Design space exploration of Mother-Daughter Concepts

for Far Offshore Wind Farm O&M

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RENEWABLE ENERGY

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Design space exploration of Mother-Daughter Concepts

for Far Offshore Wind Farm O&M

By

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Preface

“I want to design ships” was my second answer to the question: “What do you want to be when you grow up?”, when I was 6. The first answer was that I wanted to drive a digger because it looked so cool when they were redoing the street in front of my school. I however had no reasoning for why I wanted to design ships. I only found those reasons when I applied to the bachelor in Rotterdam and through learning the craft. Understanding the purpose of a vessel and then finding the best design that can fulfill that purpose has since captivated me.

This thesis topic therefore really appealed to me. I had to talk to a lot of people within the company to really understand the offshore wind operations and maintenance business and understand the challenges in this field. This led me to people all around the world and taught me some valuable lessons in information gathering from these types of sources. Translating this information into a model to determine optimum design characteristics is something I have been interested in since I saw some examples of this in Finland 4 years ago. I am therefore grateful for this opportunity and quite proud of the model that I have delivered to the company.

This thesis topic is however not exactly the topic for which I came to Siemens Gamesa. The scope of the original topic was much smaller but keeping a wide view and an open mind transformed it into a more useful topic for the company and an even more interesting one for me. The guidance of Rene has definitely helped with this due to its focus on facilitating this type of thinking, which I personally really liked. The weekly out-of-the-box solutions I had to come up with are a great example of this. The first few weeks were a bit tough but once I got the hang of it they were really quite fun and always led to interesting conversations. I want to thank you Rene for this great guidance. Sophia, I also want to thank you. Having you as my sparring partner and your daily supervision has really elevated my work. The last but not least of the people who have guided me during my thesis, Austin, thank you for linking me to Siemens Gamesa and your feedback throughout this project.

Additionally, I would like to thank my friends and family for their support, interest, and escape they provided for me to switch off my thesis brain and relax. I would specifically like to express my appreciation to my two friends with whom I have sailed this course together. We have shared our passion throughout the last 7 years and I am sure we will continue for many years to come. It has been a true pleasure.

I hope you enjoy reading this thesis.

G.C.A. Uppenkamp
Delft, April 2024

Abstract

Offshore wind farms are increasing in size and moving further from shore. Service operation vessels (SOVs) are used for offshore wind operation and maintenance (O&M) at these large far offshore sites. These large vessels typically have a smaller daughter craft (DC) on board that can assist them. This DC is however too small to provide the seakeeping capabilities needed at most far offshore sites, causing it to become essentially unusable. Previous studies at Siemens Gamesa Renewable Energy (SGRE) have looked into improving the capabilities of the DC while considering the constraints of the SOV, this was deemed insufficiently possible by Brans (2021). The second study looked at increasing the size of the DC, which saw significant improvements (Kamerbeek, 2022).

The work of Kamerbeek (2022) however raises new questions such as what is the optimum number of these larger DCs? Would another type of craft serve as a better mothership or DC? Is having the mothership perform maintenance the most efficient? SGRE is therefore interested in exploring mother-daughter concepts to perform offshore wind farm O&M activities at large far offshore wind farms, to see if these can outperform the status quo. A mothership is the home of the technicians offshore and the daughters are the craft that bring the technicians from the mothership to and from the turbines. The main research question is therefore:

What method can best be used to explore the design-space of mother-daughter concepts for offshore wind farm O&M?

This research first focuses on understanding offshore wind farm O&M and finding the most important restrictions and challenges that need to be taken into account within a model. This has been done through a literature review and discussions with experts from SGRE. The work then focuses on selecting a modeling method and explaining the proposed method. This method is validated using a comparison with a real-life wind farm. A case study is done at the end using a dummy wind farm to demonstrate the workings of the method.

The method uses a discrete-event simulation that simulates the transport of technicians to and from the turbines to estimate the performance of the concepts. Any wind farm, turbine failure rates, or fleet can be inserted into the model for analysis to ensure a wide range of applications. The performance of the fleets is assessed based on the estimated downtime/availability and emission estimates that the model produces. The financial and technical feasibility should be evaluated in the next stage when a selection of promising solutions has been made based on this first logistical analysis of the fleets. The visits are planned within the model based on the weather conditions, number of available technicians, craft availability, and the evacuation requirement.

