer examples are available compared to exact models. However, developing a simulation model fills a gap, as one can then compare exact models with the simulation model developed in this study.

The model is developed to optimize the fleet size and mix problem for offshore wind farm maintenance activities. The model involves both decisions from the tactical and operational echelon described in section 2.1. The methodology is developed in Python version 3.10 and uses the DES package Salabim (van der Ham, 2022). The resolution of the simulation model is 20 minutes (one period represents 20 minutes). The resolution is determined based on the required time for the most detailed thing considered important for this research, which is the inter-transit time including the time to board technicians. Similar to other simulation models, like (Dalgic et al., 2015a) and (Hofmann and Sperstad, 2013), an average inter-transit time is used for each vessel type to travel between two turbines.

O&M activities can be simulated over several years to estimate performance indicators related to the maintenance activities. Monte Carlo simulations are performed to account for the uncertainty in turbine component failures and weather conditions. The outcomes of the model and how the results can support decisions regarding the fleet size and mix are discussed in the case study (section 4). However, the model is developed in such a way that it can be used as a universal analysis tool for simulating the O&M activities and forecasting the cost related to offshore wind farm maintenance activities. Therefore, input parameters can be changed very easily to analyse the results of different cases.

This section contains five subsections. First, the maintenance strategy for which the simulation model is built is presented. Second, what characterizes a scenario and how it is generated is explained. Third, the simulation inputs that need to be defined before performing the simulations are explained. Fourth, the modeling assumptions and logistics are discussed. Finally, the outputs of the developed methodology are explained.

3.1 Maintenance strategy

In this research, a maintenance strategy is considered that is based on the age of turbine components. This research aims to optimize the fleet management plan for a given maintenance strategy at offshore wind farms. In other words, the maintenance strategy is an input of this study and is defined outside the scope of this research. Accordingly, optimizing issues related to the maintenance strategy is outside the scope of this research. In this subsection, the given maintenance strategy is discussed.

In the aged-based maintenance strategy, four components per turbine are considered: the rotor, the bearing, the gearbox, and the generator. In the model, these components are referred to as ‘roto’, ‘bear’, ‘gear’, and ‘gene’, respectively. The lifetime of each of these components is defined by a Weibull distribution with given shape and scale parameters. Components age over time and eventually fail if the lifetime of a component is entirely used. Corresponding to the age percentage of components, which is the fraction of the consumed age relative to the components’ lifetime, a component is categorised in a zone and for each zone a different type of maintenance is required. There are four types of maintenance: minor repair, major repair, preventive replacement, and corrective replacement. The maintenance activities minor and major repair maintenance result in an age reduction of the components. If a component is replaced, the lifetime of the new component is sampled from the components' Weibull distribution. The cost and required time of maintenance activities are estimated and collected from Sarker and Faiz (2016), Carroll et al. (2015), and Le and Andrews (2015).

Maintenance activities can be performed within a so-called maintenance cycle. A maintenance cycle can be initiated by two triggers: (i) if the number of failed components equals or exceeds a defined threshold or (ii) if the number of components in zone 4 equals or exceeds a defined threshold. A maintenance cycle is ended if all maintenance tasks are completed. There is a soft time limit for the duration of a cycle of 60 days. For each day that a cycle lasts longer than 60 days, a penalty of 50 000 €/day is imposed.

The four different types of maintenance require different types of vessels. For a minor repair, a crew transfer vessel (CTV) is required that transports a team of technicians to the turbine. It is assumed that a major repair will require medium-weighed parts to be lifted onto the turbine. Therefore, a field support vessel (FSV) equipped with a small crane is required for a major repair. For replacement tasks (preventive and corrective) it is required to lift heavy parts to the hub height of the OWT. Therefore, these maintenance activities require a heavy lifting vessel (HLV) with jack-up capabilities and a big crane. The maintenance types, corresponding component age, zone, required vessel type, and required number of technicians are listed in Table 1. Each maintenance task requires a certain number of technicians that is equal for all turbine components. The failure distribution (the lifetime) of each component is listed in Table 2. The cost and time per maintenance type for each component are listed in Table 3 and Table 4, respectively. The trigger values (thresholds) for a maintenance cycle to start are listed in Table 5.

maintenance type	**component age (%)**	**zone**	**age reduction**	**vessel type**	**number of technicians**
no maintenance	[0, 50)	zone 1	-	-	-
minor repair	[50, 70)	zone 2	30%	CTV	3
major repair	[70, 90)	zone 3	50%	FSV	6
preventive replacement	[90, 100)	zone 4	new component	HLV	8
corrective replacement	$\geq$ 100	failed	new component	HLV	8

Table 1: The age window of components, the corresponding zone, age reduction after maintenance, and required vessel type and number of technicians for each maintenance type.

component	**Weibull shape parameter**	**Weibull scale parameter (days)**
rotor	3	3 000
bearing	2	3 750
gearbox	3	2 400
generator	2	3 300

Table 2: Weibull parameters for lifetime of components

	cost (k€)			
maintenance type	**rotor**	**bearing**	**gearbox**	**generator**
minor repair	4	1	5	1.5
major repair	15	3.75	18.75	5
preventive replacement	60	15	75	20
corrective replacement	185	45	230	60

Table 3: Maintenance cost per maintenance type per component.

time (h)				
maintenance type	**rotor**	**bearing**	**gearbox**	**generator**
minor repair	9	6	8	7
major repair	18	12	16	14
preventive replacement	70	50	70	60
corrective replacement	100	70	100	81

Table 4: Maintenance time per maintenance type per component.

cycle trigger	threshold
number of failed components	1
number of zone 4 components	5

Table 5: Threshold values for a maintenance cycle to start.

3.2 Scenario generation

A scenario consists of weather conditions for each period and the initial lifetime of components. In this research, three types of environmental constraints are considered: wave height, wind speed at sea level, and wind speed at hub level. Seasonal effects of weather conditions are disregarded in this research. Weibull distributions are used to generate synthetic climate datasets. It is assumed that the weather conditions are constant for the length of 4 hours (12 periods).

The Weibull shape and scale parameters are according to Barth and Eecen (2006) and are listed in Table 6 and represent weather conditions of the north sea 18km off the coast of the Netherlands. The shape and scale parameters for wind speed characterize a measurement height of 21 meters. Similar to Dalgic et al. (2015a), the wind power law is used to extrapolate the wind speed to different altitudes (Justus and Mikhail, 1976):

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha}, \tag{3.1}$$

where v_2 and v_1 are the wind speeds at h_2 and h_1, respectively, and α is a shear component.

	Weibull shape parameter	**Weibull scale parameter**
wind speed (at 21m)	2.43	8.58 m/s
wave height	1.99	1.35 m

Table 6: Weibull parameters for wind speed and wave height.

The scenarios, hereinafter referred to as ‘sets’, must be created before performing simulations. One set contains conditions of wave height, wind speed at sea, wind speed at hub height, and the initial lifetime of components (created according to Table 2). The total number of sets to create can be defined by the user. Each set is created using a different and unique random seed, such that the weather conditions and lifetime of components of each set are different.

3.3 Simulation inputs

The simulation inputs define the information that needs to be defined before running the simulations. In this section, the inputs of the simulation model are explained and the assumed parameter values for the case study in section 4 are listed. The non self-explanatory parameters are explained in the subsections and are referred to with numbers and brackets “[ ]” according to the tables.

3.3.1 Owned vessels inputs

The number of owned vessels of each type can be defined for the simulations. Table 7 shows the assumed number of owned vessels per type for the case study in this research. These values can be changed by the user for a different case study.

	Name	Value
[1]	Number of HLVs owned (num_HLVs_owned)	0
[2]	Number of FSVs owned (num_FSVs_owned)	0
[3]	Number of CTVs owned (num_CTVs_owned)	1

Table 7: Number of owned vessels inputs.

3.3.2 Wind farm and turbine inputs

Table 8 shows the wind farm and turbine inputs [1-7]. Input [1] is the number of turbines within the offshore wind farm. Inputs [2-6] are specifications of a single turbine. Input [7] is the distance between the offshore wind farm and the onshore base.

	Name	Value	Unit
[1]	Number of turbines	50	turbine
[2]	Rated power output	3.6	MW
[3]	Rated output wind speed	13	m/s
[4]	Cut in speed	4	m/s
[5]	Cut out speed	25	m/s
[6]	Hub height	77.5	m
[7]	Distance from shore	50	km

Table 8: Wind farm and turbine inputs.

3.3.3 Vessel characteristics, constraints and inputs

Subject to the given maintenance strategy (an input of this research), three various vessel types need to be considered: the HLV, FSV, and CTV. The characteristics and constraints, which affect the operations and logistics, for these vessel types are shown in Table 9. Characteristic [1] indicates which vessel type can stay on-site (offshore) for multiple days. The HLV and FSV can stay offshore for multiple days, while the CTV cannot. Constraint [2] indicates which vessel type is constrained by shift hours. Since the costs associated with HLVs are high, they can work 24 hours a day on three shift basis. The FSV and CTV are constrained by shift hours, resulting in the FSV staying on-site after shift end and the CTV returning to base after shift end. Constraints [3-5] are weather constraints. The FSV and CTV are not constrained by the wind speed at hub level, since only the HLV needs to lift parts to hub level of the turbine. The vessel characteristics and constraints of Table 9 are no inputs of the model, in other words, these cannot be changed by the user without adjusting the model itself.

The vessel specification for three considered vessel types are shown in Table 10 by inputs [1-14]. Input [1] is the travel speed, which is assumed to be constant and not dependent on weather conditions. Input [2] is the inter-transit time between two turbines, including the time required for a team to enter the turbine. In practice, the inter-transit time between two turbines depends on the layout of turbines within the wind farm. In this research, for simplicity the inter-transit time is assumed to be constant. Input [3] is the minimum working window and indicates the time window that at least must be available for a vessel or team to work on a maintenance task before starting or resuming it. This implies that the window of good weather and the remaining time in shift (if the vessel type is constrained by shift hours) must be at least equal to the minimum working window before a vessel will start/resume a maintenance task. Input [4] is the number of technicians on board a vessel and is related to the number of technicians per team required for a maintenance task. The required number of technicians for maintenance tasks is given as part of the maintenance strategy, see section 3.1. As mentioned before, the HLV can work 24 hours on three shift basis. Therefore, it is assumed that 3 teams of 8 technicians are located on the HLV that take turns completing the maintenance tasks. The FSV and CTV are equipped with 2 and 4 teams, respectively. Input [5] is the maximum number of parallel teams and indicates how many teams of the vessel can work on different maintenance tasks simultaneously. Since it is assumed that HLVs and FSVs cannot work on multiple tasks simultaneously (because these vessels themselves are involved in completing maintenance tasks by lifting parts to and from the turbine), input [5] for the HLV and FSV is set to 1 and cannot be changed for the model. Making input [5] for the HLV and FSV dynamic is included in the recommendations in section 8. Input [5] for the CTV is set to 4, equal to the number of teams on board. The influence of input [5] on the logistics of the CTVs is explained in section 3.4. Inputs [6-8] are weather-related limits. Inputs [11-13] are related to chartering vessels. Input [11], the mobilisation time, indicates the time required for a chartered vessel to get the vessel ready for work. Input [12] is the length of a charter period. If a charter period has ended, it may be decided to extend the charter period. Input [13] indicates the length of such an extended charter period. The model may be extended by making input [12-13] a decision variable, see the recommendations in section 8. Input [14] indicates the fuel consumption while traveling.

	Name	**HLV**	**FSV**	**CTV**
[1]	can stay multiple days on-site	✓	✓	×
[2]	constrained by shift hours	×	✓	✓
[3]	constrained by wave height	✓	✓	✓
[4]	constrained by wind speed at sea	✓	✓	✓
[5]	constrained by wind speed at hub	✓	×	×

Table 9: Characteristics and constraints for each vessel type (cannot be changed).

	Name	**HLV**	**FSV**	**CTV**	**Unit**
[1]	travel speed	11	13.5	24	knot
[2]	inter-transit time	40	40	20	min
[3]	minimum working window	α*	120	60	min
[4]	technicians on board	24	12	12	person
[5]	maximum parallel teams	1*	1*	4	team
[6]	limit wave height	2.8	2	1.7	m
[7]	limit wind speed at sea	36.1	25	25	m/s
[8]	limit wind speed at hub	15.3	-	-	m/s
[9]	jack up time	3	-	-	hour
[10]	jack down time	3	-	-	hour
[11]	mobilisation time	30	21	7	day
[12]	charter length	30	30	30	day
[13]	extend charter period length	15	15	15	day
[14]	fuel consumption	0.55	0.2	0.24	mt/h

α: The minimum working window for the HLV is equal to the total time required for the maintenance task.
* Cannot be changed.

Table 10: Vessel specification inputs.

3.3.4 Cost inputs

Table 11 shows the cost inputs [1-12]. Input [1], the electricity price, is used to calculate the revenue of electricity production. The electricity price is assumed to be constant over the simulated time horizon, as (Sperstad et al., 2017b) concluded that the decisions on fleet size and mix are not very sensitive to electricity price fluctuations over time. Inputs [2-7] are costs associated with chartering vessels. Inputs [8-10] are fuel costs for each vessel type associated with the transportation of the vessel. Inputs [11-13] are technician costs for each vessel type. Technician costs for owned vessels are considered during an entire cycle, while technician costs for chartered vessels are only considered during the charter period.

	Name	Value	Unit
[1]	electricity price	150	€/MWh
[2]	HLV mobilisation cost	800 000	€/mobilisation
[3]	FSV mobilisation cost	200 000	€/mobilisation
[4]	CTV mobilisation cost	50 000	€/mobilisation
[5]	HLV charter rate	110 000	€/HLV/day
[6]	FSV charter rate	10 000	€/FSV/day
[7]	CTV charter rate	2 500	€/CTV/day
[8]	HLV fuel cost	450	€/mt
[9]	FSV fuel cost	300	€/mt
[10]	CTV fuel cost	300	€/mt
[11]	HLV technician cost	100 000	€/techn/year
[12]	FSV technician cost	100 000	€/techn/year
[13]	CTV technician cost	60 000	€/techn/year

Table 11: Cost inputs.

3.3.5 Additional parameter inputs

Table 12 shows the additional parameters inputs [1-7]. Input [1] indicates the simulation time horizon. Inputs [2-3] are the shift start and end, respectively. Inputs [4-5] are used to create climate data sets. Input [4] indicates the relevant height above sea level for vessel wind speed limits and is used to create the weather conditions of 'wind speed at sea'. Input [5] is the shear components to extrapolate wind speed to different altitudes (Equation 3.1).

At the start of a maintenance cycle, it is decided how many vessels will be chartered. During the cycle, it is periodically checked if more vessels should be chartered for which input [6] indicates the interval. Input [7] specifies the multiplier of charter cost per vessel per day in case the chartered vessel is returned after the charter period has ended. A chartered vessel may be returned late due to the modeling assumption that started maintenance tasks need to be finished before the chartered vessel is returned. Input [8] is the soft limit for the duration of a cycle. For every day a maintenance cycle takes longer than input [8], a penalty cost (input [9]) is imposed.

	Name	Value	Unit
[1]	years to simulate	15	year
[2]	shift start	08:00	hh:mm
[3]	shift end	20:00	hh:mm
[4]	relevant height above sea	5	m
[5]	shear component	0.1	-
[6]	check to charter every	15	day
[7]	multiplier for late return	2	-
[8]	cycle duration soft time limit	60	day
[9]	penalty for exceeding [8]	50 000	€/day

Table 12: Additional parameter inputs.

3.3.6 Decision variables and chartering vessels

The simulation model aims to optimize the fleet size and mix (comprising of HLVs, FSVs, and CTVs) for O&M activities of an offshore wind farm (given an owned vessel fleet). Various types of decision variable have been considered. It is possible to directly set the number of vessels to be chartered as decision variables. Then at the start of each maintenance cycle, a certain number of vessels of each type is chartered. However, this is a fairly static approach. The first reason is that with this approach vessels could only be chartered at the start of a maintenance cycle. Secondly, it may not make sense to charter the same number of vessels for every maintenance cycle. This is because the number of tasks for each vessel type can be very different in different maintenance cycles. Most likely, more components require major repairs and replacements in cycles near the end of the simulation time horizon compared to the first few cycles, since in the final years of the wind farm more turbine components will be in an old state. From this perspective, chartering the same number of vessels for each cycle does not seem to be the best approach. A second approach can be to define the number of vessels of each type to be chartered for each maintenance cycle. However, it is not known in advance how many maintenance cycles there will be throughout the planning horizon. Secondly, it is not known in advance how many tasks for each vessel type in each cycle there will be. Therefore, it is difficult to determine a sensible number of vessels to charter for each cycle a priori. To overcome these issues, the model is equipped with a decision logic to determine the number of vessels automatically and make these dynamic decisions based on the number of the maintenance tasks per vessel type to be completed. The decision logic is explained below in Example 1. The value of a decision variable indicates for how many tasks one vessel is desired. The values of the decision variables must be defined before executing a simulation. By performing multiple simulations with different numbers for the decision variables, the best set values of the decision variables can be determined. The decision variables for which values must be defined before performing a simulation are:

- tasks_per_HLV
- tasks_per_FSV
- tasks_per_CTV

The general equations used to decide how many vessels of each type to charter are given by:

$$\text{num\_charter\_HLVs} = \left\lceil \frac{\text{num\_tasks\_for\_HLV}}{\text{tasks\_per\_HLV}} \right\rceil - \text{num\_HLVs\_owned}, \tag{3.2}$$

$$\text{num\_charter\_FSVs} = \left\lceil \frac{\text{num\_tasks\_for\_FSV}}{\text{tasks\_per\_FSV}} \right\rceil - \text{num\_FSVs\_owned}, \tag{3.3}$$

$$\text{num\_charter\_CTVs} = \left\lceil \frac{\text{num\_tasks\_for\_CTV}}{\text{tasks\_per\_CTV}} \right\rceil - \text{num\_CTVs\_owned}, \tag{3.4}$$

where $\lceil \cdot \rceil$ denotes the ceiling operation.

Example 1: decide how many vessel to charter

Input: owned vessel fleet

- num_HLVs_owned: 0
- num_FSVs_owned: 0
- num_CTVs_owned: 1

Define the decision variables before performing the simulation:

- tasks_per_HLV: 5
- tasks_per_FSV: 30
- tasks_per_CTV: 60

Checked by the model: number of maintenance tasks per vessel type to be performed

- num_tasks_for_HLV: 3 (arbitrary number for this example)
- num_tasks_for_FSV: 39 (arbitrary number for this example)
- num_tasks_for_CTV: 45 (arbitrary number for this example)

Decisions to charter:

$$\text{num\_charter\_HLVs} = \left\lceil \frac{3}{5} \right\rceil - 0 \quad = \lceil 0.6 \rceil - 0 \quad = 1 - 0 \quad = 1$$
$$\text{num\_charter\_FSVs} = \left\lceil \frac{39}{30} \right\rceil - 0 \quad = \lceil 1.3 \rceil - 0 \quad = 2 - 0 \quad = 2$$
$$\text{num\_charter\_CTVs} = \left\lceil \frac{45}{60} \right\rceil - 1 \quad = \lceil 0.75 \rceil - 1 \quad = 1 - 1 \quad = 0$$

The decision would be charter 1 HLV, 2 FSVs, and 0 CTVs.

In case the user wants to perform a simulation in which, for example, the FSV type is never chartered (regardless of the number of tasks for FSV or number of FSVs owned), tasks_per_FSV must be set to 0.

If the charter period of, e.g., a HLV has ended, it may be decided to extend the charter period of that HLV by Table 10 input [13] if there are still sufficiently remaining tasks left relative to tasks_per_HLV and num_HLVs_owned. The decision logic to decide whether a charter period should be extended or not is explained in Example 2 and given by:

$$\text{extend\_charter\_period} = \begin{cases} \text{Yes} & \text{num\_charter\_HLVs} + \text{num\_HLVs\_owned} \geq \text{num\_HLVs\_in\_fleet} \\ \text{No} & \text{num\_charter\_HLVs} + \text{num\_HLVs\_owned} < \text{num\_HLVs\_in\_fleet}, \end{cases} \tag{3.5}$$

where num_HLVs_in_fleet is the number of HLVs in the current fleet including the HLV for which must be determined if the charter period will be extended. The decision logic to determine if the charter period of FSVs and CTVs should be extended is similar to Equation 3.5, but with 'HLV' replaced by 'FSV' and 'CTV', respectively.

In case a charter period has ended, the vessel always return to base, regardless of whether the charter period will be extended. It is modeled like this, since it is assumed that the technicians on board need to be renewed and the vessel needs to be resupplied. In case it is decided to extend the charter period, the vessel will return back to site at shift start (08h00) the day after it arrived at base.

Example 2: decide whether to extend the ended charter period of vessel

Suppose the charter period of the chartered HLV in Example 1 has ended.
Should it be extended or not?

Similar to Example 1:

- num_HLVs_owned: 0
- tasks_per_HLV: 5

Checked by the model: number of maintenance tasks for HLV to be performed

Scenario 1:

- num_tasks_for_HLV: 4 (arbitrary number for this example)

Scenario 2:

- num_tasks_for_HLV: 0 (arbitrary number for this example)

Scenario 3:

- num_tasks_for_HLV: 9 (arbitrary number for this example)

Decide to extend or not:

Scenario 1:

$$\text{num\_charter\_HLVs} = \left\lceil \frac{4}{5} \right\rceil - 0 = \lceil 0.8 \rceil - 0 = 1 - 0 = 1$$

extend_charter_period = Yes, since $1 + 0 \geq 1$ (Equation 3.5)

Scenario 2:

$$\text{num\_charter\_HLVs} = \left\lceil \frac{0}{5} \right\rceil - 0 = \lceil 0 \rceil - 0 = 0 - 0 = 0$$

extend_charter_period = No, since $0 + 0 < 1$ (Equation 3.5)

Scenario 3:

$$\text{num\_charter\_HLVs} = \left\lceil \frac{9}{5} \right\rceil - 0 = \lceil 1.8 \rceil - 0 = 2 - 0 = 2$$

extend_charter_period = Yes, since $2 + 0 \geq 1$ (Equation 3.5)

3.4 Modeling assumptions and logistics

In this section, the modeling assumptions are explained first. Thereafter, the logistics for each vessel type are explained. Lastly, the model is briefly explained by describing the simulation components.

3.4.1 Modeling assumptions

In the following paragraphs, several modeling assumptions are explained.

3.4.1.1 Maintenance cycle start and end

According to the given maintenance strategy (section 3.1), a maintenance cycle is started if one of the cycle triggers (Table 5) has been reached. At the start of the maintenance cycle, it checked if any vessels should be chartered. Thereafter, it is periodically checked if any additional vessels should be chartered during the cycle. This is done to prevent the number of maintenance tasks from continuing to grow, what can happen if the initial number of chartered vessels is not sufficient for the maintenance tasks that arise after the start of the cycle.

According to the given maintenance strategy, a maintenance cycle is ended if all tasks are completed. In case a simulation is done for which a certain vessel type is not owned and that vessel type will never be chartered, the end of a maintenance cycle is not affected by maintenance tasks for that vessel type. For example, if num_FSVs_owned=0 and tasks_per_FSV=0, meaning that an FSV will never be in the fleet (since no FSV is owned and an FSV will never be chartered), a maintenance cycle will end if all tasks for the other vessel types (HLV and CTV) are completed.

To account for some extreme cases where a maintenance cycle is ongoing for a very long time, the following modeling assumptions are made. A minor repair cannot be performed twice on a component within the same maintenance cycle. Similarly, a major repair cannot be performed twice on a component within the same cycle. Without these assumptions, a maintenance cycle can take an unlimited amount of time by performing repair tasks over and over again. A component that has been replaced can be repaired in the same maintenance cycle, since it is considered a new component.

It may happen that if it is decided to charter an additional vessel, that the mobilisation is started and that all maintenance tasks are completed by other vessels before the vessel mobilisation is finished. In this case, the maintenance cycle is ended before the mobilisation is finished. If this happens, the mobilisation is stopped and the full mobilisation costs are imposed.

3.4.1.2 Maintenance time

The required time for a maintenance activity is given in Table 4. In practice, the maintenance time (for replacements of large components) may be dependent on the weather conditions. The required maintenance time may be longer in case the wind speed is high (but below the operational limit). In this research, it is assumed that the maintenance time is constant and not affected by weather conditions.

3.4.1.3 Maintenance activities

Maintenance activities for different components of a turbine can be performed simultaneously. Once a maintenance activity is started by a vessel, it must be finished before the vessel can be assigned to a new maintenance task. A chartered vessel will always finish a started maintenance task regardless of whether the charter period has ended. If the chartered vessel is returned after the charter period has ended, the charter cost per day (Table 11 inputs [5-7]) is multiplied by Table 12 input [7] for each day the vessel is returned late. After the end of a charter period, a vessel can finish its current maintenance tasks, but will never be assigned to start a new maintenance task.

3.4.1.4 Turbine operations

A turbine stops operating during maintenance work on its components or if any of its components failed. In other words, a turbine is operating only if none of its components are being maintained and none of its components are defective. If a turbine is not operating, all its components stop aging.

3.4.1.5 Weather and failure scenarios

Each scenario (also referred to as a 'set') includes weather conditions for each period in the simulation time horizon and the initial lifetime for each component of each turbine within the wind farm. The three weather conditions (wave height, wind speed at sea, and wind speed at hub) are independent. Also, weather conditions are not dependent on previous weather conditions. The weather conditions are assumed to be constant for a length of four hours (12 periods). The lifetime of a component is independent of other components.

3.4.1.6 Vessel travel time

The travel speed of vessels is assumed to be constant, therefore, the travel time between base and site is equal in both directions and constant (independent of weather conditions). The inter-transit time between two turbines is assumed to be constant (not affected by the layout of turbines within the wind farm).

3.4.1.7 Spare parts

It is assumed that spare parts are always available and vessels are equipped with sufficient spare parts. The logistics related to spare part inventory management are not modeled explicitly. It is assumed that a vessel is resupplied with spare parts and consumables every time it returns to base.

3.4.1.8 Charter rates and mobilisation costs

It is assumed that the charter rates and mobilisation cost are deterministic and constant for the entire simulation time horizon. Vessels are always available at the charter rate of Table 11 inputs [5-7]. If a charter period or mobilisation is initiated, it is assumed that the cost of the entire charter period or mobilisation must be paid.

3.4.1.9 Technicians

Vessels are always equipped with the maximum number of technicians (Table 10 input [4]). The number of vessels that can be chartered is not limited by the number of available technicians. In other words, it is assumed that a chartered vessel can always be equipped with technicians. The technicians on board an owned vessel are paid for the entire duration of each maintenance cycle. The technicians on board a chartered vessel are paid from the start of a charter period until the vessel is returned. The costs of non-maintenance personnel are assumed to be included in the charter rate of the vessel.

3.4.1.10 Length of charter period

The charter length, specified by Table 10 input [12], defines the minimum length of the charter period. The charter period is not restricted by a maximum length. The charter period may be extended an unlimited number of times.

3.4.1.11 Priority of maintenance tasks

The maintenance tasks for each vessel type are sorted according to the age of the components. Components with a higher age requiring maintenance are prioritised over components with a lower age.