The design space of mother-daughter concepts should be explored by running the model using the exploratory set of fleet configurations and inputting various wind farm layouts with varying realistic visit agendas and weather conditions. The output of each of these cases should then be analyzed by dividing all the fleet configurations into groups based on the craft each fleet contains. This grouping allows the performance of each type of fleet to be compared to one another, while the performance difference within the groups shows the effects of different transfer limits. The analysis should then focus on identifying cross-over points between different configurations and on selecting specific fleets based on performance and expected configuration cost.

Contents

List of Figures

List of Tables

Nomenclature

AMER	North, Central, and South America
APAC	Asia-Pacific
B2W	Bring to Work
CAPEX	Capital Expendatures
CSOV	Construction/Commissioning Service Operation Vessel
CTV	Crew Transfer Vessel
DC	Daughter Craft
DES	Discrete Event Simulation
EMEA	Europe, Middle East, and Africa
EPW	End Plannable Window
GW	Giga Watt
Hs	Significant wave height
HVAC	Heating Ventilation and Air Conditioning
LAT	Lowest Astronomical Tide
MDO	Marine Diesel Oil
MW	Mega Watt
O&M	Operation and Maintenance
OEM	Original Equipment Manufacturer
SATV	Service Accommodation Transfer Vessel
SES	Surface Effect Ship
SGRE	Siemens Gamesa Renewable Energy
SOV	Service Operation Vessel
SPW	Start Plannable Window
SWATH	Small Waterplane Area Twin Hull
TP	Transition Piece
W2W	Walk to Work

1 Introduction

This report is the master's thesis to obtain a master of science degree in marine technology at the TU Delft. This chapter will discuss the background of the problem in section 1.1 and the research gap in section 1.2. The problem statement and research objective are discussed in section 1.3 and 1.4 followed by a demarcation of the scope of this thesis in section 1.5. The main research question and sub-questions are presented in section 1.6 and the scientific and societal relevance is discussed in 1.7. This chapter concludes with a chapter outline.

1.1 Background

This thesis is written in collaboration with Siemens Gamesa Renewable Energy (SGRE). SGRE is the largest supplier of offshore wind turbines worldwide (Wood Mackenzie, 2023) and is therefore concerned with the design, manufacturing, installation, and maintenance of wind turbines. The department concerned with offshore maintenance logistics has had two previous students perform a master's thesis in this line of reasoning (Brans, 2021; Kamerbeek, 2022). This thesis is a continuation of the ideas behind these previous theses.

Offshore wind turbines and wind farms are increasing in size and are moving further from shore (Wood Mackenzie, 2023). Service operation vessels (SOVs) are used to perform the operation and maintenance (O&M) activities at these large far offshore wind farms. These vessels typically have a small daugthercraft (DC) that can assist the SOV. Figure 1.1 shows a DC stored on an SOV.

The seakeeping capabilities of these DC are however severely limited due to their size. The practical transfer limit for transferring technicians from the DC to a turbine is typically around 1m significant wave height (Hs). The average significant wave height in the North Sea, an area where a significant portion of these large far offshore wind farms are located, can be around 1.6m Hs at far offshore sited during the summer (MetOceanView, n.d.).

Figure 1.1: Daughter craft (adapted from (Ulstein, 2023))

This deficiency of the SOV's DC, sparked the interest of SGRE to research better alternatives. The first study by Brans (2021) focused on improving the seakeeping capabilities of the DC considering the constraints of existing SOVs. This study concluded that the seakeeping capabilities of a DC can be improved but not to the level required to be significantly useful. A follow-up study by Kamerbeek (2022) looked at using an enlarged DC to assist the SOV at far offshore sites. The performance of three storage methods were analyzed: storing the enlarged DC onboard the SOV; towing the enlarged DC with the SOV and mooring the enlarged DC to buoys in the wind farm while waiting for work. This study concluded that all three options outperformed the current SOV with a conventional DC but that the enlarged DC stored onboard the SOV was the best option. The work of Kamerbeek (2022) however raises new questions such as what is the optimum number of these larger DCs? Would another type of craft serve as a better mothership or DC? Is having the mothership perform maintenance the most efficient?