3.4.1.12 Priority for vessel allocation

Maintenance tasks are assigned to teams of technicians who are tied to a specific vessel. First, the model prioritises vessels that are on-site over vessels that are at the base. Second, if there are multiple available vessels on-site, priority is given to those vessels with a greater number of teams already assigned.

3.4.2 HLV logistics

The HLV type is required for preventive and corrective replacement tasks. For both replacements tasks, it is required to lift heavy parts to the hub level of the turbine. Therefore, the HLV itself is also working at the turbine besides dropping off a team at the turbine. Since jack-up vessels are the most utilised vessels for such heavy lifting maintenance operations (Dalgic et al., 2015d), this research also considers jack-up vessels. In this research, a HLV is always considered to be a jack-up vessel. The HLV can work 24 hours a day (it is not restricted by shift hours) and it can stay offshore (on-site) for multiple days. The HLV is equipped with multiple teams of technicians that take turns completing maintenance tasks. The HLV can only work on one maintenance task at a time.

Before parts can be lifted to the hub of the turbine, the HLV must be stabilised, which is done by stationing its legs on the seabed. Then the hull can be raised over the sea surface, providing a stable setting for lifting operation under rough weather conditions. Jacking up/down is constrained by the wind speed at sea and wave height. Therefore, the HLV will only jack up/down if the HLV limits for wind speed at sea and wave height (Table 10 inputs [6-7]) are not exceeded for the required time to jack up/down. In case the weather window is not sufficient, the HLV will wait before jacking up/down until the conditions are met. Once the HLV is jacked-up, it can stay jacked up under any weather condition. After jacking up, the maintenance task can be started if the weather conditions for lifting operations are sufficient. The lifting operation is constrained by wind speed at hub level. Therefore, the HLV can only start a maintenance task if the wind speed at hub level does exceed the limit for wind speed at hub level for the duration of the minimum working window plus a safety margin. The minimum working window of the HLV is the entire time required for the maintenance activity. The safety margin for the HLV is one period (20 minutes) and ensures that the team of technicians has time to leave the turbine and enter the HLV before the weather limit is exceeded. The safety margin can be regarded as the required time for a team of technicians to leave the turbine and enter the vessel.

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

3.4.3 FSV logistics

The FSV type is required for major repair maintenance tasks. For these tasks, it is assumed that medium-weighted parts must be lifted onto the turbine's platform. This type of vessel is equipped with dynamic positioning systems and a motion-compensating gangway system through which technicians can be transferred on the turbine in rougher weather conditions compared to a CTV. The FSV type can only work within shift hours and can stay offshore for multiple days. The FSV is equipped with multiple teams of technicians that take turns completing maintenance tasks. The FSV can only work on one maintenance task at a time.

The FSV is constrained by conditions of wave height and wind speed at sea. These weather conditions are operational conditions, meaning that if any of these weather conditions exceed the FSV weather condition limits, the FSV (and its teams) cannot work on a maintenance task. During rough weather conditions, the FSV can stay on-site at the turbine or travel. The FSV will only drop off a team of technicians and start working at a turbine if the weather window is sufficient. Similar to the HLV, the FSV has a safety margin of one period that ensures that the team of technicians has time to leave the turbine and enter the FSV before the weather becomes too rough. Therefore, the weather window must at least be of the length of the minimum working window (Table 10 input [3]) plus the safety margin before a maintenance operation is started/resumed. The safety margin can be regarded as the required time for a team of technicians to leave the turbine and enter the vessel.

In case the FSV and a team of technicians is working on a maintenance task and the shift has ended, the maintenance operation will be ceased and the team of technicians will enter the vessel. The maintenance operation is resumed at the shift start the next day (if the weather window is sufficient). If a maintenance operation was ceased due to rough weather and the weather window becomes OK again, the maintenance task will only be resumed if the remaining time in the current shift is greater or equal to the minimum working window.

If there are no remaining maintenance tasks for the FSV, the FSV will travel back to base and stay idle at the base until the end of the maintenance cycle, until the end of the charter period, or until it is assigned to a new maintenance task in which case it will travel to the site.

3.4.4 CTV logistics

The CTV type is required for minor repair maintenance tasks. For these tasks, it is assumed that it is only required to drop off a team of technicians at the turbine. This vessel type is significantly smaller than an FSV and HLV and, therefore, has a higher chance of capsizing in rough weather conditions. Consequently, the weather limits for the CTV are stricter compared to the FSV and HLV. The CTV does not work on a maintenance task itself, but just transports teams of technicians and drops them off. The CTV has a capacity for four teams of three technicians. The CTV can only operate within shift hours and cannot stay offshore for multiple shifts.

If maintenance tasks have been assigned to more than one team of the CTV, the CTV delivers the first team at a turbine and travels to the next turbine until all teams have delivered. The priority of delivery is according to the repair time. The team with the least required time for a repair will be delivered first. Once all teams have been delivered, the CTV travels back to the turbine of the first delivered team, because the first delivered team is the first to finish its task. This is the most time-efficient manner to operate the CTV. If the CTV arrives at the turbine of the first delivered team before this team has finished its task, the CTV will wait (stay idle on-site at this turbine) until the team has finished its task. Once the team has finished its task, the team will be picked up by the CTV, a new task will be assigned to this team (if any tasks are left) and the CTV will travel to the turbine of this new task (if the task is at another turbine). In case only 3 teams were assigned and delivered initially and the CTV is waiting at a turbine for a team to finish its task and the fourth team is assigned to a task, the CTV will deliver the fourth team and then travel back to the turbine of the first delivered team. The CTV will prioritise delivering teams over picking up finished teams and the CTV will always travel to the turbine of the team that first finishes its task if no more teams must be delivered or picked up.

At the end of the shift, the CTV will pick up every team that is working on a maintenance task. The maintenance task of each team is ceased once the team leaves the turbine. The remaining time left of the maintenance operations is tracked by the model. Once all teams have been picked up, the CTV will travel back to base. The next day at shift start, the CTV will travel back to the site and deliver all teams that have been interrupted. Some teams of the CTV may not have been interrupted (since they were not working on a maintenance task at shift end) but may be assigned to a new maintenance task at the start of the shift.

The CTV can only be at sea if the weather conditions of wave height and wind speed at sea do not exceed the CTV limits (Table 10 inputs [6-7]). In other words, at the moment any of the weather conditions exceed the limit, the CTV must be at the base. This implies that the CTV must pick up teams and travel back to base ahead of rough weather conditions. The maximum time required for the CTV to pick up all teams and travel back to base is equal to the maximum number of parallel teams (Table 10 input [5]) times the inter-transit time (Table 10 input [2]) plus the time required to travel back to base. This entire term is referred to as the safety margin and ensures that CTV is back at base before the weather becomes too rough.

If a CTV is idle at the base and it has teams that are assigned to maintenance tasks, two conditions are checked before the CTV will travel to the site. First, the weather window is checked. The window of OK weather must be at least the length of the required time to travel to base plus the safety margin plus the minimum working window. If the weather window is sufficient, secondly, it is checked if there is sufficient remaining time in the shift for all teams to start/resume the maintenance task. The CTV will only travel to the base if all assigned teams can work on the maintenance task for at least the minimum working window (Table 10 input [3]). That means that the CTV will stay at the base if the minimum working window plus the required time to travel to the site plus the number of assigned teams times the inter-transit time is greater than the remaining time in the shift. An unassigned team of the CTV will only be assigned to a new maintenance task if it can work on the task for at least the minimum working window, otherwise the tasks to be completed will be assigned the next day at the start of the shift.

3.4.5 Simulation components

The model contains eight different simulation components (Python classes), hereinafter referred to as 'sim-Comps'. Each sim-Comp is responsible for a certain process. The current status of a sim-Comp is represented by its mode, e.g., a turbine can have the modes 'working' or 'not working' and a vessel can have the modes 'idle at base', 'travel to site', etc. The three most important process interactions are 'activate', 'passivate', and 'hold'. Activate is used to continue a sim-Comp's process at the current period. Passivate is used to stop the sim-Comp's process (the sim-Comp becomes passive). Hold is used to delay the sim-Comp's process (the sim-Comp becomes active at the scheduled time). In the following paragraphs, the sim-Comps Turbine, Turbine Component, Maintenance Cycle Control, Scheduler, Vessel, Technician Team, Weather Control, and Shift Control are described.

3.4.5.1 sim-Comp: Turbine

Each turbine in the offshore wind farm is represented by a sim-Comp Turbine. The turbine consists of 4 turbine components: roto (rotor), bear (bearing), gear (gearbox), and gene (generator). The lifetime of each component is sampled from its Weibull distribution. It is assumed that none of the turbine components are faulty at the start of the simulation. Therefore, the turbine starts producing electricity at the start of the simulation. The turbine stops working as soon as one or more of its components fails or when maintenance is performed at one or more of its components. The turbine will continue to operate only when none of the turbine components are faulty and none turbine components are under maintenance. The four components of the turbine only age when the turbine is operating and, hence, all turbine components stop aging when the turbine is not operating.

3.4.5.2 sim-Comp: Turbine Component

Each turbine component of each turbine is represented by a sim-Comp Turbine Component, which all have an individual lifetime before they fail (a component may never fail if it is repaired or replaced before failure). The components' age represents the fraction of its lifetime used. Corresponding with the components' age, the components are categorized in zone 1, zone 2, zone 3, zone 4, or zone f (component failed). A component ages over time and enters consecutive zones until it may eventually fail.

According to the age-based maintenance strategy, maintenance activities can only be performed within a maintenance cycle. A maintenance cycle is started when the number of failed or zone 4 components equals (or exceeds) the defined thresholds. The sim-Comp Turbine Component checks if these thresholds are reached and initiate a maintenance cycle (by activating the sim-Comp Maintenance Cycle Control) if any threshold is reached. Turbine components in zone 2 or 3 may be repaired if a maintenance cycle is active and, therefore, only activate the sim-Comp Scheduler (which is responsible for scheduling maintenance tasks) if a maintenance cycle is active.

When a turbine component is repaired (from zone 2 or zone 3), its age is reduced according to Table 1. When a turbine component is replaced (from zone 4 or zone f), a new component is installed in the turbine. Then a new lifetime from the components' Weibull distribution is sampled and the components' age is reset to zero.

3.4.5.3 sim-Comp: Maintenance Cycle Control

There is one sim-Comp Maintenance Cycle Control (sim-Comp MCC) for the simulation environment. The sim-Comp MCC is activated if any of the maintenance cycle triggers is reached, where after a maintenance cycle is started. The sim-Comp MCC is responsible for chartering vessels. Vessels may be chartered at the start of a maintenance cycle or during the cycle. It is periodically checked, with an interval of Table 12 input [6], if additional vessels should be chartered.

3.4.5.4 sim-Comp: Scheduler

There is one sim-Comp Scheduler for the simulation environment. The Scheduler is responsible for assigning maintenance tasks to teams of technicians (and vessels). Every time the Scheduler is activated, it determines the remaining maintenance tasks of each type and sorts the tasks in descending order according to the age of the parts (see section 3.4.1.11). The Scheduler assigns the maintenance tasks to teams of technicians tied to vessels according to the priority of vessel allocation (section 3.4.1.12). If all maintenance tasks are completed and all the vessels are back at base, the Scheduler gives the signal to the sim-Comp MCC that the maintenance cycle can be ended.

3.4.5.5 sim-Comp: Vessel

Each vessel in the fleet (chartered and owned) is represented by a sim-Comp Vessel. Whether a vessel is chartered vessels or owned is denoted by '(C)' or '(O)' within the vessel's name, respectively. The processes vary for the different vessel types and chartered or owned vessels. Owned vessels are idle at the base if no maintenance cycle is active. If it is decided to charter a new vessel (within the sim-Comp MCC), a sim-Comp Vessel is created and the vessel is added to the fleet. The chartered vessel is available after the mobilisation time. If a maintenance cycle is active, a vessel can be assigned or not assigned. If the vessel is assigned, it means that at least one team of technicians of the vessels is assigned to a maintenance task. If the vessel is assigned, there are five main sub-processes, one process for if: (1) all teams of the turbine are delivered at a turbine, (2) any team of the vessel completed its task, (3) any team of the vessel is not at the turbine, (4) the vessel is interrupted by the end of the shift, (5) the vessel is interrupted by bad weather. If the maintenance cycle has ended, all chartered vessels are removed from the fleet. In case the charter period of a chartered vessel has ended during a maintenance cycle, it is checked if the charter period should be extended. If the charter period is not extended, the chartered vessel is removed from the fleet.

3.4.5.6 sim-Comp: Technician Team

Every time a maintenance task is assigned to a team of technicians, a sim-Comp Technician Team is created. The created sim-Comp Technician Team terminates once the team has finished the maintenance task and is picked up by the vessel.

3.4.5.7 sim-Comp: Weather Control

Each vessel in the fleet has its own sim-Comp Weather Control. Within the sim-Comp Vessel it is checked whether the weather window is sufficient to travel to the site and deliver teams and/or start a maintenance task. The sim-Comp Weather Control is responsible for interrupting a vessel that is in operation and must respond to rough future weather conditions (by stopping the maintenance activity or traveling back to the base).

3.4.5.8 sim-Comp: Shift Control

There is one sim-Comp Shift Control for the simulation environment that makes sure that the vessels constrained by shift hours are activated at shift start and start picking up teams at shift end. At the end of each day (00h00) during a maintenance cycle, Shift Control prints the mode of each vessel to get an overview of the location and activity of each vessel in the fleet.

3.5 Simulation outputs

One of the model outputs is a log of every event throughout the simulation. Additionally, the developed methodology tracks the following information of a simulation:

- turbine information
- cycle information
- component information
- vessel charter information
- vessel travel information
- vessel time information

Based on the information of the above-mentioned things, the total costs and the costs per produced MWh are calculated. The cost per MWh is an important performance evaluation metric as it can be used to evaluate the trade-off between costs and production.

3.5.1 Turbine information

The model tracks when a turbine is operating and when it is not. Based on this information, the following things are calculated:

- total wind farm electricity production
- wind farm time-based availability
- wind farm power-based availability

To determine the total electricity production of the wind farm, the electricity production of individual turbines must be determined. The relationship between the wind speed at hub level (v_t) and the generated power ($P_t(v_t)$) during period t is given by (Abdollahzadeh et al., 2016):

$$P_t(v_t) = \begin{cases} 0 & v_t < v^{ci} \text{ or } v > v_t^{co} \\ P^r\Big(a + bv_t + cv_t^2\Big) & v^{ci} \leq v_t < v^r \\ P^r & v^r \leq v_t \leq v^{co}, \end{cases} \tag{3.6}$$

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

$$a = \frac{1}{\Big(v^{ci} - v^r\Big)^2}\left[v^{ci}\Big(v^{ci} + v^r\Big) - 4v^r v^{ci}\left(\frac{v^{ci} + v^r}{2v^r}\right)^3\right], \tag{3.7}$$

$$b = \frac{1}{\Big(v^{ci} - v^r\Big)^2}\left[4\Big(v^{ci} + v^r\Big)\left(\frac{v^{ci} + v^r}{2v^r}\right)^3 - \Big(3v^{ci} + v^r\Big)\right], \tag{3.8}$$

$$c = \frac{1}{\Big(v^{ci} - v^r\Big)^2}\left[2 - 4\left(\frac{v^{ci} + v^r}{2v^r}\right)^3\right]. \tag{3.9}$$

The time-based availability is defined as the operational time (total time minus downtime due to maintenance or failures) divided by the simulation time horizon. It is “the percentage of time that an individual wind turbine or wind farm is available to generate electricity expressed as a percentage of the theoretical maximum” (Tavner (2012), p. 13).

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

3.5.2 Cycle information

The model tracks when maintenance cycles start and end. Based on this information, the following things are calculated:

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

3.5.3 Component information

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

- number of maintenance activities of each maintenance type
- costs of maintenance activities of each maintenance type

3.5.4 Vessel charter information

The developed methodology tracks information related to chartering vessels: the start and end time of a mobilisation, the cycle number when a mobilisation and charter period starts, the start and end time of a charter period, whether the charter period is ended by the end of a cycle or just by the end of the charter period, whether the chartered vessels are returned on time or late (and how many days), and whether a mobilisation is stopped by the end of a cycle. Based on this information, the following things are calculated:

- the number and cost of charters per vessel type
- the number and cost of extended charter periods per type
- the number and cost of mobilisations per vessel type
- the total number of days and cost of late returned chartered vessel per vessel type
- the cost of technicians

It is assumed technicians are only paid when they are working. Therefore, the technicians on chartered vessels are paid for the duration of the charter period and the technicians on an owned vessel are paid for the duration of the maintenance cycles.

3.5.5 Vessel travel information

For each vessel ever in the fleet, the developed methodology tracks the number of travels from base to the site, the number of travels from site to base, and the number of inter-transits. Based on this information, the following things are calculated:

- the fuel costs of traveling

3.5.6 Vessel utilisation information

For each vessel ever in the fleet, the developed methodology tracks the time spent on several things:

- time spent on traveling to base
- time spent on traveling to site
- time spent on inter-transit travels
- time spent on maintenance tasks
- time restricted by weather conditions
- time restricted by shift hours
- time of being idle at base in cycle
- time of being idle on-site in cycle
- time spent on jacking up/down

Not all the above-mentioned things are relevant for all vessel types. The CTV type does not spend time on maintenance tasks (it only drops off teams) and does not have to jack up/down. The FSV type will never be idle on-site in the cycle (it returns to base if there are no more tasks) and does not have to jack up/down. The HLV type will never be restricted by shift hours and will never be idle on-site in the cycle (it returns to base if there are no more tasks).

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

4 Case study

In this section, a case study is performed to illustrate the developed methodology. The simulation inputs used for this case study are listed in the tables in section 3.3. To cover the variations in outcomes due to uncertainty in turbine component failures and weather conditions, ten sets (scenarios) were created with random seed values 42 to 51 for sets one to ten, respectively. Thus, ten simulations are performed for every configuration (combination of values of the decision variables). In section 4.1.2.2, it is reasoned why ten sets are assumed to be sufficient for this case study.

In total, two batches of simulations were performed to conclude the best values of the three decision variables (tasks_per_HLV, tasks_per_FSV, and tasks_per_CTV). A batch is defined by a series of values for each of the decision variables and simulations are performed for each combination. The results of the first batch are used to further narrow down the solution space (decision variable values) in order to find the best values. In the following two subsections, information and results of the first and second batches are presented. The results of the first batch are described in less detail, as these are only intermediate results.

The simulations were executed on a server with the following specifications: Intel (R) Xeon(R) Gold 5218 CPU @ 2.30GHz / 192 GB RAM / Tesla V100S PCIe 32GB GPU. The is server is equipped with multiple CPUs, which makes it possible to perform simulations in parallel. Ten CPUs were made available for this research. Therefore, ten simulation could be performed in parallel.

4.1 Batch 1: 2022-05-14-20h05

The first batch of simulations was started on '2022-05-14-20h05' using the sets (scenarios) created on '2022-05-14-20h04'. The output log of each simulation performed can be found via https://1drv.ms/u/s!AqqFTU9267_1h6RJgZw3q2e4tjKJaA?e=bk0MtJ. The series of decision variables and the results of this batch are presented in the following two sections, respectively. Finally, a conclusion of the first batch is given.

4.1.1 Series of decision variables

The following values of the decision variables are used for the simulations of this batch. These values are chosen arbitrarily with no prior knowledge of whether these values would be good.

series tasks_per_HLV:	4,	6,	8,	10,	12					
series tasks_per_FSV:	0,	10,	15,	20,	25,	30,	35			
series tasks_per_CTV:	0,	10,	15,	20,	25,	30,	35,	50,	75,	100

Every combination of the above-listed values per decision variable represents a 'configuration'. In total, there are $5 \cdot 7 \cdot 10 = 350$ combinations, hence, there are 350 configurations. For each configuration, ten simulations are performed (since ten scenarios were created), resulting in a total of 3500 simulations for this batch. To clarify:

	config 1	config 2	config 3	...	config 350
tasks_per_HLV:	4	4	4	...	12
tasks_per_FSV:	0	0	0	...	35
tasks_per_CTV:	0	10	15	...	100

4.1.2 Results

The key performance indicator to evaluate the O&M activities is the cost per unit of electricity production. The cost per MWh produced best reflects the trade-off between cost and electricity production (revenue). Therefore, the 'best configuration' refers to the configuration with the lowest average cost per MWh produced hereinafter. Similarly, the 'ten best configurations' refer to the ten configurations with the lowest average cost per MWh produced hereinafter, etc.

4.1.2.1 Cost per MWh produced

The average, maximum, and minimum cost per MWh produced of the ten sets for each configuration is depicted in Figure 2. The configurations are ranked from best to worst average €/MWh. It can be seen that the €/MWh can vary quite a bit between different configurations.

In Figure 3, the average, maximum, and minimum cost per MWh produced of the ten scenarios for the best 20 configurations are depicted. The average cost per MWh and the values of the decision variables for the 20 best configurations are listed in the table of Figure 3. It can be concluded from this that the best configuration are combinations of tasks_per_HLV = [8, 10, 12], tasks_per_FSV = [15, 20, 25, 30], and tasks_per_CTV = [0, 50, 75, 100]. As can be noticed from Figure 3, different configurations can result in the same average cost per MWh (see configurations 169 and 218). These phenomena is explained in section 4.1.3.

In Figure 4, the cost per MWh produced for every set for the best ten configurations of the first batch is depicted, including a table with the values. It stands out that the order of best to worst cost per MWh produced (€/MWh) of the ten sets is relatively similar for these ten best configurations. This suggest that a certain set represents a favorable or unfavorable scenario in general, regardless of decision variable values of the configuration of the best ten configurations.

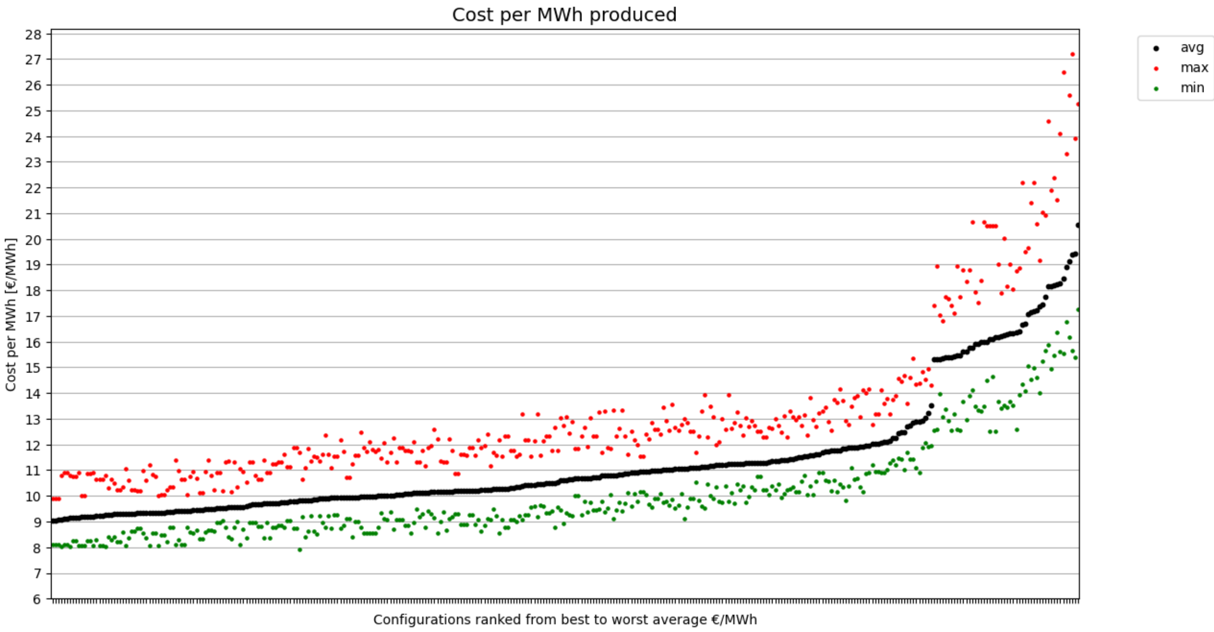
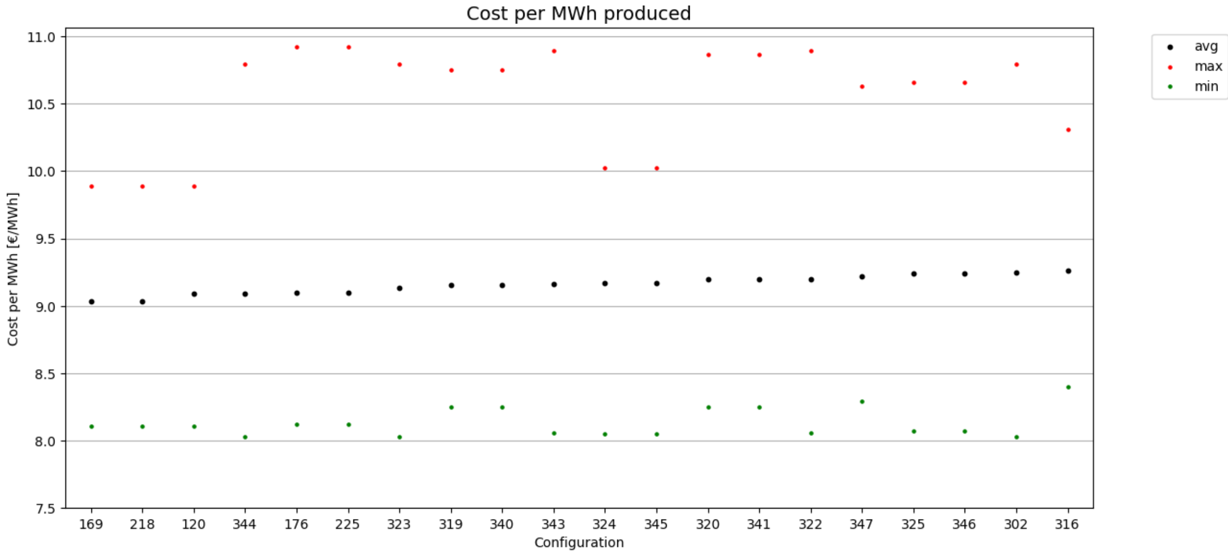
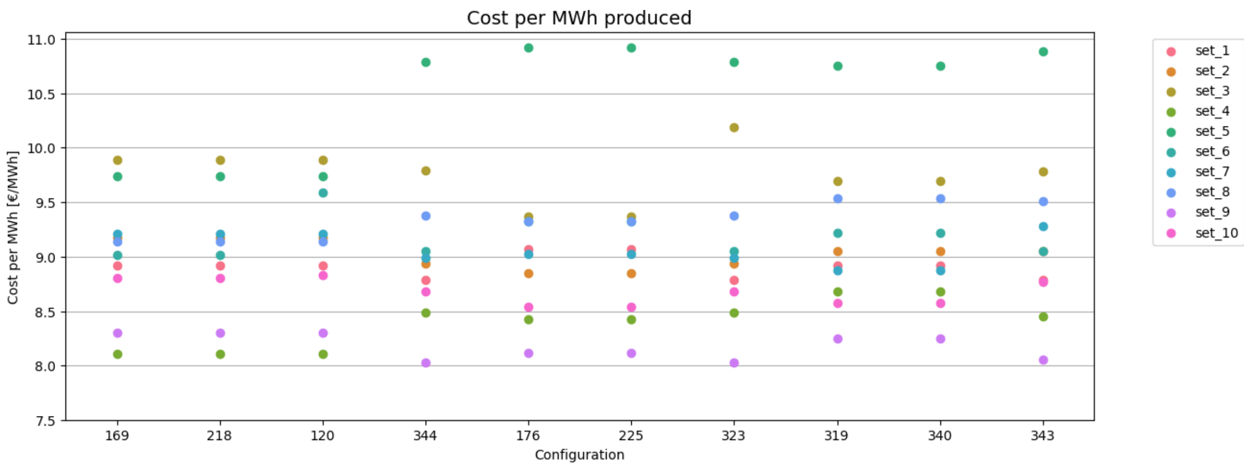


Figure 2: Cost per MWh produced, all configurations (batch 1).



Configuration:	169	218	120	344	176	225	323	319	340	343	324	345	320	341	322	347	325	346	302	316
avg_cost_per_MWh	9.032	9.032	9.091	9.093	9.099	9.099	9.133	9.157	9.157	9.163	9.169	9.169	9.194	9.194	9.201	9.219	9.237	9.237	9.247	9.263
tasks_per_HLV	10	12	8	12	10	12	10	10	12	12	10	12	10	12	10	12	10	12	8	10
tasks_per_FSV	20	20	20	25	25	25	25	20	20	25	30	30	20	20	25	30	30	30	25	15
tasks_per_CTV	0	0	0	100	0	0	100	75	75	75	50	50	100	100	75	100	75	75	100	75

Figure 3: Cost per MWh produced, best 20 configurations (batch 1).



Unit: €/MWh	169	218	120	344	176	225	323	319	340	343
set_1	8.920	8.920	8.920	8.790	9.070	9.070	8.790	8.920	8.920	8.790
set_2	9.180	9.180	9.180	8.940	8.850	8.850	8.940	9.050	9.050	9.050
set_3	9.890	9.890	9.890	9.790	9.370	9.370	10.190	9.700	9.700	9.780
set_4	8.110	8.110	8.110	8.490	8.430	8.430	8.490	8.680	8.680	8.450
set_5	9.740	9.740	9.740	10.790	10.920	10.920	10.790	10.750	10.750	10.890
set_6	9.020	9.020	9.590	9.050	9.330	9.330	9.050	9.220	9.220	9.050
set_7	9.210	9.210	9.210	8.990	9.030	9.030	8.990	8.880	8.880	9.280
set_8	9.140	9.140	9.140	9.380	9.330	9.330	9.380	9.540	9.540	9.510
set_9	8.300	8.300	8.300	8.030	8.120	8.120	8.030	8.250	8.250	8.060
set_10	8.810	8.810	8.830	8.680	8.540	8.540	8.680	8.580	8.580	8.770
avg.	**9.032**	**9.032**	**9.091**	**9.093**	**9.099**	**9.099**	**9.133**	**9.157**	**9.157**	**9.163**

Figure 4: Cost per MWh produced, best 10 configurations (batch 1).

4.1.2.2 Accuracy of results

The accuracy of the results depends on the number of generated sets (scenarios). The more sets are used per configuration, the smaller the confidence interval likely will be and the higher the accuracy. However, using more sets per configuration requires performing more simulation. Therefore, more computational power and time are required. The number of used sets per configuration depends on the required accuracy, available computational power, and available time of the user.

For the case study in this research, there was a limited amount of computational power and available time. Moreover, finding the best configuration with high accuracy for this case study is not necessarily important in itself, instead, the case study is intended to illustrate how the developed methodology can be used for fleet management decisions. Figure 5 and 6 depict the coefficient of variation and the 95% confidence interval of the cost per MWh produced per configuration, respectively. Based on these results and the aforementioned reasons, it was assumed that ten sets per configuration were sufficient. However, these results can be used to determine if the number of used sets leads to the required accuracy of the user. Accordingly, more or fewer sets can be generated and used by the user.

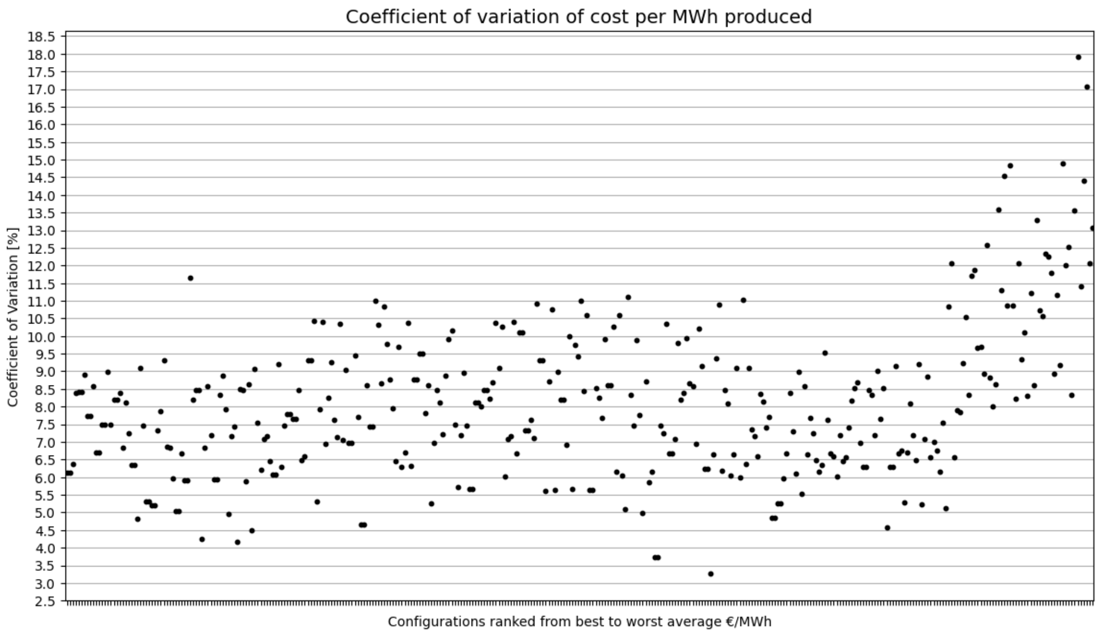
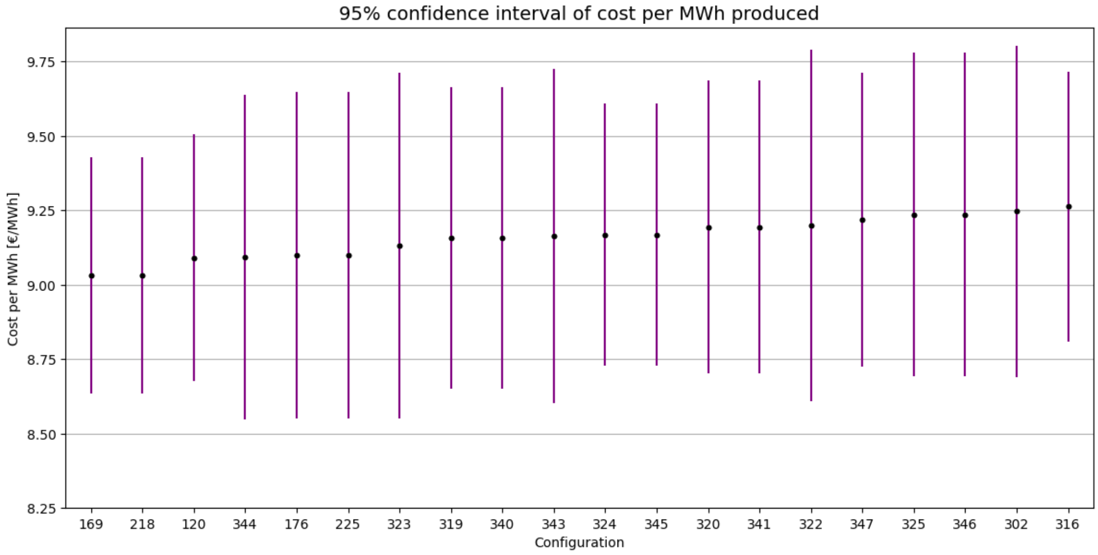


Figure 5: Coefficient of variation of cost per MWh produced, all configurations (batch 1).



Configuration:	169	218	120	344	176	225	323	319	340	343	324	345	320	341	322	347	325	346	302	316
avg_cost_per_MWh	9.032	9.032	9.091	9.093	9.099	9.099	9.133	9.157	9.157	9.163	9.169	9.169	9.194	9.194	9.201	9.219	9.237	9.237	9.247	9.263
tasks_per_HLV	10	12	8	12	10	12	10	10	12	12	10	12	10	12	10	12	10	12	8	10
tasks_per_FSV	20	20	20	25	25	25	25	20	20	25	30	30	20	20	25	30	30	30	25	15
tasks_per_CTV	0	0	0	100	0	0	100	75	75	75	50	50	100	100	75	100	75	75	100	75

Figure 6: 95% confidence interval of cost per MWh produced, best 20 configurations (batch 1).

4.1.2.3 Computational time

The average, maximum, and minimum runtime of the simulations of the first batch are:

- average runtime: 144.61 seconds per simulation
- maximum runtime: 330.36 seconds per simulation
- minimum runtime: 118.45 seconds per simulation

4.1.3 Remark on results

As was stated in section 4.1.2.1 based on Figure 3, different configurations can result in the same average cost per MWh (see configuration 169 and 218). This is because different configurations (and thus different values of the decision variables) can result in the same vessel chartering decisions. This will be explained in two ways. First, an example of chartering decision for two different configurations (169 and 218 of the first batch) is given. Secondly, it is proven that the chartering decisions of configurations 169 and 218 of the first batch are the same.

As can be seen in Figure 3, the decision variable values of configurations 169 and 218 are:

	config 169	config 218
tasks_per_HLV:	10	12
tasks_per_FSV:	20	20
tasks_per_CTV:	0	0

In the following Example 3, it will be illustrated that the HLV chartering decisions at a certain moment can be the same for these two configurations.

Example 3: decision on how many HLVs to charter for configs 169 and 218

Input: owned number of HLVs

- num_HLVs_owned: 0 (defined for the case study, same for both configs)

Decision variable value:

Configuration 169:

- tasks_per_HLV: 10

Configuration 218:

- tasks_per_HLV: 12

Checked by the model: number of maintenance tasks for HLV to be performed

- num_tasks_for_HLV: 6 (arbitrary number for this example)

Decisions to charter:

Configuration 169:

$$\text{num\_charter\_HLVs} = \left\lceil \frac{6}{10} \right\rceil - 0 = \lceil 0.6 \rceil - 0 = 1 - 0 = 1 \text{ (Equation 3.2)}$$

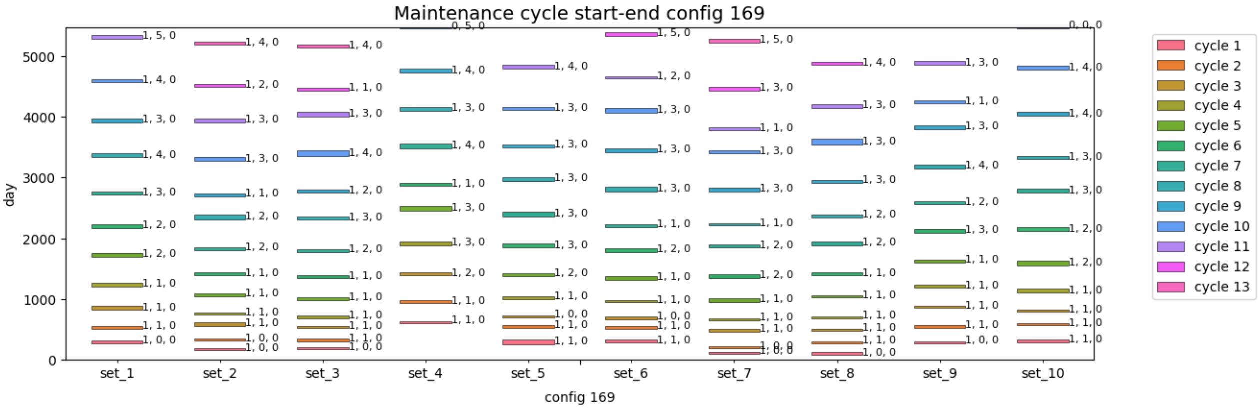
Configuration 218:

$$\text{num\_charter\_HLVs} = \left\lceil \frac{6}{12} \right\rceil - 0 = \lceil 0.5 \rceil - 0 = 1 - 0 = 1 \text{ (Equation 3.2)}$$

For both configurations, the decision would be charter 1 HLV.

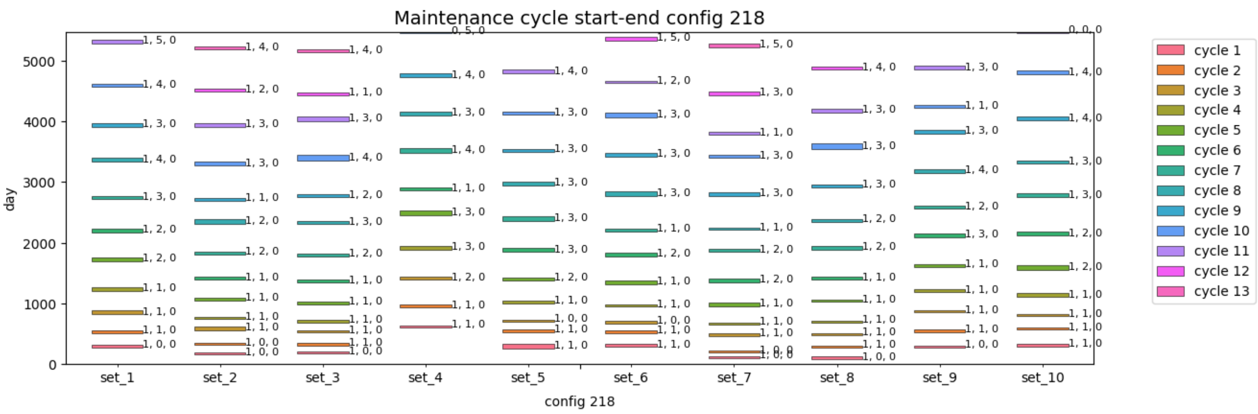
Example 3 illustrates how the chartering decisions can be the same for two configurations at a certain moment of the planning horizon. The chartering decisions over the entire planning horizon (15 years for this case study) may be identical for two different configurations too. If that is the case, the entire simulation for different configurations is identical. This is the case for, e.g., configurations 169 and 218 of the first batch. This was already indicated by the identical cost per MWh produced in Figure 4. In addition, Figure 7 and 8 prove that the simulations for the two configurations for every set is identical. For each set of both configurations, maintenance cycles start and end at the same time. Moreover, the same number of vessels of each type were chartered, which is indicated in text besides each cycle in the plot (in the order of HLV, FSV, CTV).

It stands out that, for both configurations, the number of chartered vessels of each type in the last cycle (cycle 11) of set 10 are: 0, 0, 0. This is due to the fact that the simulation was ended before any mobilisation was finished and thus the charter periods of the vessels had not yet started. The tables of Figure 7 and 8 indicate that cycle 11 of set 10 was ongoing for 18 days, where after the simulation was stopped. At the start of this maintenance cycle (initiated by a failed component, which can be seen in the output log), it was decided to charter 1 HLV, 3 FSVs, and 0 CTVs (can be seen in the output log). However, these vessels will only become available after the mobilisation time, which is 30 and 21 days for the HLV and FSV, respectively (Table 10 input [11]). Consequently, the charter periods for these vessels were not started yet before the end of the simulation, therefore, the numbers besides cycle 11 of set 10 are 0, 0, 0.



Unit: day	config 169									
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10
cycle 1 length	43	35	34	37	84	43	33	43	33	40
cycle 2 length	46	38	41	46	49	48	41	33	39	44
cycle 3 length	60	55	45	56	33	40	36	38	41	33
cycle 4 length	54	38	44	57	40	41	33	34	45	69
cycle 5 length	66	37	45	80	47	57	53	43	50	83
cycle 6 length	59	48	44	49	64	60	57	43	57	67
cycle 7 length	57	46	45	70	79	54	58	71	45	59
cycle 8 length	64	71	58	57	61	76	36	48	69	45
cycle 9 length	61	41	56	60	47	53	60	51	60	64
cycle 10 length	46	69	86	23*	54	64	51	86	55	64
cycle 11 length	59	57	72	-	72	43	55	51	69	18*
cycle 12 length	-	59	43	-	-	53	63	59	-	-
cycle 13 length	-	58	48	-	-	-	63	-	-	-
total	**615**	**652**	**661**	**535**	**630**	**632**	**639**	**600**	**563**	**586**

Figure 7: Maintenance cycle information and vessels charters for config 169 (batch 1). The number of started charter periods within each cycle is indicated in text in the plot in the order of HLV, FSV, CTV. The * in the table indicates that a cycle was still ongoing at the end of the planning horizon.



Unit: day	config 218									
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10
cycle 1 length	43	35	34	37	84	43	33	43	33	40
cycle 2 length	46	38	41	46	49	48	41	33	39	44
cycle 3 length	60	55	45	56	33	40	36	38	41	33
cycle 4 length	54	38	44	57	40	41	33	34	45	69
cycle 5 length	66	37	45	80	47	57	53	43	50	83
cycle 6 length	59	48	44	49	64	60	57	43	57	67
cycle 7 length	57	46	45	70	79	54	58	71	45	59
cycle 8 length	64	71	58	57	61	76	36	48	69	45
cycle 9 length	61	41	56	60	47	53	60	51	60	64
cycle 10 length	46	69	86	23*	54	64	51	86	55	64
cycle 11 length	59	57	72	-	72	43	55	51	69	18*
cycle 12 length	-	59	43	-	-	53	63	59	-	-
cycle 13 length	-	58	48	-	-	-	63	-	-	-
total	**615**	**652**	**661**	**535**	**630**	**632**	**639**	**600**	**563**	**586**

Figure 8: Maintenance cycle information and vessels charters for config 218 (batch 1). The number of started charter periods within each cycle is indicated in text in the plot in the order of HLV, FSV, CTV. The * in the table indicates that a cycle was still ongoing at the end of the planning horizon.

4.1.4 Conclusion of batch 1

It cannot yet be determined if the best configuration of the first batch represents the optimal values of the decision variables, since the step-size of the series of decision variables (section 4.1.1) is relatively big, especially for the tasks_per_CTV. Therefore, a second batch of simulations is performed.

4.2 Batch 2: 2022-05-18-13h06

The second batch of simulations was started on '2022-05-18-13h06' using the sets (scenarios) created on '2022-05-14-20h04'. The output log of each simulation performed can be found via https://1drv.ms/u/s!AqqFTU9267_1iK1rZQMReocbcsMvDg?e=5V6KHn.

4.2.1 Series of decision variables

The following values of the decision variables are used for the simulations of this batch. These values are chosen based on the decision variable values of the best configurations of the first batch.

series tasks_per_HLV:	6,	7,	8,	9,	10,	11,	12,	13,	14
series tasks_per_FSV:	0,	10,	15,	20,	25,	30,	35		
series tasks_per_CTV:	0,	80,	90,	100,	110,	120,	130,	140,	150

In total, there are $9 \cdot 7 \cdot 9 = 567$ combinations, hence, there are 567 configurations. For each configuration, ten simulations are performed (since ten scenarios were created), resulting in a total of 5670 simulations for this batch.

It was decided to use a step size of one for the series tasks_per_HLV, a step size of five for the series tasks_per_FSV, and a step size of ten for the series tasks_per_CTV. Additionally, simulations are performed for which no FSVs and/or CTVs are chartered (decision variable equals zero). The step sizes for the decision variables are different since the magnitude of the best value for each decision variable likely differs in order of magnitude (based on the results of the first batch). It was supposed that these step sizes are sufficiently small to come to a conclusion for this case study. Decreasing the step size will likely results in many identical results for different configurations (see section 4.1.3).

4.2.2 Results

The results of the simulations of the second batch are presented in this section in much greater detail compared to those of the first batch in section 4.1.2. The reason for this is that from the results of the second batch, the best combination of values of the decision variables for this case study is concluded, while the results of the first batch were only used to define new series of decision variable values. In the following paragraphs, the results of the cost per MWh produced, accuracy, and the computational time of the entire batch of simulations is presented first. Thereafter, several detailed results of the best configuration produced is presented. Finally, some remarks on the results are discussed.

4.2.2.1 Cost per MWh produced

The average, maximum, and minimum cost per MWh produced of the ten sets for each configuration is depicted in Figure 9. The configurations are ranked from best to worst average €/MWh. In Figure 10, the average, maximum, and minimum cost per MWh produced of the ten scenarios for the best 20 configurations are depicted. The average cost per MWh and the values of the decision variables for the 20 best configurations are listed in the table of Figure 10. Again, it can be seen that different configurations result in identical average cost per MWh produced. In Figure 11, the cost per MWh produced for every set for the best ten configurations of batch 2 is depicted, including a table with the values. A different configuration with a lower average cost per MWh produced was found in the second batch compared to the first batch of simulations.

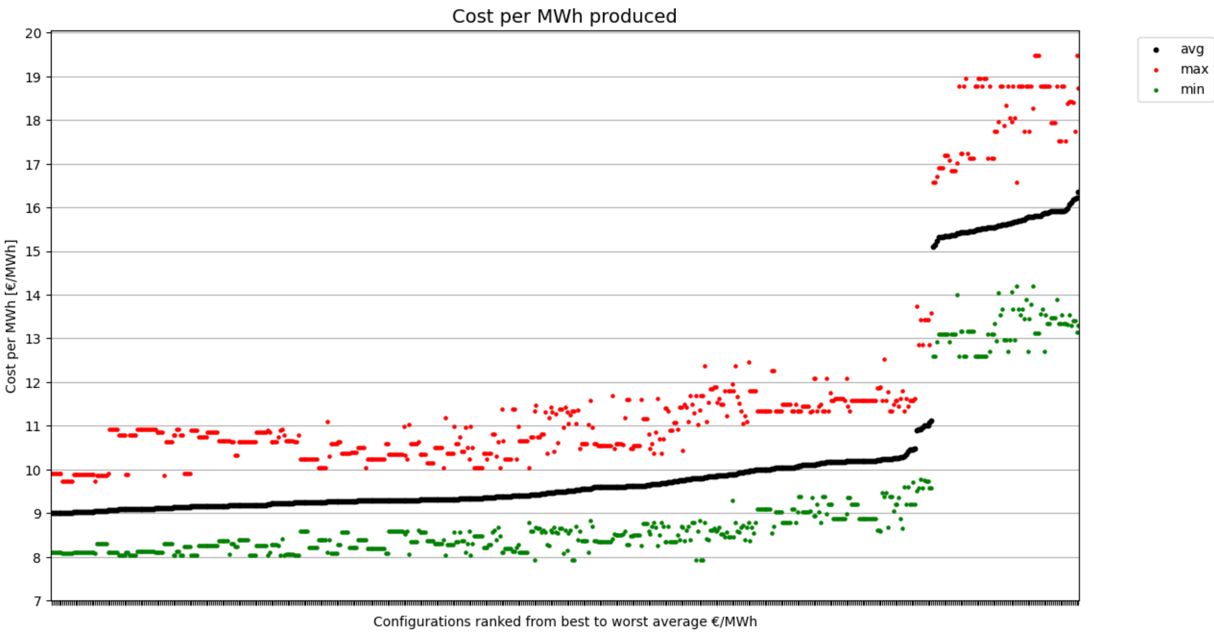
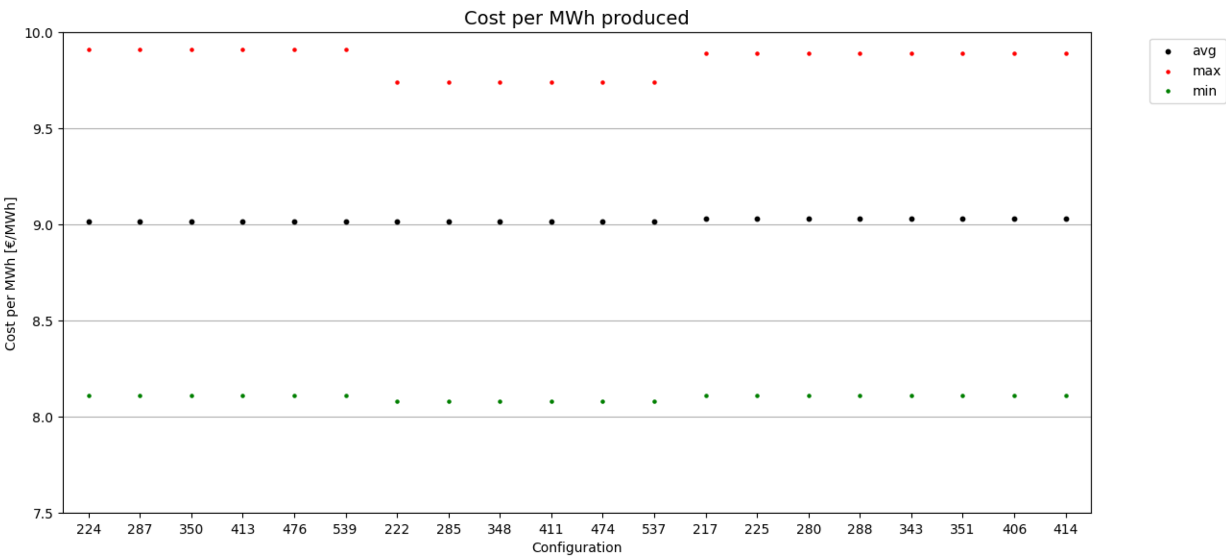
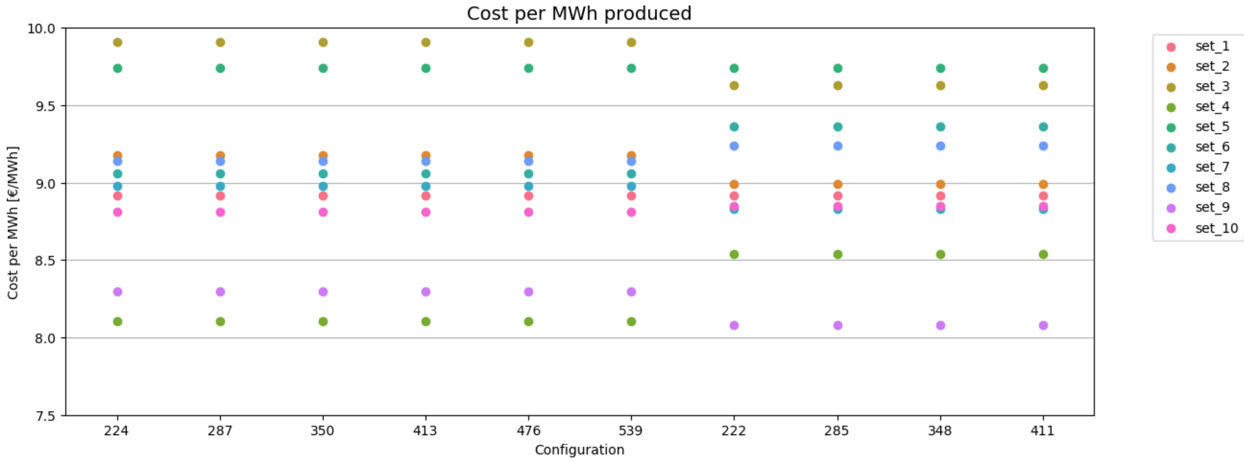


Figure 9: Cost per MWh produced, all configurations (batch 2).