SGRE is therefore interested in exploring mother-daughter concepts to perform offshore wind farm O&M activities at large far offshore wind farms, to see if these can outperform the status quo.

A mother-daughter concept is defined as a concept consisting of a mothership and (multiple) DCs. A DC is seen as a craft that receives technicians from the mothership and works in the offshore wind farm. The mothership (which can also be a fixed offshore base) is the home of the technicians while in the wind farm. It can in most cases also harbor the DC so it does not have to return to port during adverse weather conditions.

1.2 Research Gap

There is extensive literature on fleet optimization for offshore wind farm O&M. The fleets in these studies usually only consist of maintenance craft that are already in use today. The only alternative vessel concepts that are proposed in literature are motherships that operate in a similar way as described in the previous section. These few concepts differ significantly and they appear somewhat randomly chosen. Using a structured method to explore the design-space of mother-daughter concept has therefore not been done in literature. The case study wind farms that are used in literature to evaluate these concepts are also either relatively small or use older turbines that have smaller inter-turbine distances which make it less likely that a mother-daughter concept will outperform the status quo. The use of helicopters in offshore wind farm O&M is currently suboptimal according to experts and has not seen significant attention in literature. This thesis will therefore also include the use of helicopters in the mother-daughter concepts.

1.3 Problem Statement

Wind farms and turbines are increasing in size and are moving further offshore where environmental conditions worsen. An SOV with a DC is normally used to perform O&M activities at these types of farms. The DC's seakeeping capabilities are however insufficient to be a useful asset at these new sites and this limits the effectiveness of the complete system. Studies to enhance the capabilities of the DC have been performed and concluded that the DC needs to increase in size to increase the capabilities to the desired level (Brans, 2021). Increasing the size of the DC might then enable it to play a more integral part in the O&M activities. It is therefore unclear if simply increasing the size of the DC results in an optimal solution.

1.4 Research Objective

The objective is to enable SGRE to explore a large number of different mother-daughter concepts and determine what the best few concepts are for a variety of offshore wind farms. These concepts can then be worked out and researched further in future work. The ultimate goal is to find out if a mother-daughter concept could perform better than the status quo at these far offshore wind farms. This can however not be done in this thesis because this would require the sharing of confidential data. This thesis will therefore develop a method that can be used to explore the design-space of mother-daughter concepts.

1.5 Scope

This thesis will only evaluate mother-daughter concepts because this is the logical next step based on the previous work and is the most logical type of concept with the most potential to outperform the status quo. Most, if not all, marine-based fleet compositions of currently existing O&M craft have been researched, operationally considered, or are already used. A new marine-based concept that is dissimilar to all other currently operating craft would be a large surface ship that would operate from an onshore base. This type of vessel would however likely operate similarly to an SOV in the wind farm but would have to transit to and from the wind farm every 12 hours, which is less efficient than an SOV or mothership. This type of vessel would become an SOV or mothership-type craft if it would be able to accommodate technicians outside of their working hours. Submarines could also be considered but is deemed too unlikely to be cost-efficient compared to the mother-daughter concepts. The evaluation of the use of helicopters in offshore wind O&M is also included in this thesis. Helicopters will be incorporated into the mother-daughter concepts as DC. Considering other airborne concepts such as an airborne base for helicopters is deemed not likely to be able to compete with the marine-based options based on cost-effectiveness and are therfore not considered in this study.

The method developed in this thesis should be possible to apply to any site around the world. The method will focus on the maintenance craft and the transportation of technicians to, from, and within the wind farm since that is the most crucial part for these concepts. The transportation, storage, and stock levels of parts are not the focus of this thesis and will not be modeled. Optimizing the routing of the maintenance craft is also not the focus of this thesis but the routing of the craft will be part of the modeling. The routes will be created in a simple and pragmatic way. Additionally, the aim of this thesis is to come up with a new maintenance craft concepts, so specific, existing craft will not be used as starting points or definitive options to use.