Configuration:	224	287	350	413	476	539	222	285	348	411	474	537	217	225	280	288	343	351	406	414
avg_cost_per_MWh	9.015	9.015	9.015	9.015	9.015	9.015	9.018	9.018	9.018	9.018	9.018	9.018	9.032	9.032	9.032	9.032	9.032	9.032	9.032	9.032
tasks_per_HLV	9	10	11	12	13	14	9	10	11	12	13	14	9	9	10	10	11	11	12	12
tasks_per_FSV	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
tasks_per_CTV	140	140	140	140	140	140	120	120	120	120	120	120	0	150	0	150	0	150	0	150

Figure 10: Cost per MWh produced, best 20 configurations (batch 2).



Unit: €/MWh	224	287	350	413	476	539	222	285	348	411
set_1	8.920	8.920	8.920	8.920	8.920	8.920	8.920	8.920	8.920	8.920
set_2	9.180	9.180	9.180	9.180	9.180	9.180	8.990	8.990	8.990	8.990
set_3	9.910	9.910	9.910	9.910	9.910	9.910	9.630	9.630	9.630	9.630
set_4	8.110	8.110	8.110	8.110	8.110	8.110	8.540	8.540	8.540	8.540
set_5	9.740	9.740	9.740	9.740	9.740	9.740	9.740	9.740	9.740	9.740
set_6	9.060	9.060	9.060	9.060	9.060	9.060	9.360	9.360	9.360	9.360
set_7	8.980	8.980	8.980	8.980	8.980	8.980	8.830	8.830	8.830	8.830
set_8	9.140	9.140	9.140	9.140	9.140	9.140	9.240	9.240	9.240	9.240
set_9	8.300	8.300	8.300	8.300	8.300	8.300	8.080	8.080	8.080	8.080
set_10	8.810	8.810	8.810	8.810	8.810	8.810	8.850	8.850	8.850	8.850
avg.	**9.015**	**9.015**	**9.015**	**9.015**	**9.015**	**9.015**	**9.018**	**9.018**	**9.018**	**9.018**

Figure 11: Cost per MWh produced, best 10 configurations (batch 2).

4.2.2.2 Accuracy of results

As was stated in section 4.1.2.2, is it assumed that ten sets lead to sufficient accuracy for the purpose of this case study. The results of the accuracy analysis are depicted in Figure 12 and 13.

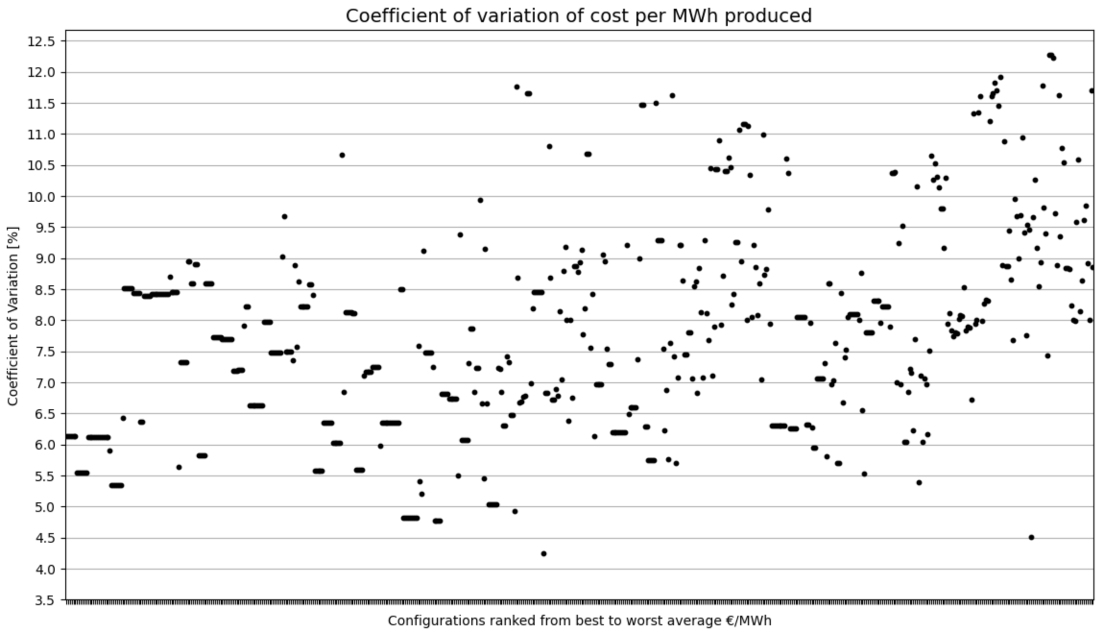
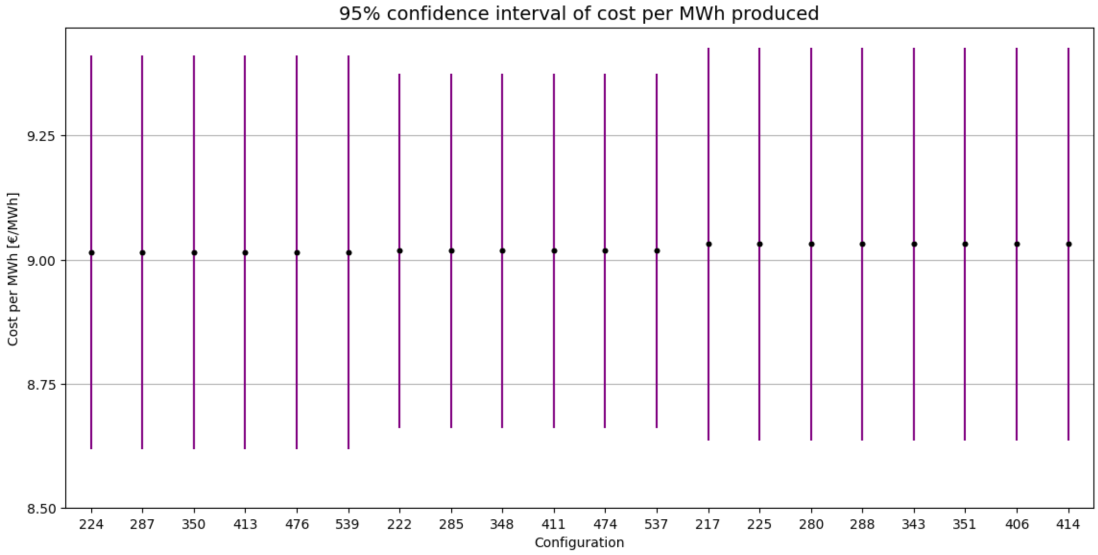


Figure 12: Coefficient of variation of cost per MWh produced, all configurations (batch 2).



Configuration:	224	287	350	413	476	539	222	285	348	411	474	537	217	225	280	288	343	351	406	414
avg_cost_per_MWh	9.015	9.015	9.015	9.015	9.015	9.015	9.018	9.018	9.018	9.018	9.018	9.018	9.032	9.032	9.032	9.032	9.032	9.032	9.032	9.032
tasks_per_HLV	9	10	11	12	13	14	9	10	11	12	13	14	9	9	10	10	11	11	12	12
tasks_per_FSV	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
tasks_per_CTV	140	140	140	140	140	140	120	120	120	120	120	120	0	150	0	150	0	150	0	150

Figure 13: 95% confidence interval of cost per MWh produced, best 20 configurations (batch 2).

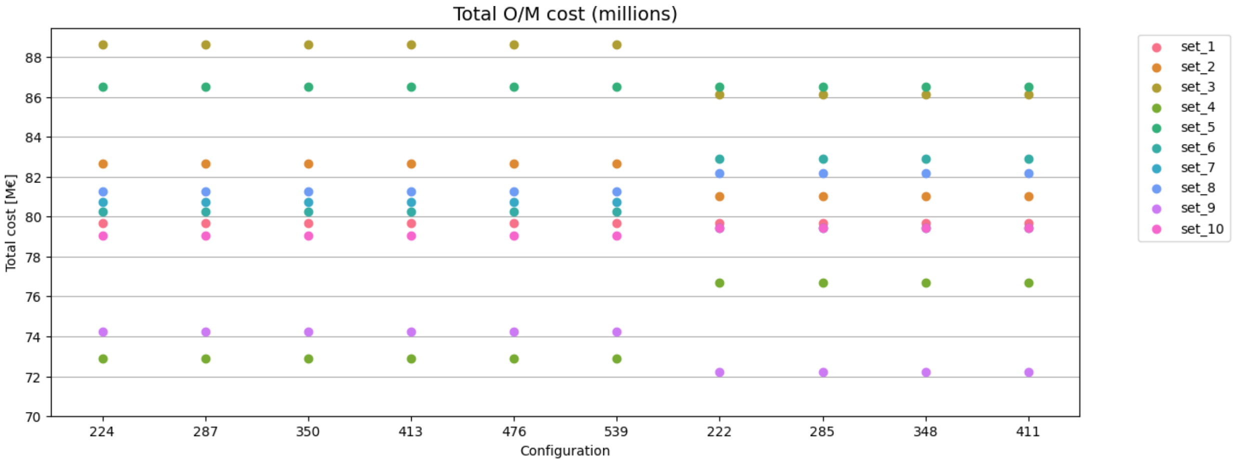
4.2.2.3 Computational time

The average, maximum, and minimum runtime of the simulations of second batch are:

- average runtime: 174.36 seconds per simulation
- maximum runtime: 310.26 seconds per simulation
- minimum runtime: 120.92 seconds per simulation

4.2.2.4 Total O&M cost

In Figure 14, the total O&M cost over the entire planning horizon of 15 years for the ten best configurations are presented.

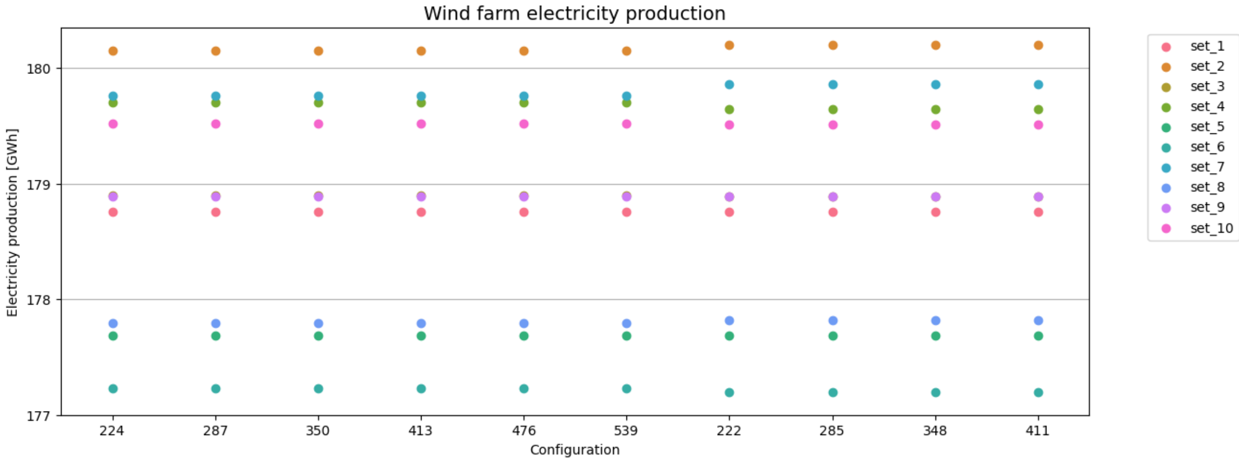


Unit: M€	224	287	350	413	476	539	222	285	348	411
set_1	79.681	79.681	79.681	79.681	79.681	79.681	79.681	79.681	79.681	79.681
set_2	82.647	82.647	82.647	82.647	82.647	82.647	81.013	81.013	81.013	81.013
set_3	88.643	88.643	88.643	88.643	88.643	88.643	86.109	86.109	86.109	86.109
set_4	72.896	72.896	72.896	72.896	72.896	72.896	76.716	76.716	76.716	76.716
set_5	86.524	86.524	86.524	86.524	86.524	86.524	86.524	86.524	86.524	86.524
set_6	80.259	80.259	80.259	80.259	80.259	80.259	82.925	82.925	82.925	82.925
set_7	80.750	80.750	80.750	80.750	80.750	80.750	79.420	79.420	79.420	79.420
set_8	81.258	81.258	81.258	81.258	81.258	81.258	82.179	82.179	82.179	82.179
set_9	74.226	74.226	74.226	74.226	74.226	74.226	72.234	72.234	72.234	72.234
set_10	79.051	79.051	79.051	79.051	79.051	79.051	79.427	79.427	79.427	79.427
avg.	**80.594**	**80.594**	**80.594**	**80.594**	**80.594**	**80.594**	**80.623**	**80.623**	**80.623**	**80.623**

Figure 14: Total O&M cost, best 10 configurations (batch 2).

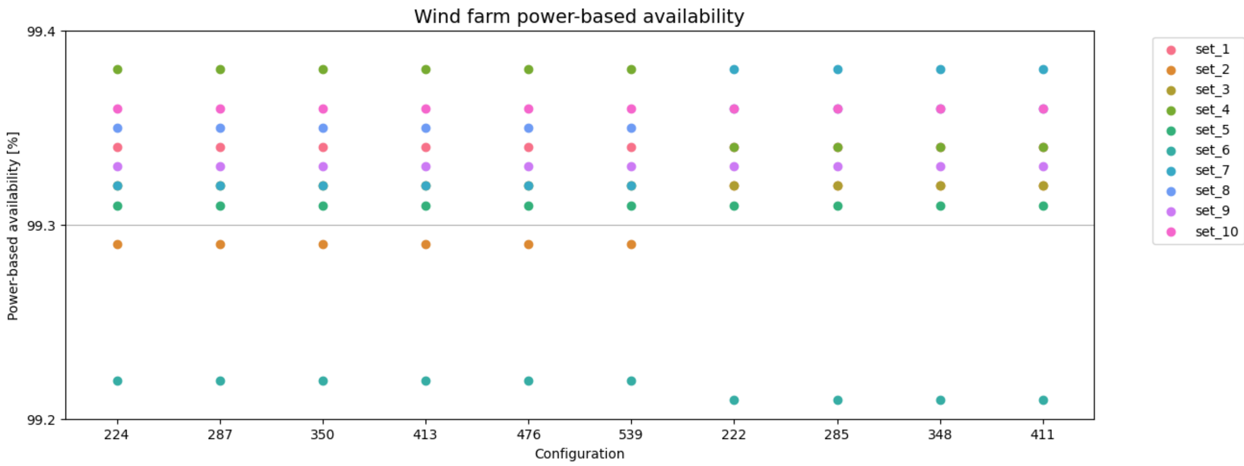
4.2.2.5 Wind farm results

In Figure 15, the wind farm's electricity production over the entire planning horizon for each set of the ten best configurations is depicted. Figure 16 depicts the power-based availability of the wind farm.



Unit: GWh	224	287	350	413	476	539	222	285	348	411
set_1	178.76	178.76	178.76	178.76	178.76	178.76	178.76	178.76	178.76	178.76
set_2	180.15	180.15	180.15	180.15	180.15	180.15	180.20	180.20	180.20	180.20
set_3	178.90	178.90	178.90	178.90	178.90	178.90	178.89	178.89	178.89	178.89
set_4	179.70	179.70	179.70	179.70	179.70	179.70	179.64	179.64	179.64	179.64
set_5	177.69	177.69	177.69	177.69	177.69	177.69	177.69	177.69	177.69	177.69
set_6	177.23	177.23	177.23	177.23	177.23	177.23	177.20	177.20	177.20	177.20
set_7	179.76	179.76	179.76	179.76	179.76	179.76	179.86	179.86	179.86	179.86
set_8	177.80	177.80	177.80	177.80	177.80	177.80	177.82	177.82	177.82	177.82
set_9	178.89	178.89	178.89	178.89	178.89	178.89	178.89	178.89	178.89	178.89
set_10	179.52	179.52	179.52	179.52	179.52	179.52	179.51	179.51	179.51	179.51
avg.	**178.84**	**178.84**	**178.84**	**178.84**	**178.84**	**178.84**	**178.85**	**178.85**	**178.85**	**178.85**

Figure 15: Wind farm electricity production, best 10 configurations (batch 2).

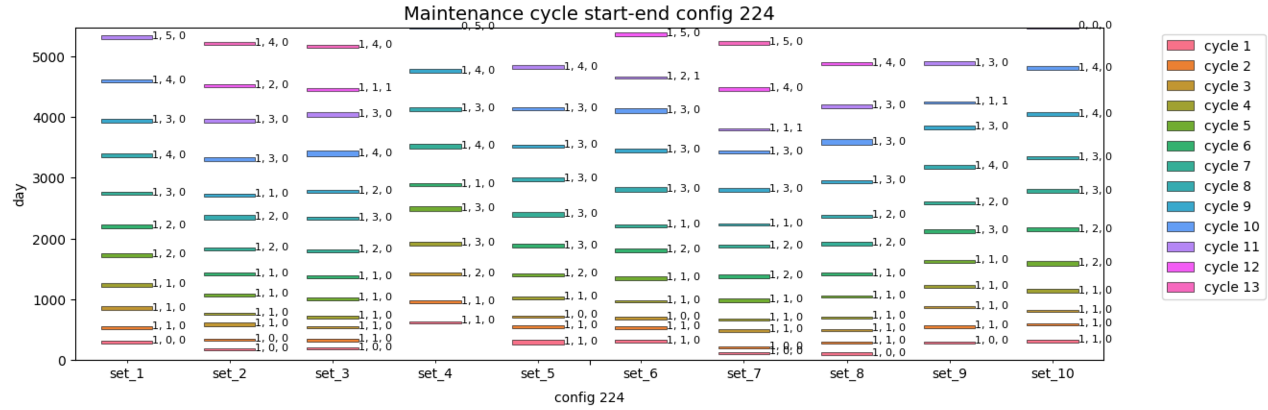


Unit: %	224	287	350	413	476	539	222	285	348	411
set_1	99.34	99.34	99.34	99.34	99.34	99.34	99.34	99.34	99.34	99.34
set_2	99.29	99.29	99.29	99.29	99.29	99.29	99.32	99.32	99.32	99.32
set_3	99.32	99.32	99.32	99.32	99.32	99.32	99.32	99.32	99.32	99.32
set_4	99.38	99.38	99.38	99.38	99.38	99.38	99.34	99.34	99.34	99.34
set_5	99.31	99.31	99.31	99.31	99.31	99.31	99.31	99.31	99.31	99.31
set_6	99.22	99.22	99.22	99.22	99.22	99.22	99.21	99.21	99.21	99.21
set_7	99.32	99.32	99.32	99.32	99.32	99.32	99.38	99.38	99.38	99.38
set_8	99.35	99.35	99.35	99.35	99.35	99.35	99.36	99.36	99.36	99.36
set_9	99.33	99.33	99.33	99.33	99.33	99.33	99.33	99.33	99.33	99.33
set_10	99.36	99.36	99.36	99.36	99.36	99.36	99.36	99.36	99.36	99.36
avg.	**99.32**	**99.32**	**99.32**	**99.32**	**99.32**	**99.32**	**99.33**	**99.33**	**99.33**	**99.33**

Figure 16: Wind farm power-based availability, best 10 configurations (batch 2).

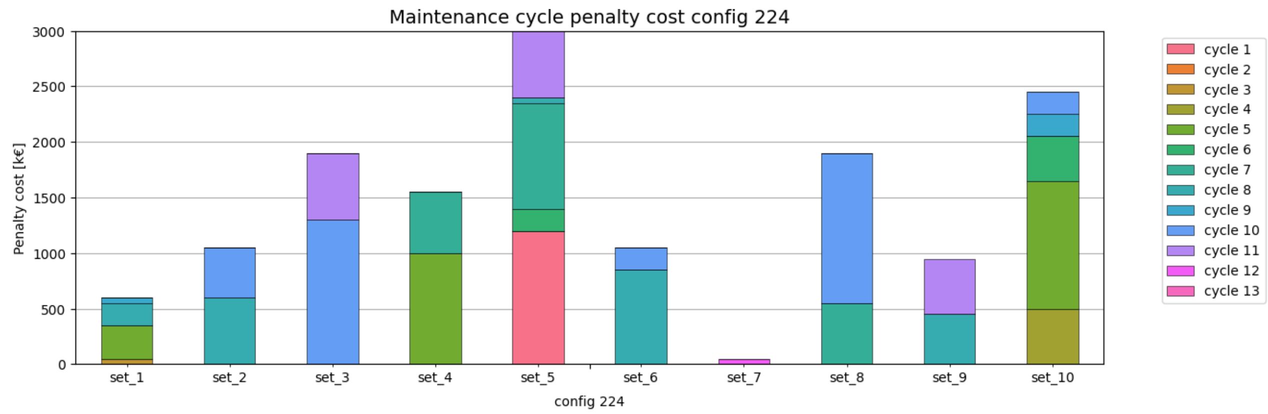
4.2.2.6 Maintenance cycle results

The start and end of each maintenance cycle of configuration 224 are depicted in Figure 17, including the length of each cycle in the table. The numbers in the plot besides each cycle indicate the number of chartered vessels in that cycle (in the order of HLV, FSV, CTV). Figure 18 depicts the penalty cost related to cycles lasting longer than 60 days (Table 12 inputs [8-9]).



Unit: day	config 224									
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10
cycle 1 length	43	35	34	37	84	43	33	43	33	40
cycle 2 length	46	38	41	46	49	48	41	33	39	44
cycle 3 length	60	55	45	56	33	40	36	38	41	33
cycle 4 length	54	38	44	57	40	41	33	34	45	69
cycle 5 length	66	37	45	80	47	57	53	43	50	83
cycle 6 length	59	48	44	49	64	60	57	43	57	67
cycle 7 length	57	46	45	70	79	54	58	71	45	59
cycle 8 length	64	71	58	57	61	76	36	48	69	45
cycle 9 length	61	41	56	60	47	53	60	51	60	64
cycle 10 length	46	69	86	23*	54	64	51	86	33	64
cycle 11 length	59	57	72	-	72	43	33	51	70	18*
cycle 12 length	-	59	38	-	-	58	61	59	-	-
cycle 13 length	-	58	51	-	-	-	57	-	-	-
total	**615**	**652**	**659**	**535**	**630**	**637**	**609**	**600**	**542**	**586**

Figure 17: Maintenance cycle information and vessels charters for config 224 (batch 2). The number of started charter periods within each cycle is indicated in text in the plot in the order of HLV, FSV, CTV. The * in the table indicates that a cycle was still ongoing at the end of the planning horizon.

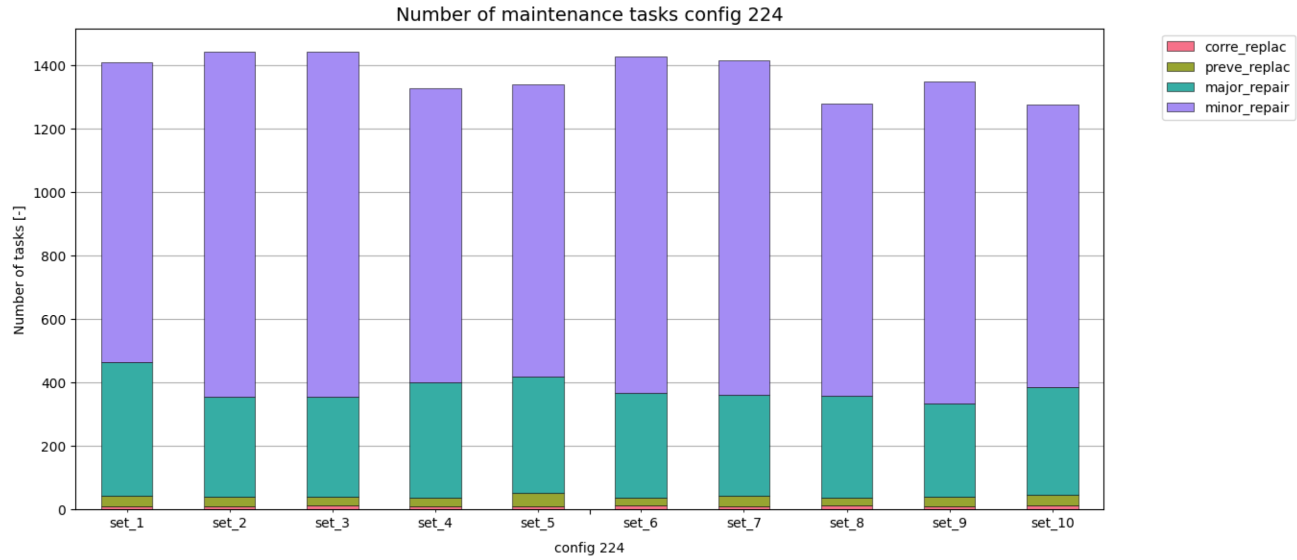


Unit: k€	config 224									
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10
cycle 1	0	0	0	0	1200	0	0	0	0	0
cycle 2	0	0	0	0	0	0	0	0	0	0
cycle 3	50	0	0	0	0	0	0	0	0	0
cycle 4	0	0	0	0	0	0	0	0	0	500
cycle 5	300	0	0	1000	0	0	0	0	0	1150
cycle 6	0	0	0	0	200	0	0	0	0	400
cycle 7	0	0	0	550	950	0	0	550	0	0
cycle 8	200	600	0	0	50	850	0	0	450	0
cycle 9	50	0	0	0	0	0	0	0	0	200
cycle 10	0	450	1300	0*	0	200	0	1350	0	200
cycle 11	0	0	600	-	600	0	0	0	500	0*
cycle 12	-	0	0	-	-	0	50	0	-	-
cycle 13	-	0	0	-	-	-	0	-	-	-
total	**600**	**1050**	**1900**	**1550**	**3000**	**1050**	**50**	**1900**	**950**	**2450**

Figure 18: Maintenance cycle penalty cost for config 224 (batch 2). The * in the table indicates that a cycle was still ongoing at the end of the planning horizon.