1.6 Research Questions

Main research question:

What method can best be used to explore the design-space of mother-daughter concepts for offshore wind farm O&M?

Sub-questions:

1. What maintenance needs to be performed at offshore wind farms and how will this develop in the future? (chapter 2)
2. How will offshore wind farms develop in the future? (chapter 3)
3. Which craft are involved in offshore wind farm maintenance and what mother-daughter concepts are discussed in literature? (chapter 4)
4. What modeling method can best be used to estimate the performance of the concepts? (chapter 5)
5. How accurately can the method predict the performance of the concepts? (chapter 6)
6. How sensitive is the model to input changes? (chapter 7)
7. Which new fleet configurations show promising performance based on the results of a case study considering a potential future wind farm? (chapter 8)

1.7 Scientific and Societal Relevance

This thesis is the first to explore the design-space of mother-daughter concepts for far offshore wind farm O&M. Other studies have evaluated some specific mother-daughter concepts, as will be discussed in chapter 4. It is however not obvious if these concepts are optimal solutions. This research will also not limit itself to currently operating craft but will purposely describe the concepts in an abstract manner. In order to purely assess the logistical performance of the concepts. The aim is to find a concept that performs better than the current solutions and could eventually be more cost-effective. The method proposed in this thesis can be used to decide if a new mother-daughter concept would be useful to develop for far offshore wind farm O&M. In addition, the model that will be made could potentially also be used to assess the performance of other currently existing fleets.

This thesis is driven by the need to reduce the cost of electricity originating from offshore wind farms and increase the profitability of these farms. The new concepts that will be considered in this work could reduce the costs of producing electricity at offshore wind farms if they prove to be more efficient. This is important to make it more appealing and competitive in the energy markets. In turn, accelerating the energy transition and helping society to reach its climate goals.

1.8 Chapter Outline

Chapter 2 introduces what maintenance needs to be performed by turbine suppliers, and this will develop into the future. Chapter 3 discusses how offshore wind farms will develop into the future and how this varies between floating and non-floating wind farms and between regions. Chapter 4 then discusses the different maintenance craft currently used in offshore wind farm O&M and which mother-daughter concepts are discussed in literature. Chapter 5 will explain the method and the workings of the model. Chapter 6 then discusses the verification and validation of this model followed by a demonstration of the method in chapter 7. This thesis is then concluded with the discussion and conclusion in chapters 8 and 9.

2 Maintenance

This chapter will discuss what maintenance has to be performed by a turbine supplier (OEM) at offshore wind farms. This chapter will also discuss how this will develop in the future. Hereby answering sub-question 1: What maintenance needs to be performed at offshore wind farms and how will this develop in the future? The maintenance scope is discussed in section 2.1. The different maintenance strategies that can be employed to maintain the components in the maintenance scope are discussed in section 2.2, followed by an explanation of the different maintenance categories used under the current maintenance strategy of SGRE in section 2.3. This chapter concludes by discussing the future developments regarding offshore wind farm maintenance in section 2.4 and the final concluding insights in section 2.5.

2.1 Maintenance Scope

The information in this section has been gathered during several conversations with employees from SGRE in June and July 2023. The maintenance scope for a turbine OEM can vary per project in both time and physical scope. The length of the contracts can vary between 5 - 15 years, most are however around 5 years, which coincides with the duration of the warranty. Turbine suppliers prefer to conduct the maintenance during the warranty period because they can be certain of the maintenance procedures that are used, so there are no complicated legal battles around breaches of warranty by the service technicians of the customer. More seasoned customers in the offshore wind industry prefer to perform as much maintenance themselves as possible to reduce costs, while less experienced customers tend to prefer the OEM to service the turbines .