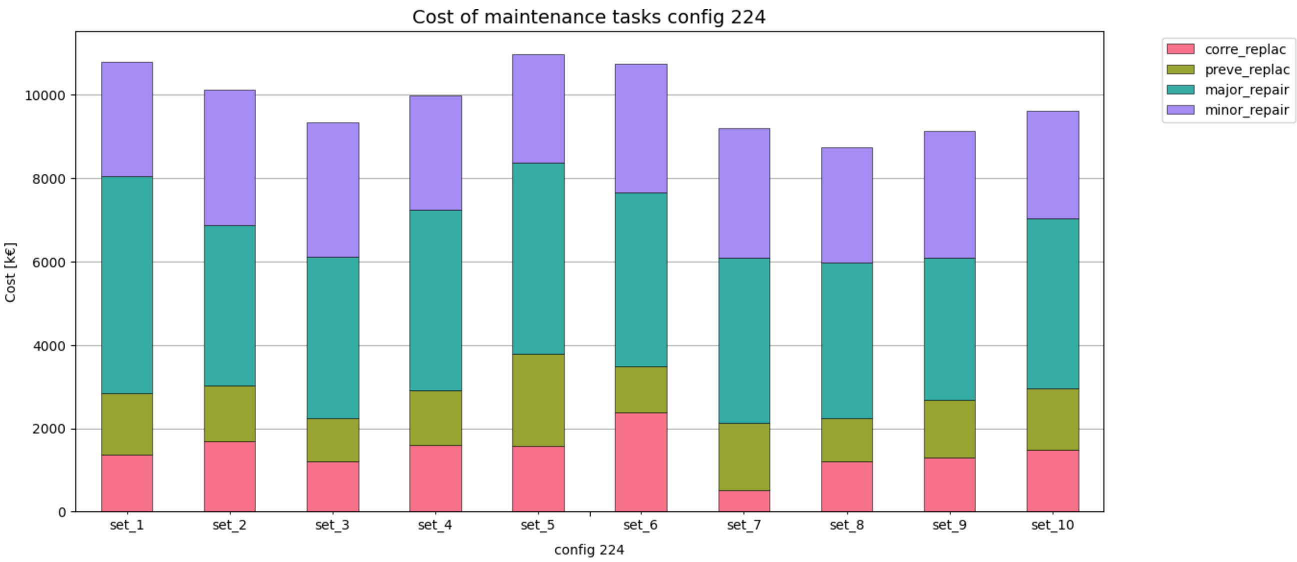
4.2.2.7 Component maintenance results

The results related to completed maintenance tasks of configuration 224 are presented below. In Figure 19 and 20, the number and cost of performed maintenance tasks are depicted, respectively.



Unit: -	config 224									
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10
corre_replac	10	12	13	10	10	15	10	14	12	15
preve_replac	34	28	27	29	42	24	33	25	30	33
major_repair	420	315	316	362	366	329	319	319	291	339
minor_repair	944	1089	1088	928	922	1060	1052	921	1017	888
total	**1408**	**1444**	**1444**	**1329**	**1340**	**1428**	**1414**	**1279**	**1350**	**1275**

Figure 19: Number of performed maintenance tasks for config 224 (batch 2).



Unit: k€	config 224									
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10
corre_replac	1375.0	1695.0	1215.0	1605.0	1575.0	2370.0	510.0	1200.0	1310.0	1475.0
preve_replac	1470.0	1335.0	1025.0	1300.0	2200.0	1110.0	1615.0	1050.0	1365.0	1490.0
major_repair	5200.0	3842.5	3857.5	4327.5	4582.5	4162.5	3963.75	3723.75	3401.25	4058.75
minor_repair	2728.5	3251.0	3224.0	2750.5	2617.0	3089.5	3112.5	2763.0	3057.0	2588.5
total	**10773.5**	**10123.5**	**9321.5**	**9983.0**	**10974.5**	**10732.0**	**9201.25**	**8736.75**	**9133.25**	**9612.25**

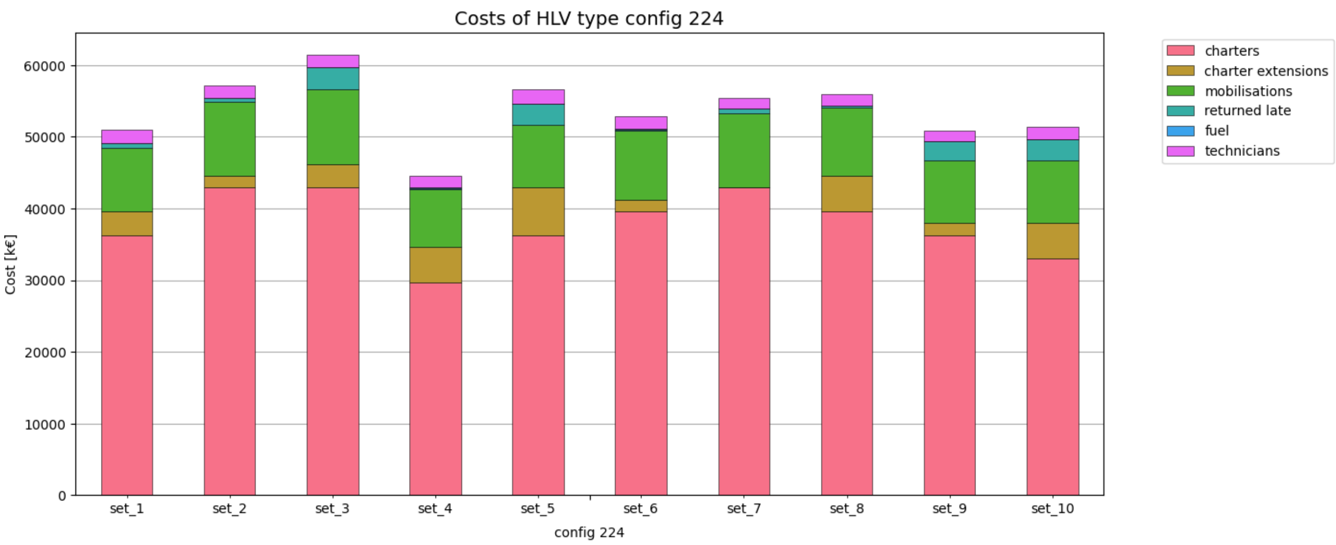
Figure 20: Cost of performed maintenance tasks for config 224 (batch 2).

4.2.2.8 Vessel operational and charter costs

The vessel operational and charter costs per vessel type for configuration 224 are depicted in Figure 21, 22, and 23. The costs are divided in six categories:

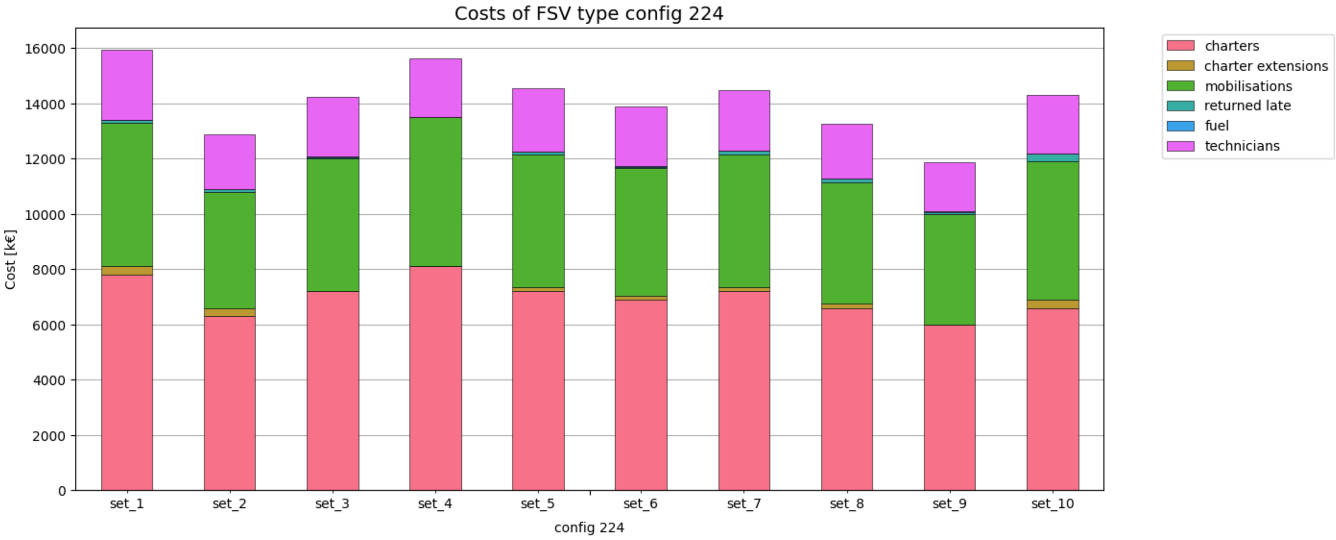
- charters: total cost of chartering
- charter extensions: total cost of extended charter periods
- mobilisations: total cost of mobilising vessels
- returned late: total cost of vessels being returned beyond the charter period
- fuel: total cost of fuel
- technicians: total cost of technicians

It is assumed that a vessel only uses fuel during traveling. The technicians on board an owned vessel are paid for the entire duration of each maintenance cycle. The technicians on board a chartered vessel are paid from the start of a charter period until the vessel is returned.



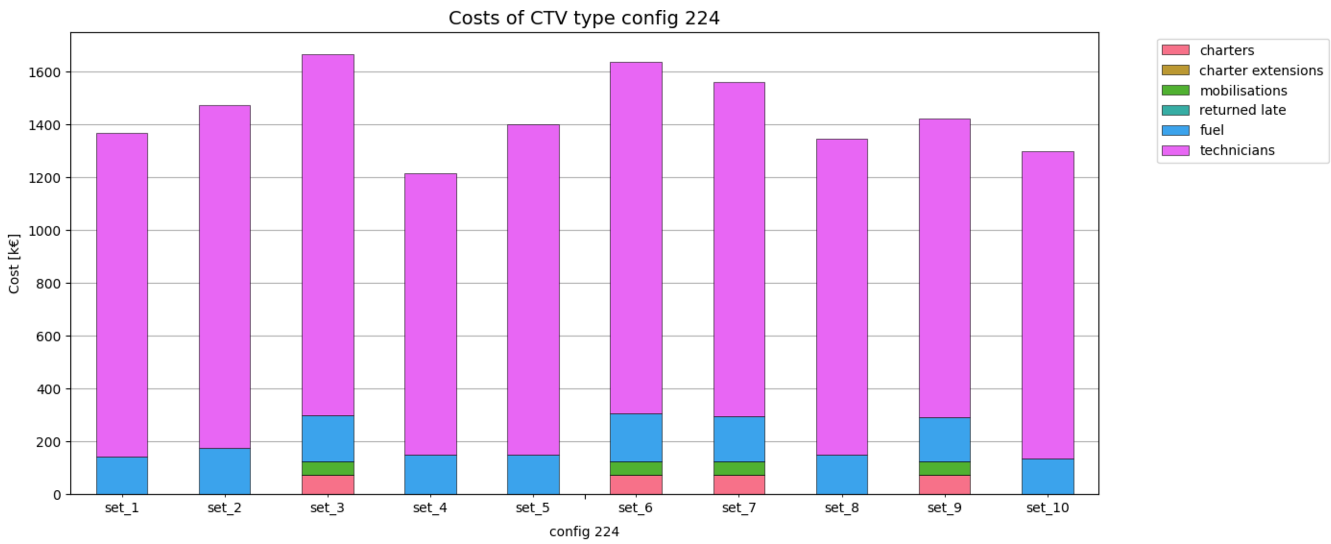
Unit: k€	config 224									
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10
charters	36300.0	42900.0	42900.0	29700.0	36300.0	39600.0	42900.0	39600.0	36300.0	33000.0
charter extensions	3300.0	1650.0	3300.0	4950.0	6600.0	1650.0	0	4950.0	1650.0	4950.0
mobilisations	8800.0	10400.0	10400.0	8000.0	8800.0	9600.0	10400.0	9600.0	8800.0	8800.0
returned late	660.0	440.0	3080.0	220.0	2860.0	220.0	660.0	220.0	2640.0	2860.0
fuel	24.1	24.8	26.4	22.3	28.2	23.6	24.3	25.9	22.8	25.1
technicians	1899.1	1714.9	1810.1	1620.5	2001.4	1838.5	1486.0	1623.8	1432.0	1759.4
total	**50983.2**	**57129.6**	**61516.5**	**44512.7**	**56589.6**	**52932.1**	**55470.3**	**56019.7**	**50844.7**	**51394.4**

Figure 21: Costs of HLV type for config 224 (batch 2).



Unit: k€	config 224									
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10
charters	7800.0	6300.0	7200.0	8100.0	7200.0	6900.0	7200.0	6600.0	6000.0	6600.0
charter extensions	300.0	300.0	0	0	150.0	150.0	150.0	150.0	0	300.0
mobilisations	5200.0	4200.0	4800.0	5400.0	4800.0	4600.0	4800.0	4400.0	4000.0	5000.0
returned late	100.0	100.0	60.0	0	100.0	60.0	140.0	120.0	80.0	280.0
fuel	20.5	15.8	16.2	18.1	18.4	16.6	16.0	15.8	14.1	16.7
technicians	2536.4	1953.3	2160.0	2116.7	2288.4	2181.0	2160.3	1968.9	1778.8	2096.9
total	**15956.9**	**12869.1**	**14236.2**	**15634.8**	**14556.8**	**13907.6**	**14466.2**	**13254.7**	**11872.9**	**14293.6**

Figure 22: Costs of FSV type for config 224 (batch 2).



Unit: k€	config 224									
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10
charters	0	0	75.0	0	0	75.0	75.0	0	75.0	0
charter extensions	0	0	0	0	0	0	0	0	0	0
mobilisations	0	0	50.0	0	0	50.0	50.0	0	50.0	0
returned late	0	0	0	0	0	0	0	0	0	0
fuel	143.3	176.0	172.9	150.4	150.8	182.3	169.3	149.7	167.1	134.4
technicians	1224.4	1299.2	1370.5	1065.4	1251.8	1329.9	1268.3	1197.3	1132.7	1166.2
total	**1367.6**	**1475.2**	**1668.5**	**1215.8**	**1402.7**	**1637.2**	**1562.6**	**1347.0**	**1424.8**	**1300.5**

Figure 23: Costs of CTV type for config 224 (batch 2).

4.2.2.9 Vessel utilisation results

The vessel time distribution (time spent per activity) per vessel type for configuration 224 is depicted in Figure 24, 25, and 26. The time distribution of owned and chartered vessels is presented separately, since the available time of owned and chartered vessels are different. For owned vessels, the time spent per activity is relative to the total duration of maintenance cycles (as owned vessels can be used during the entire maintenance cycle). For chartered vessels, the time spent per activity is relative to the total charter length of that vessel type.

Figure 24 indicates that chartered HLVs cannot work on maintenance tasks due to bad weather conditions for about 40% of the available time. Also, about 40% of the available time is used to work on maintenance tasks (indicated by 'repairs', which actually should be 'replacements').

Figure 25 indicates that chartered FSVs are working on maintenance tasks (repairs) for about 30-40% of the available time. Since FSVs cannot work outside shift hours, it is expected that FSVs are constrained by shift hours for a large portion of the available time. Compared to HLVs, the operations of FSVs are much less constrained by weather conditions. This is due to the fact that the minimum working of FSVs is much smaller than that of HLVs (Table 10 input [3]).

From Figure 26 a few things can concluded. First, it can be seen that for configuration 224 CTVs are only chartered for sets 3, 6, 7, and 9, which corresponds with the results depicted in Figure 17 and 23. Second, it can be seen that the owned CTV spends relatively much time on 'idle_at_base_in_cycle'. The CTV will stay idle at the base during a cycle if there are no more tasks for the CTV. Therefore, it can be concluded that the CTV often completes all its tasks before the end of the cycle. In other words, the duration of maintenance cycles is (on average) not much affected by the time it takes for the CTV to complete all its tasks. This is also due to the fact that the other vessel types (HLV and FSV) are not owned and need to be mobilised before they can start working on maintenance tasks. Thus, in the meantime other vessel types are mobilised, the owned CTV can already work on maintenance tasks. Third, it stands out that for set 7 the chartered CTV does not spend much time at the base during the cycle. In Figure 17 can be seen that only one CTV was chartered during the entire simulation, which was in maintenance cycle 11. Since the time spent on 'idle_at_base_in_cycle' for this chartered CTV is relatively small, it can be concluded that the chartered CTV was utilised for almost the entire cycle duration.

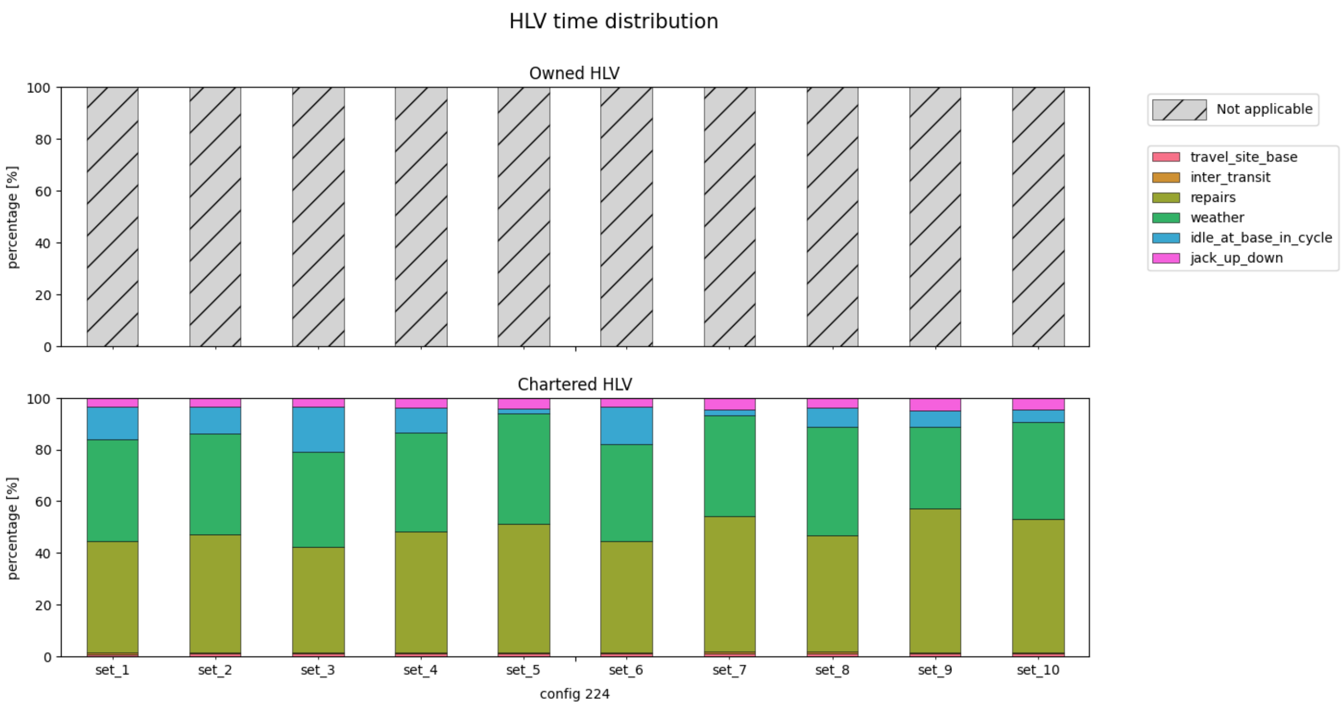


Figure 24: Utilisation of HLV type for config 224 (batch 2). HLVs do not repair components but only replace components. Therefore, 'repairs' should actually be 'replacements' and indicates the time spent of working on maintenance tasks.

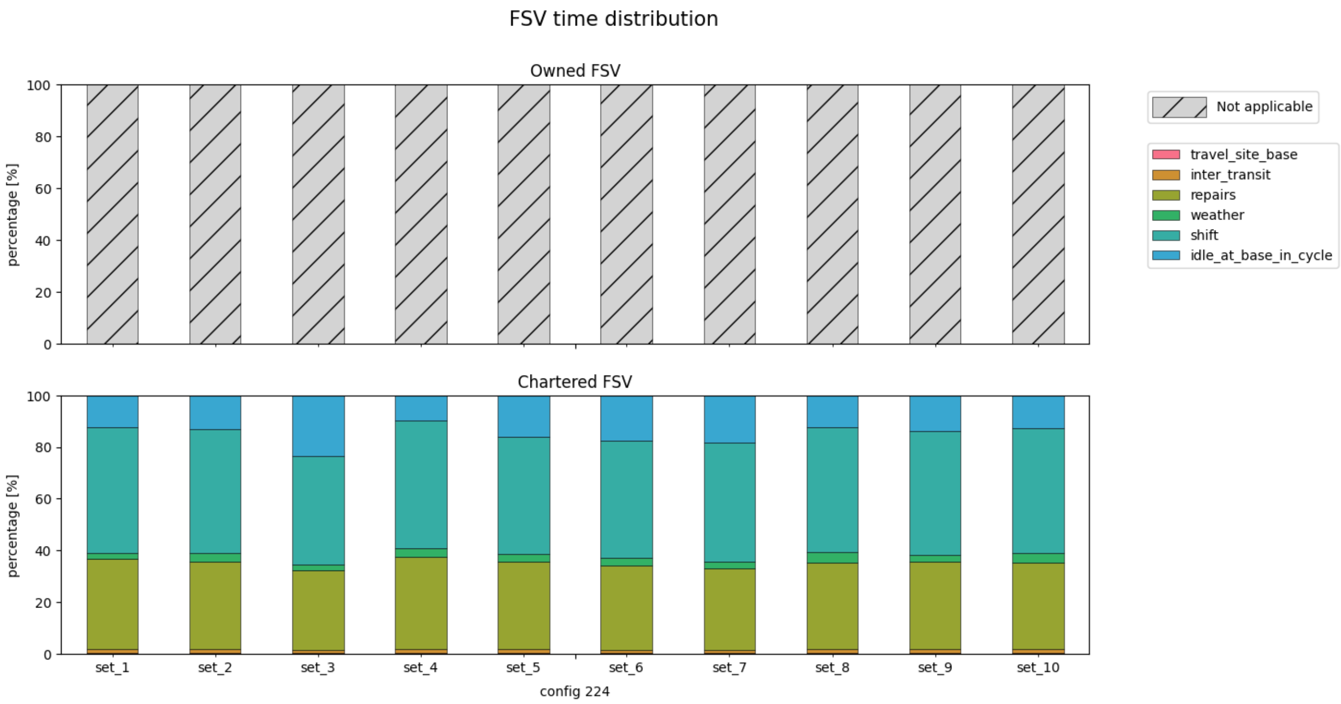


Figure 25: Utilisation of FSV type for config 224 (batch 2).

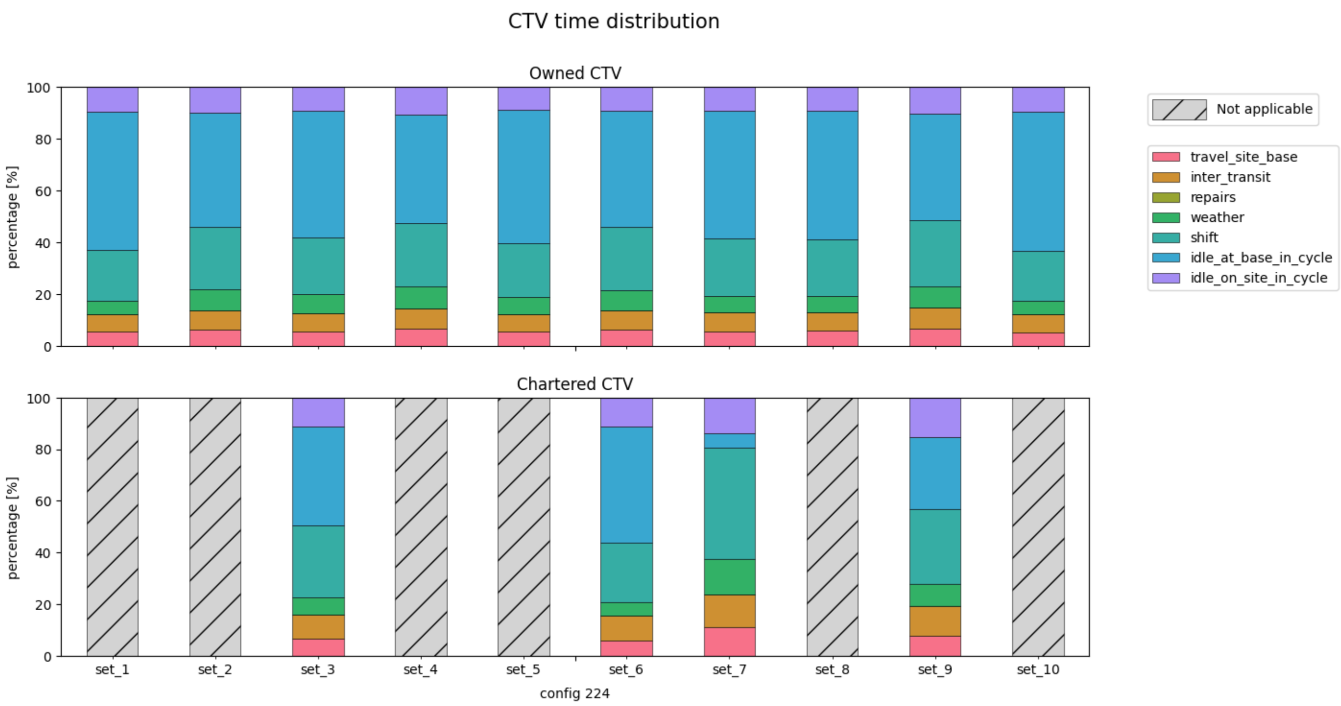


Figure 26: Utilisation of CTV type for config 224 (batch 2). Note that the time spent on 'repairs' is always zero for the CTV. This is due the fact that the CTV does not work on maintenance tasks itself, but is only used to transport teams of technicians.

4.2.3 Remark on results

As in the first batch, different configurations have identical results in the second batch. This outcome is due to exactly the same charter decisions during the simulations although the configurations have different values of the decision variables. How different configurations can have identical charter decisions for the entire planning horizon is explained in section 4.1.3. From Figure 10, it can be seen that configurations 224, 287, 350, 413, 476, and 539 have identical results (it is checked if the charter decisions are identical for these six configurations, which is the case). If more sets were to be used for the simulations, it becomes more likely that different configurations will have different results. In fact, for this case study, there are an unlimited number of configurations that will have the same results as configuration 224 with tasks_per_HLV=9, tasks_per_FSV=20, and tasks_per_CTV=140. Namely, with tasks_per_FSV=20 and tasks_per_CTV=140, any configuration with a value for tasks_per_HLV that is higher than nine, thus $[10, 11, 12, ..., \infty)$, will result in the same charter decisions as configuration 224. Therefore, all of these configurations will have the same outcomes.

4.3 Conclusion of the case study

The simulation inputs for this case study were defined in section 3.3. Due to a limited amount of computational power and available time to run the simulations, it was decided to use ten sets per configuration. Even though ten simulations per configuration is a fairly low number for Monte Carlo simulations, the accuracy of the results was assumed to be sufficient for the purpose of this case study. Namely, this case study is supposed to give insights into the developed model and show how it can be used to support fleet management decisions. In order to identify one best configuration, the configuration with the lowest average cost/MWh and the lowest values of the decision variables compared to configurations with the same average cost/MWh is considered the best configuration, which is configuration 224 of the second batch. This configuration was an improvement compared to the best configuration of the first batch of simulations.

While it cannot be stated with certainty that configuration 224 represents the optimal combination of decision variable values, it can be stated that it likely is close to the optimal configuration, as the solution space in the neighborhood of this configuration was examined. This is done by examining fairly similar but different values of the decision variables, none of which resulted in a better average cost per MWh produced (see section 4.2.1 for the series of decision variables of the second batch). In principle, a third batch of simulations could be performed for which the step sizes could be further decreased for new series of the decision variables. Then, a configuration slightly better than configuration 224 of the second batch may be found. Due to a limited amount of computational power and available time, a third batch of simulations is not performed for the case study in this research.

The best combination of values of the decision variables for this case study are tasks_per_HLV=9, tasks_per_FSV=20, and tasks_per_CTV=140 (configuration 224 of the second batch). The best decision variable values should be interpreted as follows. If the case study is an accurate representation of a real-world application, the values of the decision variables of the best configuration can be used to decide how many vessels of each type should be chartered. Suppose that a maintenance cycle is started in practice and at that time it is known how many tasks there are for each vessel type. Then, based on the decision variable values of the best configuration, the number of vessels to be chartered for that cycle can be determined (using Equation 3.2 - 3.4). Taking this approach will result in the lowest cost per MWh produced over the planning horizon.

The benefit of the developed simulation model is that the user may choose additional or other criteria for the key performance indicators. For example, if the user of the model desires to have a little less risk, it may consider configuration 222 of the second batch as the best configuration. In Figure 10 and 13, it can be seen that configuration 222 has a lower maximum cost/MWh and a narrower 95% confidence interval compared to configuration 224, while the average cost/MWh is just slightly higher. Therefore, configuration 222 has less risk compared to configuration 224 of the second batch. It is up to the user of the model to define accuracy requirements and choose the key performance indicators.

5 Model verification

In this section, verification of the developed methodology is presented. Model verification is essential to ensure that the model matches the modeling assumptions and underlying conceptual model. The model is verified by conducting experiments for which the inputs are changed compared to the case study inputs, where after the expected and actual results of these experiments are compared. In the following subsections, the results of several verification experiments are discussed. Unless otherwise stated, the results of the verification experiment are compared to the results of the best configuration of the case study (tasks_per_HLV=9, tasks_per_FSV=20, and tasks_per_CTV=140).

5.1 Lower CTV wave height limit

For this verification experiment, the wave height limit of the CTV (Table 10 input [6]) has been lowered from 1.7 m to 1.0 m. Therefore, it is expected that the CTV will be more constrained by wave height conditions. As a consequence, it is expected that maintenance cycles will take longer since it takes a longer time for the CTV to complete all the tasks. The average €/MWh of this verification experiment should be higher compared to the best configuration of the case study.

Several results of this verification experiment are depicted in Figure 27 and 28 (where 'config 1' refers to the configuration with identical values of the decision variable as the best configuration of the case study). By comparing Figure 26 and 27, it can be concluded that the CTV is constrained more by weather conditions for this verification experiment than for the case study. Since the CTV takes a longer time to complete all its tasks, the maintenance cycles should take longer which can be concluded by comparing Figure 17 and 28. Also, the average cost per MWh produced has increased from 9.015 to 9.809 €/MWh. All results of this verification experiment are in line with the expectations.

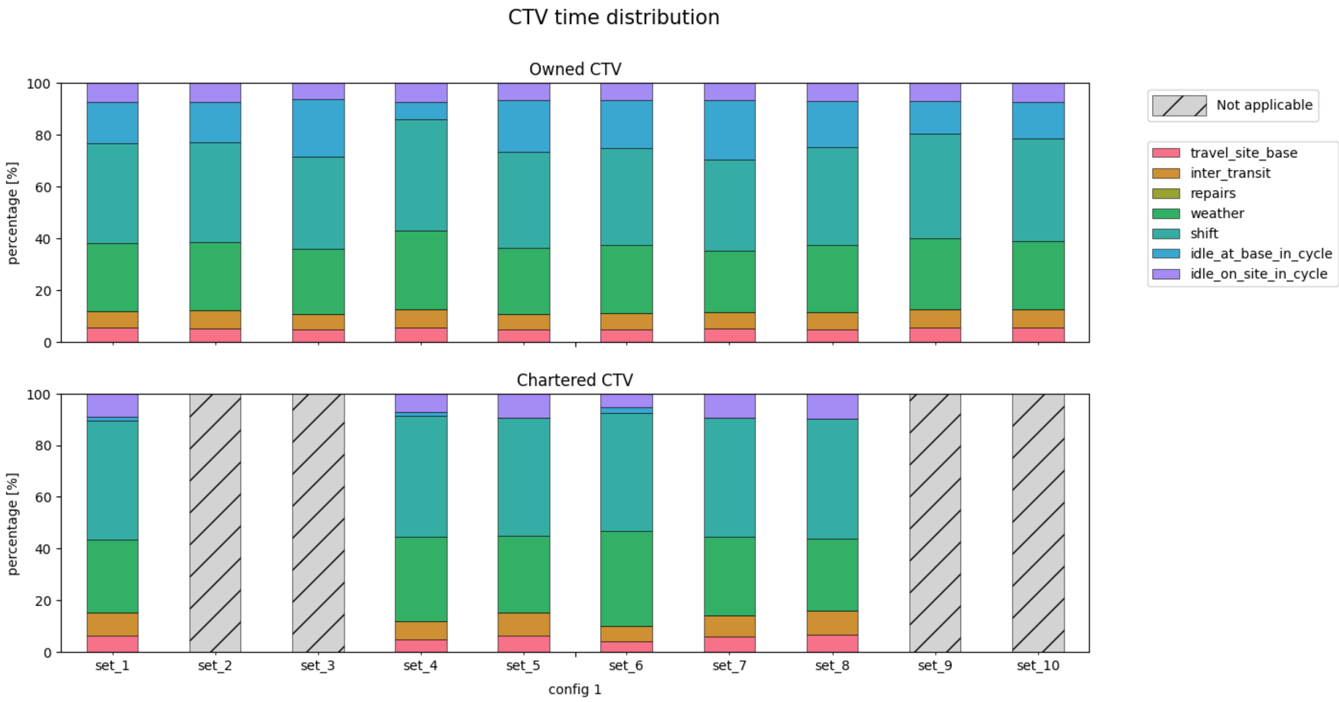
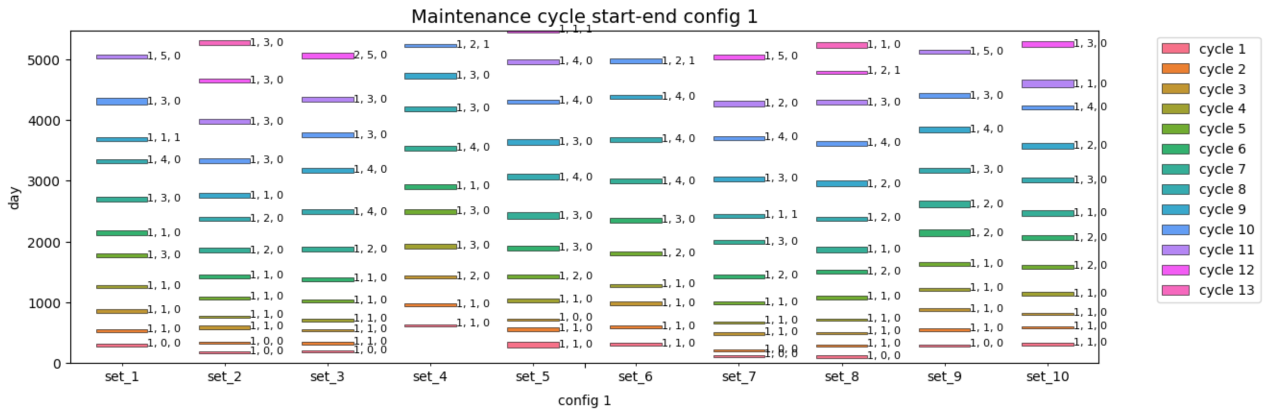


Figure 27: Model verification: lower CTV wave height limit. Utilisation of CTV type, configuration: tasks_per_HLV=9, tasks_per_FSV=20, and tasks_per_CTV=140.



Unit: day	config 1									
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10
cycle 1 length	43	35	34	38	87	50	33	43	33	40
cycle 2 length	46	42	41	49	61	45	40	33	43	44
cycle 3 length	59	54	46	56	34	75	36	35	46	33
cycle 4 length	56	36	44	72	51	48	33	36	46	72
cycle 5 length	66	44	55	77	67	66	54	59	63	62
cycle 6 length	87	56	70	84	73	72	59	62	106	83
cycle 7 length	83	85	78	85	106	85	63	93	103	96
cycle 8 length	62	76	76	83	90	67	63	68	73	78
cycle 9 length	57	76	73	95	94	72	68	100	97	85
cycle 10 length	113	80	84	62	68	87	67	68	86	64
cycle 11 length	67	74	89	-	69	-	85	82	65	128
cycle 12 length	-	73	89	-	34*	-	71	50	-	86
cycle 13 length	-	82	-	-	-	-	-	98	-	-
total	**739**	**813**	**779**	**701**	**834**	**667**	**672**	**827**	**761**	**871**

Figure 28: Model verification: lower CTV wave height limit. Maintenance cycle information and vessels charters. The number of started charter periods within each cycle is indicated in text in the plot in the order of HLV, FSV, CTV. The * in the table indicates that a cycle was still ongoing at the end of the planning horizon.

5.2 Increased penalty cost

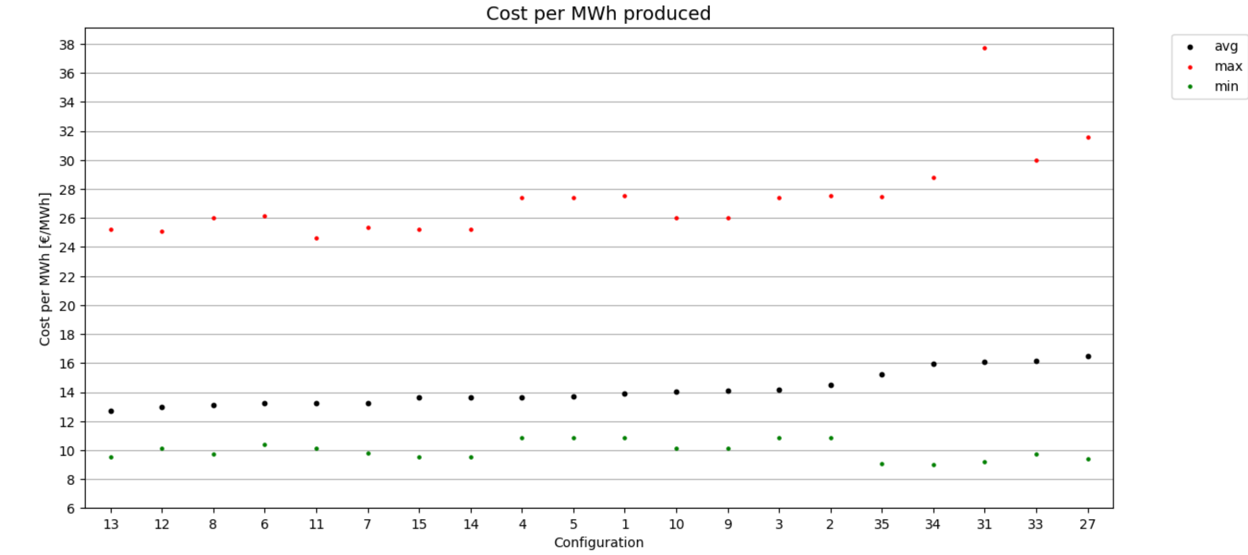
For this verification experiment, the penalty cost for exceeding the soft limit of the cycle duration (Table 12 input [9]) has been increased 100 times from 50 to 5000 k€/day. This means that for every day a cycle takes longer than 60 days, a penalty of €5M is imposed. Although the value of the penalty cost was given as an input as part of the maintenance strategy for this research assignment, it can be changed by the user. Since the penalty cost for each day that a maintenance cycle exceeds 60 days is defined within the maintenance strategy, it had to be implemented in the developed methodology of this research assignment. However, the use of such an artificial penalty can be questioned since it does not exist in practice. Therefore, it is difficult to determine what a reasonable and good value is for the penalty cost. Although the maintenance strategy is outside the scope of this research assignment, several recommendations related to the maintenance strategy (and the penalty cost) are given in section 8.

The following results are expected for this verification experiment. First, it is expected that the best configuration of this verification experiment will have a lower value for some of the decision variables. In other words, it is expected that more vessels are chartered to minimize the number of days that a cycle takes longer than 60 days. Whether the values of all decision variables will be lower is difficult to predict, since it is difficult to determine if the length of a cycle is affected by all or just a single vessel type (for example, if the FSVs and CTVs have finished all tasks and the HLVs have not finished its all tasks, the cycle will only be ended once the all tasks for the HLV type are completed). Likely, the duration of maintenance cycles is mostly affected by the HLV type, since the HLV has the longest mobilisation time and maintenance tasks for this vessel type require the most time compared to the other vessel type. Second, the number of days that the maintenance cycles last longer than 60 days is expected to be smaller compared to the best configuration of the case study.

To verify the expected results, simulations are performed for the following combinations of decision variables:

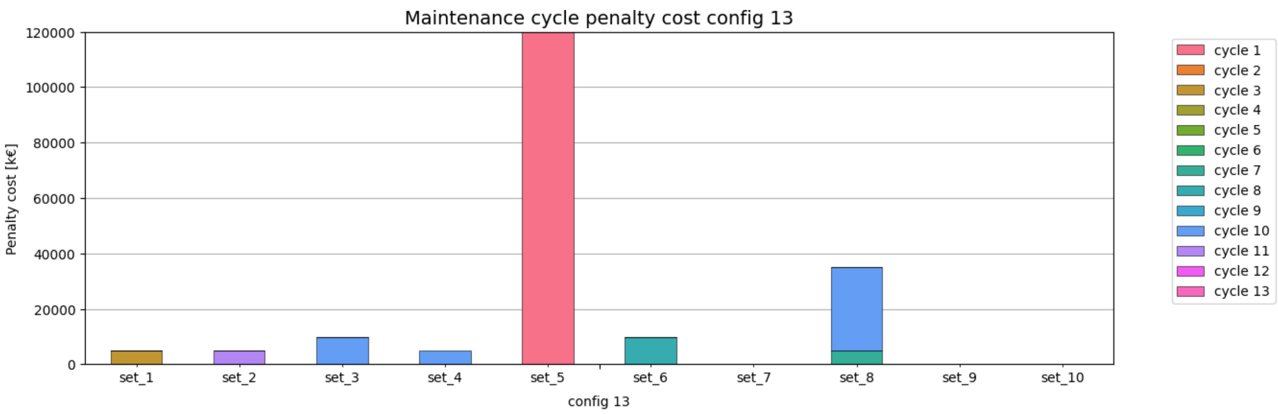
series tasks_per_HLV:	4,	5,	6,	7,	8,	9,	10
series tasks_per_FSV:	10,	15,	20,	25			
series tasks_per_CTV:	80,	100,	120,	140,	160		

Several results of this verification experiment are depicted in Figure 29 and 30. Figure 29 indicates that the value of tasks_per_HLV for the best configuration of this verification experiment is lower compared to the best configuration of the case study. Also, the value for tasks_per_CTV for the best configuration is lower compared to the case study. Figure 30 shows the penalty cost for the best configuration of this verification experiment per set. From a comparison of Figure 17 and 30 can be determined whether the number of days that the maintenance cycles last longer than 60 days has decreased. For the best configuration of this verification experiment, the average penalty cost per set is €19M and, therefore, the total number of days (over the entire planning horizon) per set that a cycle takes longer than 60 days is on average €19M $\div$ 5 M€/day = 3.8 days. For the best configuration of the case study, this is on average €1450k $\div$ 50 k€/day = 29.0 days. As is expected, the average number of days that the maintenance cycles last longer than 60 days has decreased. In Figure 30, it stands out that the penalty cost of cycle one of set five is €120M. This is due to the fact that this cycle takes 84 days, which is equal to the duration of this cycle for the case study. From the output log, it can be seen that one HLV was chartered that had to perform four corrective replacement tasks in this cycle. Two bearings, one gearbox, and one generator had to be replaced which in total approximately takes $2 \cdot 70 + 100 + 81 = 321$ hours (disregarding jack-up and -down time and travel time). When the HLV became available 30 days after the start of the cycle, these maintenance tasks could be performed within 14 days if weather conditions were good. However, the weather conditions were not good and, therefore, the HLV had to postpone the start of several of these maintenance tasks which caused the maintenance cycle to take so long. If instead of one, two HLV had been chartered, the replacement tasks would have been completed earlier and thus the maintenance cycle would have ended earlier. This would have resulted in fewer penalty cost. Since the goal of this verification experiment was to verify the model by analysing the results and not necessarily to find the best configuration for this verification experiment, more simulations with tasks_per_HLV lower than four are not performed. All results of this verification experiment are in line with the expectations.



Configuration:	13	12	8	6	11	7	15	14	4	5	1	10	9	3	2	35	34	31	33	27
avg_cost_per_MWh	12.729	12.950	13.135	13.219	13.220	13.239	13.616	13.623	13.672	13.739	13.914	14.068	14.071	14.164	14.470	15.224	15.944	16.088	16.178	16.472
tasks_per_HLV	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	5
tasks_per_FSV	20	20	15	15	20	15	20	20	10	10	10	15	15	10	10	20	20	20	20	15
tasks_per_CTV	120	100	120	80	80	100	160	140	140	160	80	160	140	120	100	160	140	80	120	100

Figure 29: Model verification: increased penalty cost. Cost per MWh produced, best 20 configurations.



Unit: k€	config 13									
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10
cycle 1	0	0	0	0	120000	0	0	0	0	0
cycle 2	0	0	0	0	0	0	0	0	0	0
cycle 3	5000	0	0	0	0	0	0	0	0	0
cycle 4	0	0	0	0	0	0	0	0	0	0
cycle 5	0	0	0	0	0	0	0	0	0	0
cycle 6	0	0	0	0	0	0	0	0	0	0
cycle 7	0	0	0	0	0	0	0	5000	0	0
cycle 8	0	0	0	0	0	10000	0	0	0	0
cycle 9	0	0	0	0	0	0	0	0	0	0
cycle 10	0	0	10000	5000	0	0	0	30000	0	0
cycle 11	0	5000	0	-	0	0	0	0	0	0
cycle 12	-	0	0	-	0	-	0	0	-	-
cycle 13	-	0	0	-	-	-	0*	-	-	-
total	**5000**	**5000**	**10000**	**5000**	**120000**	**10000**	**0**	**35000**	**0**	**0**

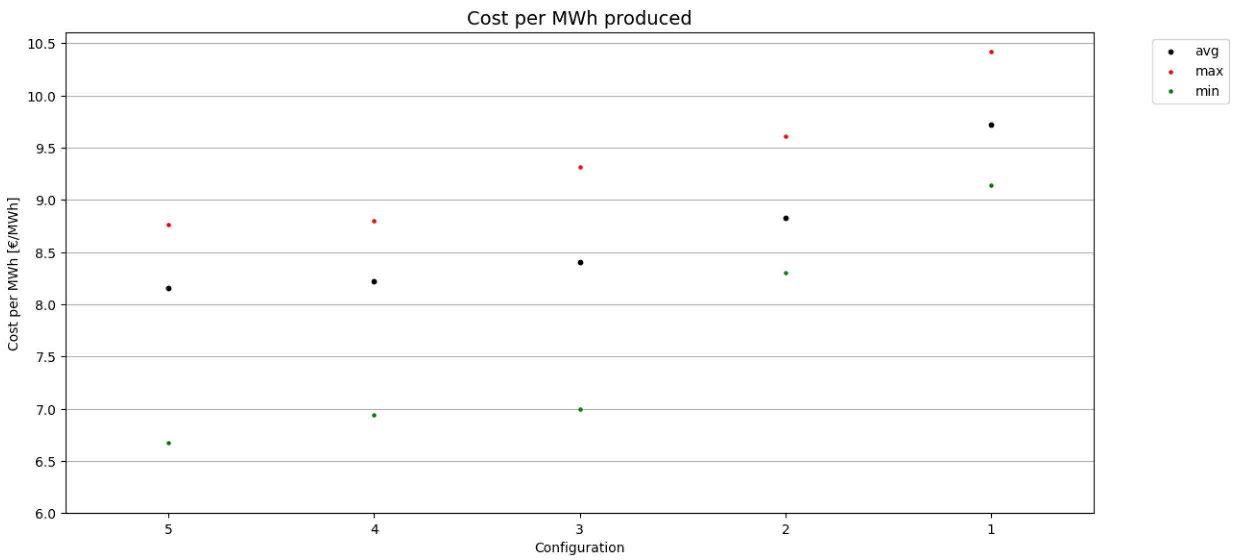
Figure 30: Model verification: increased penalty cost. Maintenance cycle penalty cost. The * in the table indicates that a cycle was still ongoing at the end of the planning horizon.

5.3 Different owned vessel fleet

For this verification experiment, the owned vessel fleet (Table 7) is changed. Whereas for the case study simulations are performed with no owned HLV, no owned FSV, and one owned CTV, the simulations for this verification experiment are performed with no owned HLV, one owned FSV, and one owned CTV. Since an FSV is also owned now, the major repair tasks (tasks for FSV type) can be started earlier in the maintenance cycles. This is due to the fact that the owned FSV is available from the beginning of the cycle, whereas chartered FSVs must be mobilised before they become available. Therefore, it is expected that the best configuration of this verification experiment will have a higher value for the decision variable tasks_per_FSV compared to the best configuration of the case study. Consequently, it is expected that fewer FSVs are chartered throughout the planning horizon. Also, it is expected that the average duration of cycles is shorter compared and that the penalty cost of prolonged maintenance cycles will be lower. Since one FSV is owned, the average €/MWh of this verification experiment should be lower compared to the best configuration of the case study. To verify the expected results, simulations are performed for the following configurations:

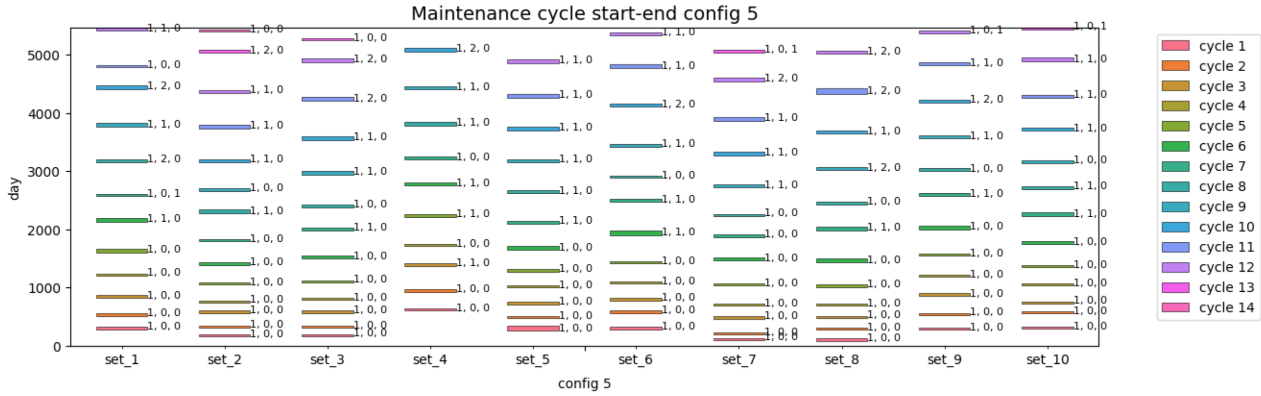
	config 1	config 2	config 3	config 4	config 5
tasks_per_HLV:	9	9	9	9	9
tasks_per_FSV:	10	15	20	25	30
tasks_per_CTV:	140	140	140	140	140

Several results of this verification experiment are depicted in Figure 31 - 33. In Figure 31 can be seen that the best configuration of this verification experiment has a higher value for the decision variable tasks_per_FSV compared to the case study. As expected, the average €/MWh for the best configuration is decreased (from 9.015 to 8.154 €/MWh). Figure 32 shows that for each set fewer FSVs are chartered throughout the planning horizon. It was also expected that the average duration of cycles would decrease and that the average penalty cost would be lower. From Figure 17 and Figure 32 is determined that the average cycle length is decreased from 52.0 to 49.5 days. From Figure 18 and Figure 33 is determined that the average penalty cost is decreased from 14500 to 9050 k€ per set. All results of this verification experiment are in line with the expectations.



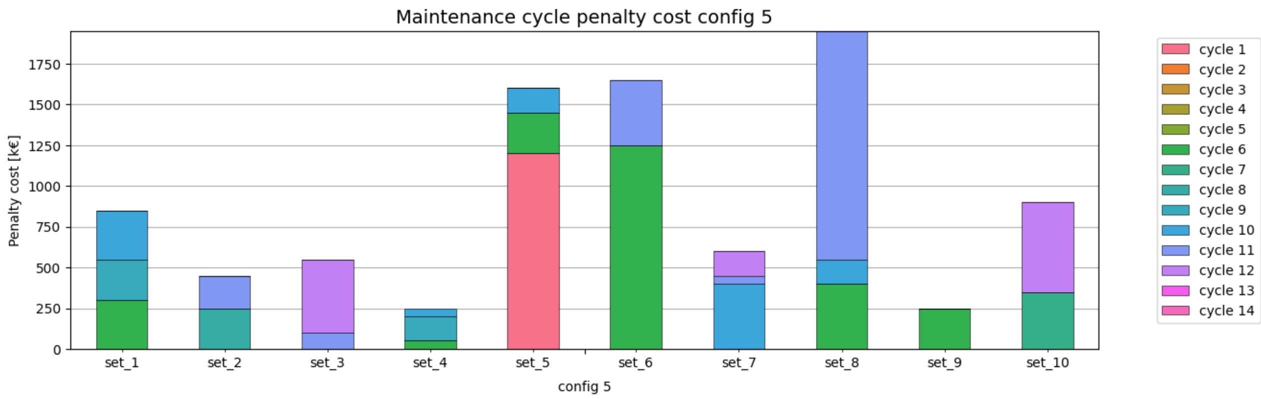
Configuration:	5	4	3	2	1
avg_cost_per_MWh	8.154	8.224	8.408	8.828	9.722
tasks_per_HLV	9	9	9	9	9
tasks_per_FSV	30	25	20	15	10
tasks_per_CTV	140	140	140	140	140

Figure 31: Model verification: different owned vessel fleet. Cost per MWh produced.



Unit: day	config 5									
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10
cycle 1 length	43	35	34	37	84	43	33	43	33	40
cycle 2 length	46	38	41	35	39	51	41	33	37	33
cycle 3 length	56	48	51	47	46	41	36	38	55	35
cycle 4 length	36	38	33	40	33	33	33	34	33	47
cycle 5 length	55	44	36	54	44	42	47	49	42	33
cycle 6 length	66	40	54	61	65	84	53	68	65	54
cycle 7 length	36	40	44	49	46	52	44	56	58	67
cycle 8 length	52	65	41	60	51	39	37	45	55	42
cycle 9 length	65	38	60	63	54	44	55	60	58	43
cycle 10 length	66	50	57	61	63	53	68	63	46	52
cycle 11 length	44	64	62	-	58	68	61	88	57	53
cycle 12 length	55	52	69	-	60	50	63	60	42	71
cycle 13 length	-	56	43	-	-	-	38	-	-	36*
cycle 14 length	-	39	-	-	-	-	-	-	-	-
total	**620**	**647**	**625**	**507**	**643**	**600**	**609**	**637**	**581**	**606**

Figure 32: Model verification: different owned vessel fleet. Maintenance cycle information and vessels charters. The number of started charter periods within each cycle is indicated in text in the plot in the order of HLV, FSV, CTV. The * in the table indicates that a cycle was still ongoing at the end of the planning horizon.



Unit: k€	config 5									
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10
cycle 1	0	0	0	0	1200	0	0	0	0	0
cycle 2	0	0	0	0	0	0	0	0	0	0
cycle 3	0	0	0	0	0	0	0	0	0	0
cycle 4	0	0	0	0	0	0	0	0	0	0
cycle 5	0	0	0	0	0	0	0	0	0	0
cycle 6	300	0	0	50	250	1250	0	400	250	0
cycle 7	0	0	0	0	0	0	0	0	0	350
cycle 8	0	250	0	0	0	0	0	0	0	0
cycle 9	250	0	0	150	0	0	0	0	0	0
cycle 10	300	0	0	50	150	0	400	150	0	0
cycle 11	0	200	100	-	0	400	50	1400	0	0
cycle 12	0	0	450	-	0	0	150	0	0	550
cycle 13	-	0	0	-	-	-	0	-	-	0*
cycle 14	-	0	-	-	-	-	-	-	-	-
total	**850**	**450**	**550**	**250**	**1600**	**1650**	**600**	**1950**	**250**	**900**

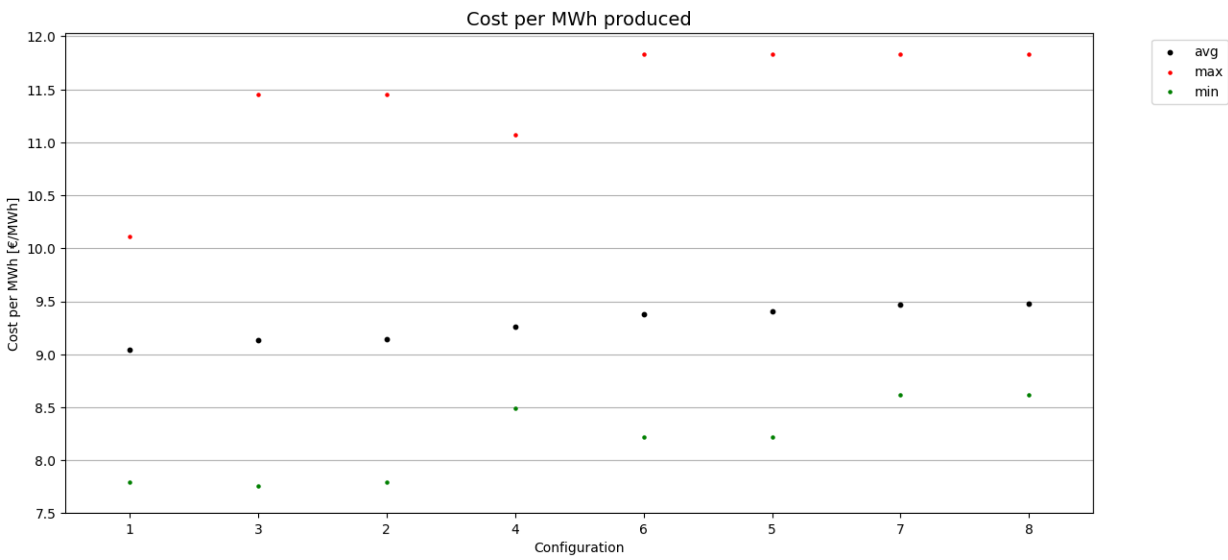
Figure 33: Model verification: different owned vessel fleet. Maintenance cycle penalty cost. The * in the table indicates that a cycle was still ongoing at the end of the planning horizon.

5.4 Fewer teams on board a CTV

For this verification experiment, the number of teams on board a CTV has been halved from four to two. Accordingly, the number of technicians on board a CTV (Table 10 input [4]) has been halved from twelve to six technicians (two teams of three technicians per team) and the maximum number of parallel teams for the CTV (Table 10 input [5]) has been halved from four to two teams. This means that instead of four teams, the CTV is equipped with two teams of technicians who can work on different maintenance tasks simultaneously. Therefore, the CTV type requires more time to complete all its tasks. Since this will likely results in more cycles taking longer than 60 days, the penalty cost will likely be higher for the configuration with tasks_per_HLV=9, tasks_per_FSV=20, and tasks_per_CTV=140 for this verification experiment compared to the case study. Therefore, it is expected that the best configuration of this verification experiment will have a lower value for the decision variable tasks_per_CTV. It is also expected that the average €/MWh is higher due to more chartered CTV. Since CTVs require more time to complete all the minor repair tasks, it is also expected that the CTVs spend less of the available at the base during a cycle (idle_at_base_in_cycle), which can be interpreted as CTVs having a higher utilisation rate. To verify the expected results, simulations are performed for the following configurations:

	config 1	config 2	config 3	config 4	config 5	config 6	config 7	config 8
tasks_per_HLV:	9	9	9	9	9	9	9	9
tasks_per_FSV:	20	20	20	20	20	20	20	20
tasks_per_CTV:	80	90	100	110	120	130	140	150

Several results of this verification experiment are depicted in Figure 34 and 35. The average, maximum, and minimum cost per MWh produced for the eight configurations can be seen in Figure 34, including the decision variable values in the table below the plot. From this can be concluded that, as expected, the best configuration of this verification experiment has a higher value for the decision variable tasks_per_CTV compared to the case study. This implies that more CTVs will be chartered throughout the planning horizon. Moreover, it can be seen that the average €/MWh is higher. Figure 35 shows that the CTV generally spends less time at the base during maintenance cycles compared to the results of the case study (Figure 26). All results of this verification experiment are in line with the expectations.



Configuration:	1	3	2	4	6	5	7	8
avg_cost_per_MWh	9.043	9.135	9.146	9.258	9.379	9.409	9.466	9.474
tasks_per_HLV	9	9	9	9	9	9	9	9
tasks_per_FSV	20	20	20	20	20	20	20	20
tasks_per_CTV	80	100	90	110	130	120	140	150

Figure 34: Model verification: different owned vessel fleet. Cost per MWh produced.

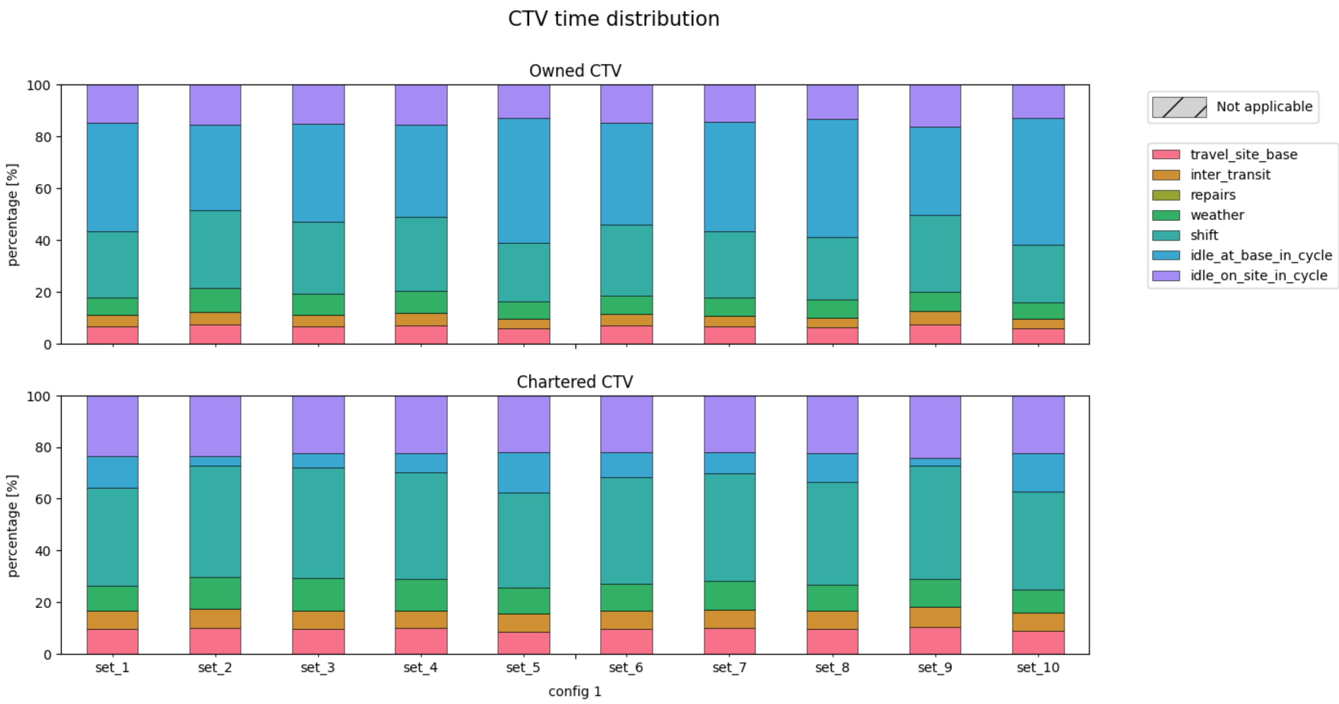


Figure 35: Model verification: different owned vessel fleet. Utilisation of CTV type.

6 Sensitivity analyses

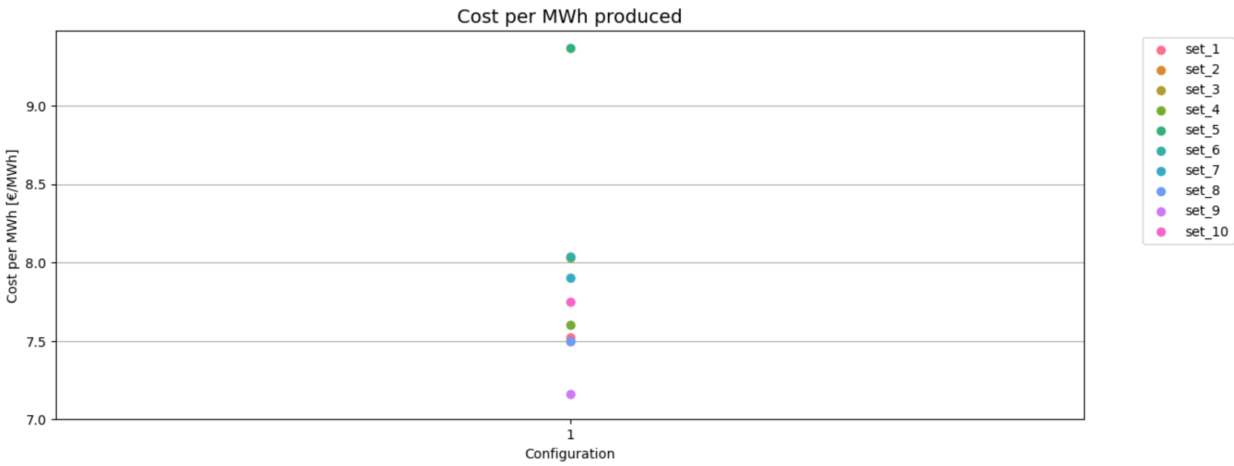
In this section, the results of several sensitivity analyses are discussed. For the sensitivity analysis, an input parameter of the case study inputs is changed to identify the difference in results for the best configuration of the case study. Also, a sensitivity analysis is conducted for which a modeling assumption has been changed. For three of the four sensitivity analyses, the difference in results for the best configuration of the case study is studied (configuration 224 of the second batch: tasks_per_HLV=9, tasks_per_FSV=20, and tasks_per_CTV=140).

It is also possible to do sensitivity analysis to identify if a change in the input would result in a different best configuration (with different values of the decision variables). However, due to a limited amount of available computational power and available time, such kind of sensitivity analysis could not be performed for each sensitivity analysis in the following subsections. Likely, changing inputs would result in a different best configuration. For example, if the mobilisation costs and charter rates of vessels (Table 11 inputs [2-7]) are decreased, the best values of the decision variables will likely be lower compared to those of the case study, such that more vessels will be chartered to complete all maintenance tasks faster and minimize the penalty cost. Another example, if the penalty cost for exceeding the soft time limit of cycles (Table 12 input [9]) is increased, the best values of the decision variables will likely be lower compared to those of the case study, such that a maintenance cycle will less often exceed the soft time limit (Table 12 input [8]). In the following subsections, the results of four sensitivity analyses are discussed.

6.1 Decreased charter length

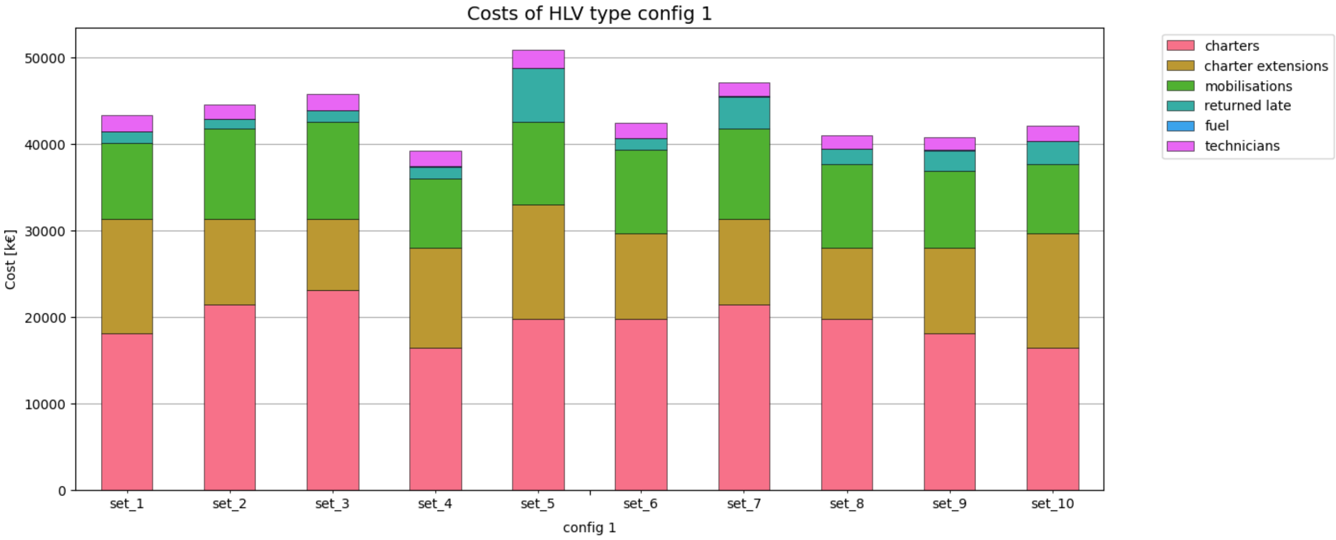
For this sensitivity analysis, the charter lengths (Table 10 input [12]) for each vessel type is decreased by 50%. The charter length for the case study was assumed to be 30 days for each vessel type. The charter length for each vessel type for this sensitivity analysis is 15 days.

Several results of this sensitivity analysis are depicted in Figure 36 - 39. From Figure 36 can be concluded that by decreasing the (minimal) charter length results in a decreased average cost per MWh produced. The average cost per MWh produced is decreased from 9.015 (Figure 10) to 7.837 €/MWh, a reduction of ± 13%. The decreased €/MWh is due to the reduction in total charter cost per vessel type, which can be seen in Figure 37 - 39 (in comparison to Figure 21 - 23). By comparing the results depicted in these figures, it can be concluded that by reducing the charter length by 50% the charter costs decrease and the costs related to charter extensions increase.



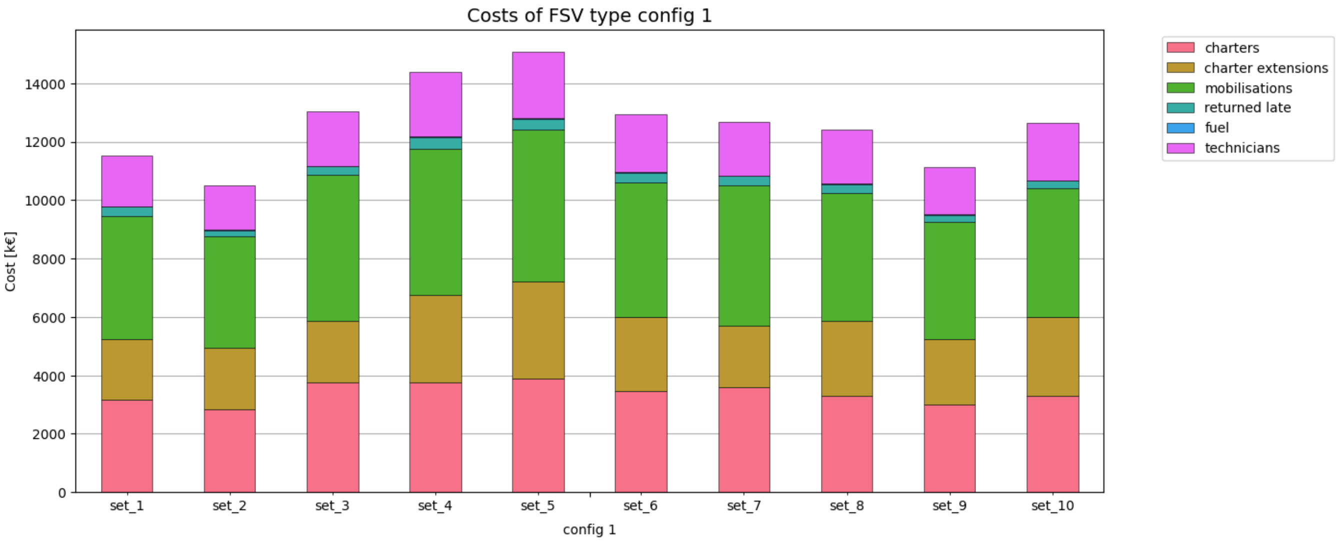
Unit: €/MWh	1
set_1	7.520
set_2	7.500
set_3	8.030
set_4	7.600
set_5	9.370
set_6	8.040
set_7	7.900
set_8	7.500
set_9	7.160
set_10	7.750
avg.	**7.837**

Figure 36: Sensitivity analysis: charter length. Cost per MWh produced, configuration: tasks_per_HLV=9, tasks_per_FSV=20, and tasks_per_CTV=140.



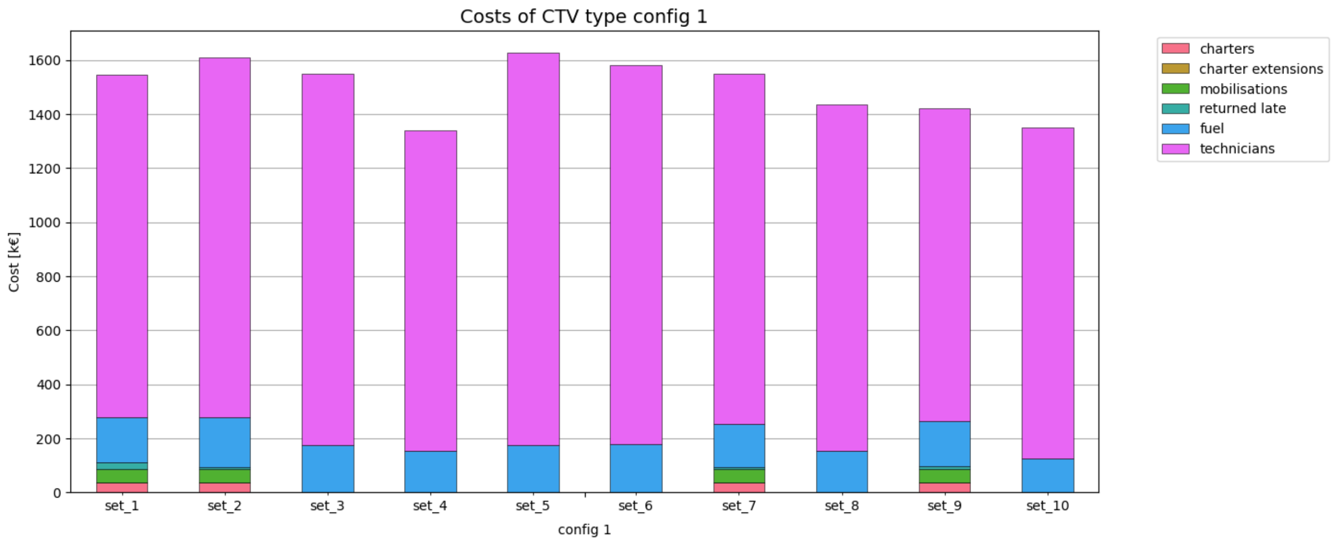
Unit: k€	config 1									
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10
charters	18150.0	21450.0	23100.0	16500.0	19800.0	19800.0	21450.0	19800.0	18150.0	16500.0
charter extensions	13200.0	9900.0	8250.0	11550.0	13200.0	9900.0	9900.0	8250.0	9900.0	13200.0
mobilisations	8800.0	10400.0	11200.0	8000.0	9600.0	9600.0	10400.0	9600.0	8800.0	8000.0
returned late	1320.0	1100.0	1320.0	1320.0	6160.0	1320.0	3740.0	1760.0	2420.0	2640.0
fuel	31.8	31.2	32.2	28.9	35.0	30.2	32.0	28.7	29.4	31.5
technicians	1837.2	1646.3	1850.6	1784.5	2135.1	1819.4	1637.3	1570.6	1476.0	1774.9
total	**43339.0**	**44527.5**	**45752.8**	**39183.3**	**50930.1**	**42469.6**	**47159.3**	**41009.3**	**40775.3**	**42146.4**

Figure 37: Sensitivity analysis: charter length. Costs of HLV type, configuration: tasks_per_HLV=9, tasks_per_FSV=20, and tasks_per_CTV=140.



Unit: k€	config 1									
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10
charters	3150.0	2850.0	3750.0	3750.0	3900.0	3450.0	3600.0	3300.0	3000.0	3300.0
charter extensions	2100.0	2100.0	2100.0	3000.0	3300.0	2550.0	2100.0	2550.0	2250.0	2700.0
mobilisations	4200.0	3800.0	5000.0	5000.0	5200.0	4600.0	4800.0	4400.0	4000.0	4400.0
returned late	320.0	220.0	300.0	400.0	380.0	340.0	320.0	300.0	240.0	260.0
fuel	19.0	16.2	19.2	25.0	24.8	20.9	20.1	20.0	17.9	21.0
technicians	1724.5	1518.7	1855.7	2207.1	2283.8	1983.5	1845.5	1850.4	1630.8	1949.4
total	**11513.5**	**10504.9**	**13024.8**	**14382.1**	**15088.7**	**12944.4**	**12685.6**	**12420.4**	**11138.7**	**12630.5**

Figure 38: Sensitivity analysis: charter length. Costs of FSV type, configuration: tasks_per_HLV=9, tasks_per_FSV=20, and tasks_per_CTV=140.



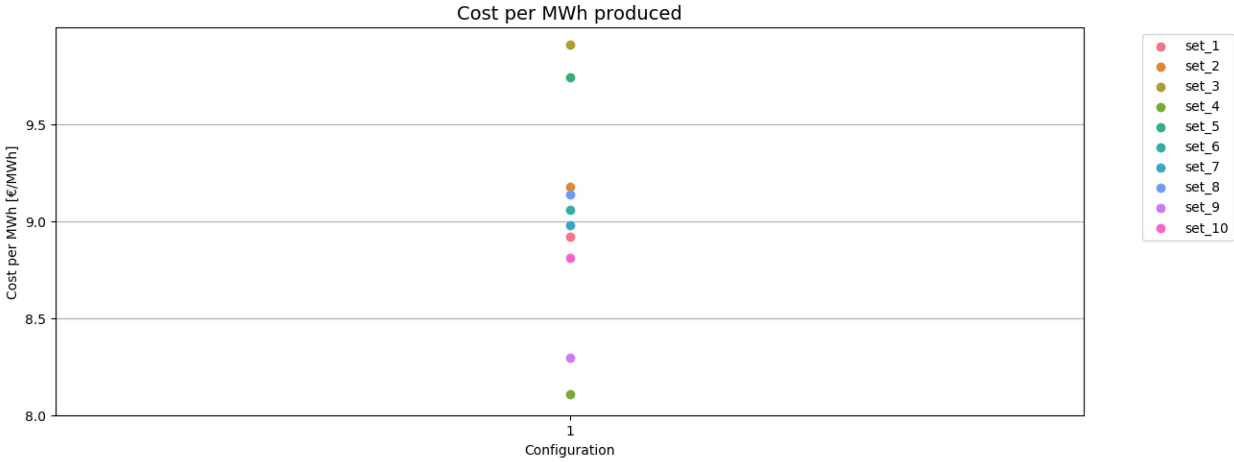
Unit: k€	config 1									
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10
charters	37.5	37.5	0	0	0	0	37.5	0	37.5	0
charter extensions	0	0	0	0	0	0	0	0	0	0
mobilisations	50.0	50.0	0	0	0	0	50.0	0	50.0	0
returned late	25.0	5.0	0	0	0	0	5.0	0	10.0	0
fuel	166.0	185.2	173.3	154.3	173.4	179.1	160.6	152.4	167.3	125.2
technicians	1265.3	1331.1	1375.1	1185.0	1454.7	1401.4	1296.2	1284.5	1156.9	1224.6
total	**1543.8**	**1608.8**	**1548.4**	**1339.3**	**1628.1**	**1580.5**	**1549.3**	**1436.9**	**1421.7**	**1349.8**

Figure 39: Sensitivity analysis: charter length. Costs of CTV type, configuration: tasks_per_HLV=9, tasks_per_FSV=20, and tasks_per_CTV=140.

6.2 Charter only at the start of a cycle

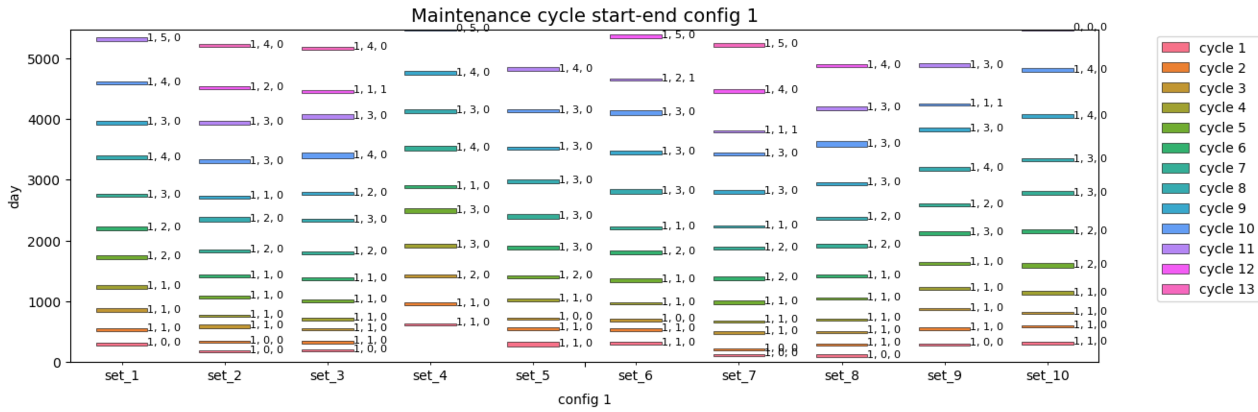
For this sensitivity analysis, simulations are performed in which vessels can only be chartered at the start of the maintenance cycle. To achieve this, the interval between checks to charter during a cycle is set to a large number. Input [6] of Table 12 has been set to 1000 days. This implies that the first check to potentially charter additional vessels is 1000 days after the start of the maintenance cycle. Since maintenance cycles will not take that long, additional vessels are never chartered during the cycle and, hence, vessels are only chartered at the cycle start.

Several results of this sensitivity analysis are depicted in Figure 40 and 41. From a comparison of these two figures with Figure 11 and 17), it can be concluded that the results of this sensitivity analysis are identical to the result of the best configuration (224) of the case study. Therefore, it can be concluded that in the simulations of the best configuration of the case study it was never decided to charter vessels after the start of a cycle.



Unit: €/MWh	1
set_1	8.920
set_2	9.180
set_3	9.910
set_4	8.110
set_5	9.740
set_6	9.060
set_7	8.980
set_8	9.140
set_9	8.300
set_10	8.810
avg.	**9.015**

Figure 40: Sensitivity analysis: charter only at the start of cycles. Cost per MWh produced, configuration: tasks_per_HLV=9, tasks_per_FSV=20, and tasks_per_CTV=140.



Unit: day	config 1									
	set_1	set_2	set_3	set_4	set_5	set_6	set_7	set_8	set_9	set_10
cycle 1 length	43	35	34	37	84	43	33	43	33	40
cycle 2 length	46	38	41	46	49	48	41	33	39	44
cycle 3 length	60	55	45	56	33	40	36	38	41	33
cycle 4 length	54	38	44	57	40	41	33	34	45	69
cycle 5 length	66	37	45	80	47	57	53	43	50	83
cycle 6 length	59	48	44	49	64	60	57	43	57	67
cycle 7 length	57	46	45	70	79	54	58	71	45	59
cycle 8 length	64	71	58	57	61	76	36	48	69	45
cycle 9 length	61	41	56	60	47	53	60	51	60	64
cycle 10 length	46	69	86	23*	54	64	51	86	33	64
cycle 11 length	59	57	72	-	72	43	33	51	70	18*
cycle 12 length	-	59	38	-	-	58	61	59	-	-
cycle 13 length	-	58	51	-	-	-	57	-	-	-
total	**615**	**652**	**659**	**535**	**630**	**637**	**609**	**600**	**542**	**586**

Figure 41: Sensitivity analysis: charter only at the start of cycles. Maintenance cycle information and vessels charters for configuration: tasks_per_HLV=9, tasks_per_FSV=20, and tasks_per_CTV=140.

6.3 Changed priority for vessel allocation

As is described in the section for the modeling assumptions (section 3.4.1.12), the priority for vessel allocation is as follows. First, the model prioritises vessels that are on-site over vessels that are at the base. Second, if there are multiple available vessels on-site, priority is given to those vessels with a greater number of teams already assigned. The priority for vessel allocation was modeled in this manner as it was expected that by prioritising vessels with a greater number of teams already assigned (which only affects the CTV operations, since the other vessel types cannot perform maintenance tasks in parallel) the fuel costs would be minimized. However, after performing the case study it was realised that fuel is saved very occasionally by this approach. The first case when fuel is saved is if the new task is assigned to a CTV that already has a team of technicians working at the same turbine as the turbine of the new task. In that case, the CTV can later pick up two teams at one turbine and, therefore, one less inter-transit travel is required. The second case when fuel is saved is if one less CTV has to travel to the wind farm the next day. Suppose two CTVs are on-site, CTV A with two assigned teams and CTV B with one assigned team, and there is only one unassigned minor repair task that cannot be completed in the current shift. Suppose the team of CTV B finishes its task before the end of the shift. In case the last minor repair task is assigned to CTV A, then, CTV B does not have to travel to the wind farm the next day since none of its teams is assigned to a maintenance task. In case the last minor repair task is assigned to CTV B, then, CTV B must travel to the wind farm the next day to drop off the team that could not finish the last minor repair task in the previous shift. With the order of priority for vessel allocation described in section 3.4.1.12, the last minor repair task will be assigned to CTV A and, therefore, fuel is saved in such cases. The disadvantage of this approach is that it takes a longer time for the CTV type to complete all the maintenance tasks, since it takes longer for the CTV with more teams assigned to deliver and pick up all teams. As the implications of the modeling assumption for the priority of vessel allocation were only realised after performing the case study, the effect of changing this order of priority is included in this sensitivity analysis.

For this sensitivity analysis, the priority for vessel allocation for assigning maintenance tasks is changed as follows. First, the model prioritises vessels that are on-site over vessels that are at the base. Second, if there are multiple available vessels on-site, priority is given to those vessels with fewer teams already assigned. To investigate whether this will result in a different configuration having the lowest cost/MWh, simulations are performed for combinations of the following decision variable values:

series tasks_per_HLV:	8,	9				
series tasks_per_FSV:	0,	10,	15,	20,	25,	30
series tasks_per_CTV:	0,	110,	120,	130,	140,	150

In total, there are $2 \cdot 6 \cdot 6 = 72$ combinations and, hence, there are 72 configurations. For each configuration, ten simulations are performed using the same ten sets as in the case study, resulting in a total of 720 simulations. Compared to the second batch of the case study, fewer configurations are simulated for this sensitivity analysis to reduce the runtime.

Several results of this sensitivity analysis are depicted in Figure 42 and 43. The average, maximum, and minimum cost per MWh produced for all configurations can be seen in Figure 42. The 12 configurations with an average cost per MWh produced of more than 15 €/MWh are configurations with tasks_per_FSV=0. Figure 43 shows the cost per MWh produced for the best 20 configurations, including a table with the decision variable values below the plot. From this figure can be concluded that a different configuration results in the lowest average cost per MWh produced for this sensitivity analysis compared to the case study. Moreover, the average and minimum €/MWh for configuration 68 of this sensitivity analysis are lower compared to the best configuration (224) of the case study. Therefore, the priority for vessel allocation of this sensitivity allocation might be better than the one used for the case study. A more in-depth investigation is needed to determine which modeling assumption for the priority for vessel allocation is better (see the recommendation of item 2 in section 8).

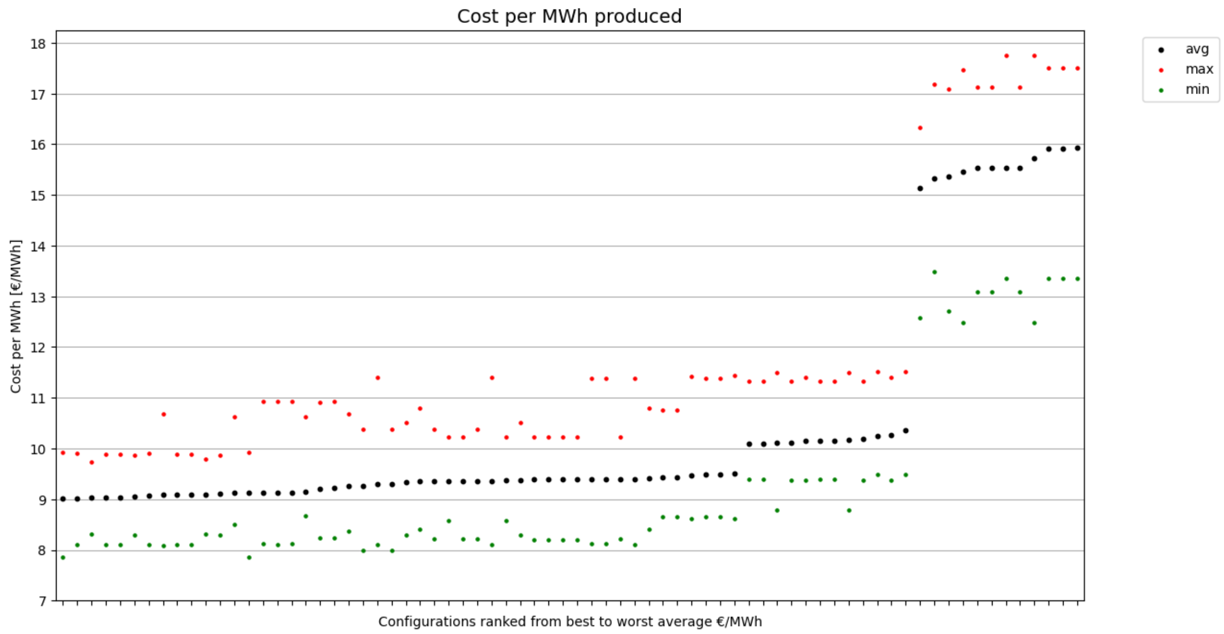
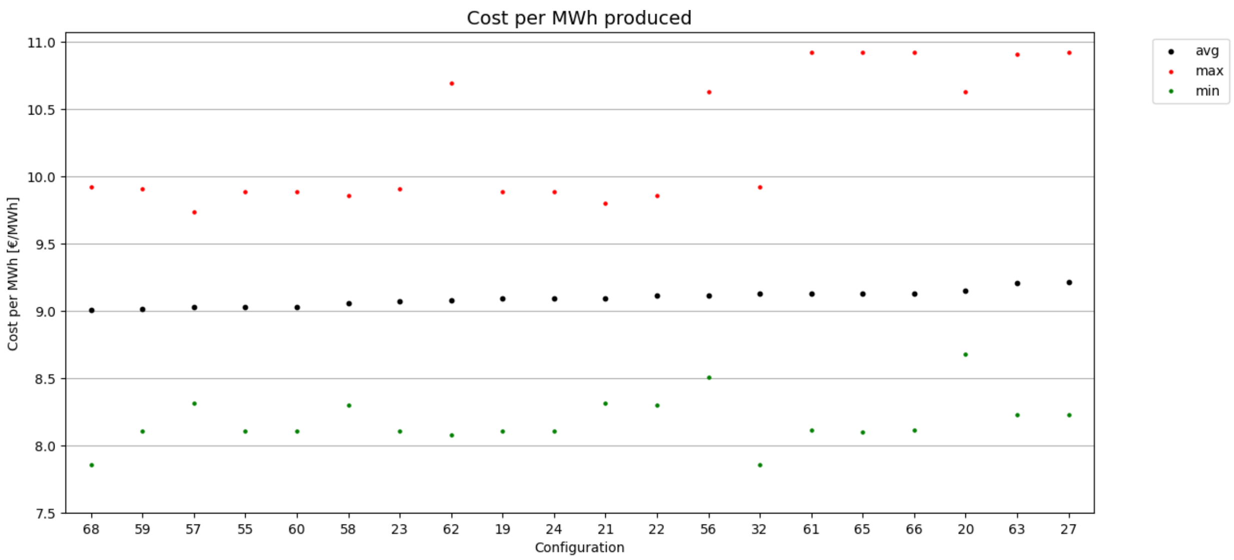


Figure 42: Sensitivity analysis: changed priority for vessel allocation. Cost per MWh produced, all configurations.



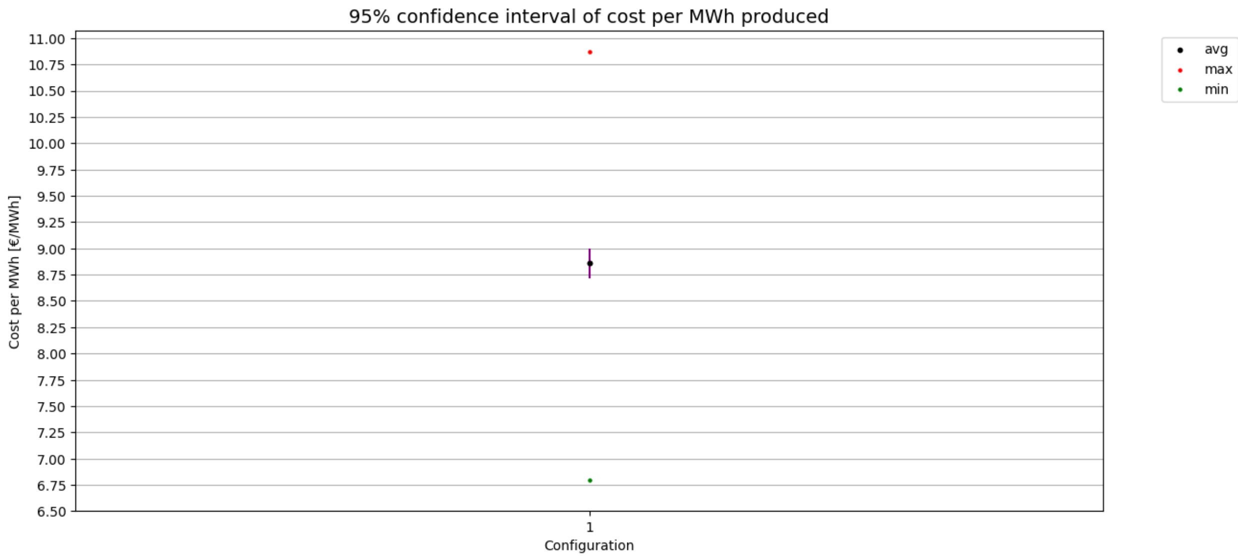
Configuration:	68	59	57	55	60	58	23	62	19	24	21	22	56	32	61	65	66	20	63	27
avg_cost_per_MWh	9.007	9.013	9.029	9.032	9.032	9.056	9.070	9.083	9.091	9.091	9.097	9.113	9.119	9.127	9.131	9.131	9.131	9.155	9.210	9.219
tasks_per_HLV	9	9	9	9	9	9	8	9	8	8	8	8	9	8	9	9	9	8	9	8
tasks_per_FSV	30	20	20	20	20	20	20	25	20	20	20	20	20	30	25	25	25	20	25	25
tasks_per_CTV	110	140	120	0	150	130	140	110	0	150	120	130	110	110	0	140	150	110	120	120

Figure 43: Sensitivity analysis: changed priority for vessel allocation. Cost per MWh produced, best 20 configurations.

6.4 Increased number of sets

For this sensitivity analysis, the number of sets is increased from 10 to 100. It would be interesting to see if this would result in a different configuration with the lowest average cost/MWh. To check this, simulations must be performed for all configurations defined in section 4.2.1, which would result in a total of 56700 simulations (567 configurations · 100 sets). With an average runtime of ± 175 seconds per simulation, 56700 simulations would approximately require 175 sec · 56700 simulations ÷ 10 (since 10 simulations can be performed in parallel) = 276 hours. Thereafter, the results must be calculated. For the second batch of the case study, it required ± 100 seconds per configuration to calculate the results. With 100 sets instead of 10, the time to calculate the results would increase to ± 1000 seconds per configuration. Therefore, the total time to calculate the results would be an additional 1000 sec · 576 configurations ÷ 10 = 16 hours. Therefore, the total computational time would approximately be 276 + 16 = 292 hours. At the time this sensitivity analysis was planned to be performed, there were some issues with the server. Therefore, the simulations for this sensitivity analysis could not be performed. However, the effect of 100 sets on the configuration with tasks_per_HLV=9, tasks_per_FSV=20, and tasks_per_CTV=140 was investigated for this sensitivity analysis.

Several results of this sensitivity analysis are depicted in Figure 44. The 95% confidence interval of the cost/MWh for the best configuration of the case study is [8.619, 9.411] for 10 sets (Figure 13) and [8.718, 8.995] for 100 sets (Figure 44). As is expected, the 95% confidence interval of cost/MWh for 100 sets is narrower compared to 10 sets. As can be concluded from the comparison of Figure 10 and 44, the average cost/MWh is reduced from 9.015 €/MWh for 10 sets to 8.857 €/MWh for 100 sets. Since the first ten of the 100 sets are identical to the ten sets of the case study, the maximum cost/MWh for the 100 sets can only be equal to or higher than the maximum cost/MWh of the same configuration of the case study and vice versa for the minimum cost/MWh. It can be concluded that the maximum and minimum cost/MWh are higher and lower, respectively, for 100 sets compared to 10 sets.



Configuration:	1
avg_cost_per_MWh	8.857
tasks_per_HLV	9
tasks_per_FSV	20
tasks_per_CTV	140

Figure 44: Sensitivity analysis: increase number of sets. 95% confidence interval, average, maximum and minimum cost/MWh for configuration: tasks_per_HLV=9, tasks_per_FSV=20, and tasks_per_CTV=140.

7 Concluding remarks

In this research, a simulation model is introduced to optimize the fleet management decision for the maintenance of offshore wind farms. In the literature, this problem is often referred to as the fleet size and mix problem. The determination of an optimal vessel chartering strategy is essential to reduce the LCOE of offshore wind energy since the cost of vessels to perform maintenance at OWTs is the largest part of the total O&M costs. A simulation method was preferred over an exact method for several reasons. First, the O&M activities can be modeled more realistically with a simulation model compared to an exact model, as a simulation model can better deal with information to be revealed over time (a rolling time horizon). Secondly, the performance of different fleets under different conditions can be analysed better with a simulation model as an exact model prescribes only one outcome. Third, although finding the best solution for the objective function is only guaranteed with an exact model, it is expected that the best solution with a simulation model can be found anyway as long as a sufficient number of simulations are performed. Fourth, simulation models are publicly not available while exact models are. Therefore, developing a simulation model fills a gap but can be more challenging since fewer examples are available compared to exact models.

The simulation model is developed for an age-based maintenance strategy, that was given as input for this research assignment. In the developed model, uncertainties related to component failures and weather conditions are taken into account. Several types of maintenance activities are considered: minor repair, major repair, preventive replacement, and corrective replacement, each of which must be performed by a specific vessel type. The O&M activities are simulated over a user-defined planning horizon of several years (or wind farm's lifetime) to optimize the fleet management decisions in the long term. The model is developed in such a manner that the inputs of the model can be changed easily. The model outputs make it possible to assess the consequences of different decisions, whereby the user can decide which key performance indicators to use.

How the developed methodology can be used to support fleet management decisions is illustrated by a case study. The model has been verified by several verification experiments and several sensitivity analyses have been performed. As was concluded in one of the sensitivity analyses, what is identified as the best values of the decision variables may change if the modeling assumption regarding the priority for vessel allocation is changed. Besides a recommendation to further study which modeling assumption regarding the priority for vessel allocation is better, several recommendations for features that can be added to the model are listed in the section 8.

The four modeling approaches that, according to (Dinwoodie et al., 2015), have a large effect on the simulation results are accounted for in the model as follows. First, regarding the possibility to perform parallel maintenance tasks in a shift: multiple vessels can be in the offshore wind farm at the same time and, additionally, the number of teams of a CTV that can work on different tasks simultaneously is an input of the simulation model. Second, the modeling approach of failures was part of the given maintenance strategy (outside the scope of this research). Third, the possibility to assign maintenance tasks to vessels that are offshore is captured in the modeling assumption of the priority for vessel allocation. The model prioritises a vessel that is offshore over a vessel that is at the base when a new task has to be assigned. Fourth, the modeling approach of chartering HLVs is in accordance with the most common approach in the literature of fleet size and mix optimization for offshore wind farm maintenance, meaning that HLVs are chartered for a fixed minimum length instead of a variable (not known in advance) length required to complete all tasks.

The developed methodology can be used to optimize fleet management decisions for a given maintenance strategy and, in addition, the consequences of various decisions can be evaluated since the model predicts the O&M costs and wind farm power production.

8 Recommendations

There are many features that can be added to the model, a list of recommendations is given below:

1. Make the charter length Table 10 input [12] (and extend charter period length, Table 10 input [13]) a decision variable or dynamic based on the number of tasks to be performed.

2. Further investigate which modeling assumption regarding the priority for vessel allocation is better: the modeling assumption of the current model version (section 3.4.1.12) or the modeling assumption described in the sensitivity analysis in section 6.3.

3. Include a heuristic to automatically find the best values of the decision variables. All simulation models referenced in section 2.2.2 are not included with an optimization algorithm to automatically find the best values of the decision variables. However, a heuristic can have added value to the model, since a heuristic may find the best configurations with fewer simulations compared to manually defining and analysing the configurations and, hence, reduce computational time. On the other hand, using a heuristic has several drawbacks. Since many configurations can have the same results (see section 4.1.3 and section 4.2.3), a heuristic method may have difficulties escaping such local optima. Also, quite different values of the decision variables can result in very similar values of the key performance indicator. With human analysis, these local optima can be compared by other performance indicators (such as risk versus benefit analysis, the accuracy of a configuration, etc.) quite easily, whereas this is more difficult for a heuristic (and to develop such a heuristic can be quite complicated.

4. Include limited (and/or seasonal) availability of vessels and/or technicians.

5. Include stochastic vessel charter rates, mobilisation cost, and/or mobilisation time.

6. Include seasonal effects on weather conditions. Also, consider seasonal effects on weather conditions in the maintenance strategy for the start of maintenance cycles (outside the scope of this research assignment). For this maintenance strategy, a maintenance cycle can start any time of the year without considering the seasons, while in practice it may not make sense (or be possible) to start a cycle in the winter season (harsh weather conditions). Considering the seasonal effect on weather conditions in this model only makes sense if it is also considered in the maintenance strategy (start of maintenance cycle).

7. Include a correlation between wave height and wind speed conditions. In this model version, the wave height and wind speed are not correlated.

8. Include spare part availability and logistics related to spare parts, for example, by explicitly modeling the delivery of spare parts to vessels that are offshore for long periods of time.

9. Include dynamic and/or stochastic electricity prices throughout the planning horizon.

10. Include weather-dependent vessel travel speeds as in Dalgic et al. (2015c). In this model version, the vessel travel speeds are assumed to be constant. In practice, the weather conditions affect the travel speed of a vessel and, therefore, the travel time between base and site and the inter-transit time between turbines.

11. Include an acclimatisation time for technicians after transits and breaks for technicians during work. In this model version, it is assumed that teams of technicians of a vessel can start working immediately after they arrive on-site. In practice, for example, the effect of sea sickness may limit the immediate start of maintenance tasks. Also, technicians need breaks during their work, which is currently not modeled explicitly. It can be assumed that the time of breaks is captured within the required time for maintenance tasks. Therefore, if the user of the model wants to take into account the time of breaks for technicians, the user has to be aware that breaks are not modeled explicitly and define the required time for maintenance tasks accordingly.

12. Include a user input for the preferred key performance indicator(s) to sort the configurations. In this model version, the configurations of a batch are automatically sorted from lowest to highest average cost/MWh. However, the user may want to sort the configurations according to a different metric, for example, the lowest maximum cost/MWh, lowest average total cost, lowest average penalty cost, highest accuracy, etc.

13. Extend the model with mothership concepts (see Dalgic et al. (2015b) for mothership concepts).

14. Extend the model such that in case of extreme weather conditions, vessels that can stay offshore for several shifts must return to base. In this model version, the HLV and FSV type can stay offshore in any weather condition. This is a common modeling approach in the literature, but may not be reasonable in practice.

15. Extend the model such that maintenance activities for multiple offshore wind farms can be simulated. In this model version, only one wind farm can be considered. However, a wind farm owner may own multiple wind farms in which case it could be beneficial to perform maintenance tasks requiring a HLV in multiple wind farms with one owned or chartered HLV.

16. Extend the model such that Table 10 input [5] for the HLV and/or FSV can be defined by the user. In this model version, Table 10 input [5] for the HLV and FSV cannot be changed. However, if possible in practice, it may be be advantageous if, while the HLV is working on a replacement task, another team of the HLV can simultaneously work on a minor/major repair task on the same turbine. Similarly, if possible in practice, it may be be advantageous if, while the FSV is working on a major repair task, another team of the FSV can simultaneously work on a major/minor repair task on the same turbine. In this manner, the fact that a vessel is working at a turbine is exploited by taking the opportunity to perform multiple maintenance tasks at the same time.

17. Extend the model and make an input that can be set to 'Yes' or 'No' to allow or restrict the access of other vessels to a turbine if another vessel (or team) is already working on that same turbine. In this model version, an FSV and a CTV have access to an OWT while a HLV is working at that OWT. This may not be possible/desirable due to safety reasons.

18. Extend the model such that the user can specify the prioritisation of maintenance tasks and/or vessel allocation.

19. Extend the model such that the inter-transit time depends on the origin and destination turbine. This can be done by allowing the user to input an $n \times n$ distance matrix between turbines (n: number of number turbines within the wind farm). Then, the inter-transit time between turbines can be calculated based on the distance to be traveled and vessel travel speed. In this model version, one inter-transit time is assumed per vessel type that corresponds to the average inter-transit time per vessel type.

20. Instead of prioritising maintenance tasks (per maintenance type) based on the age of components, extend the model with a decision logic to perform maintenance tasks in such order that the routing of vessels can be improved (routing optimization). This is only useful if the average inter-transit time is replaced by an inter-transit time that depends on the origin and destination turbine (see the recommendation above for an $n \times n$ distance matrix).

21. Extend the model such that the minimum working window for the HLV (Table 10 input [3]) can be defined by the user. In this model version, only the minimum working window for the FSV and CTV can be defined by the user. The minimum working window for the HLV cannot be changed and is equal to the required time for the maintenance task (which depends on the maintenance type and component).

22. Extend the model such that the characteristics and constraints for each vessel type (Table 9) can be defined by the user. In this model version, these cannot be changed.

23. Extend the model such that it is possible to buy vessels during the planning horizon. In this model version, it is only possible to define the owned (already bought) vessels before starting the simulation. The model could be extended with user inputs and/or decision variables to buy vessels at the start of the simulation and/or throughout the simulation.

24. Extend the model such that the user can input characteristics for each wind turbine in the wind farm separately. A wind farm may consist of turbines with different characteristics. In this model version, only a (single) homogeneous wind farm can be used.

25. Extend the file that generates figures such that the results of simulations with many sets can be visualized better. Currently, figures that depict the results of a particular configuration per set (for example Figure 17), can only properly visualize the results if the number of sets is not too big (like 20 or less), otherwise, the results do not fit into the figure. This can be solved, for example, if the number of sets to show in the figure can be defined or by showing average results (which makes the information less detailed and less useful for comparisons).

26. Consider changing some details of the maintenance strategy (and modify the simulation model accordingly). First, the use of a penalty cost for cycles exceeding 60 days can be questioned since such an artificial penalty does not exist in practice. Therefore, it is difficult to determine a reasonable and good value for the penalty cost. Second, why should cycles not take longer than 60 days? This can result in chartering expensive vessels just to finish a cycle before 60 days. Third, must the maintenance activities of all vessel types be performed exclusively in cycles? Sperstad et al. (2016) concluded that the interaction between CTV fleet optimization and HLV campaign optimization is not very related and, therefore, can be optimized separately. For example, it may be better to perform repair tasks during the summer months since the wind farm produces less electricity during these months and, thus, the cost of downtime is lower during the summer months. On the other hand, it may be better to perform preventive and corrective replacement tasks as soon as possible after they occur. Fourth, as mentioned in item 6, consider taking into account the seasons for the conditions to start maintenance cycles. For this maintenance strategy, the start of a maintenance cycle is random (since component lifetime is random). However, due to harsh weather conditions, it may not make sense or be possible to start a maintenance cycle in certain seasons.

27. Consider a correlation between the lifetime (failure rate) of components and environmental conditions (wind speed). Although the lifetime (failure rate) of components is specified outside the scope of this research assignment (see section 3.1), the model could be included with a correlation between the lifetime of components and wind speed (usage load of the turbine).

28. In this model version, if a turbine stops operating (during maintenance work on the turbine or if a turbine component has failed) all the turbine components stop aging. However, not all components may stop aging completely. Even when the turbine is not in operation, the components may still suffer from severe weather conditions (high wind speed, high wave heights, corrosion).

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