The basic scope of any turbine OEM service contract is the turbine itself and all equipment inside it, the other parts of the wind farm are typically the responsibility of the owner/operator. This can however be expanded by equipment on the TP, substation, subsea cables, and more. Maintaining equipment on the TP is relatively easy to include in the preventive maintenance schedule of the turbine. The other items are more difficult and require different knowledge, equipment, and visits to other structures. Maintaining these components of a wind farm is therefore quite project specific and is not particularly common. The maintenance scope considered in this thesis will therefore only be the maintenance of the turbine and items on the transition piece (TP).

This limited maintenance scope causes the foundation type used at a specific wind farm to be irrelevant to the maintenance that has to be performed because the foundation is the responsibility of the owner/operator. If a wind farm uses monopiles or jackets as turbine foundations, is therefore not important as long as a boat landing is present at both, which normally is true. The same goes for bottom-founded or floating farms. Floating turbines might however see faster deterioration of components due to larger motions of the entire structure and exchanging major components out at sea is significantly more difficult due to the motions of the nacelle. The scope can be divided into several groups, these are listed below. How this scope is divided over different maintenance visits is explained in the next section.

Turbine

- Safety equipment
- Lift and crane
- Bolts
- High voltage
- Oil Changes
- Cooling system
- Hydraulic system
- Blades
- De-icing inspection
- Corrosion inspection
- Weld inspection
- Dampers
- Lights
- Cleaning
- Retrofits

TP

- Access ladders
- Davit crane
- Cable inspection
- Corrosion inspection
- Weld inspection

2.2 Maintenance Strategies

Maintenance can be performed at different stages of a component's life cycle. Either after failure has occurred, when an unexpected increase of deterioration of the component is observed, and a reasonable time before failure when the component is working as designed. The moment at which maintenance is performed is determined by the maintenance strategy that is employed. Maintenance strategies can be split into two main groups: corrective (reactive) and preventive (proactive) maintenance (Ren et al., 2021). The different strategies that belong to these two groups are shown in figure 2.1. Each of these strategies is discussed below.

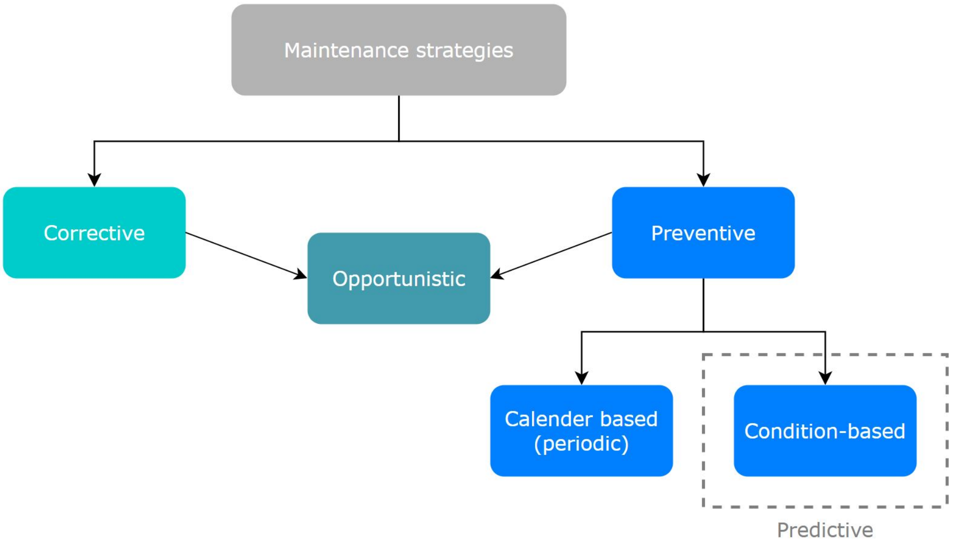

Figure 2.1: Maintenance strategies, adapted from (Ren et al., 2021; Rinaldi et al., 2021; Walgern et al., 2017)

2.2.1 Corrective Maintenance

Corrective maintenance is performing maintenance due to the occurrence of a failure or rapid deterioration of a component. Using a corrective maintenance strategy means that maintenance is only done as a reaction to the failure of a component or an alarm (Ren et al., 2021). A reactive maintenance strategy can be a lean maintenance strategy if the system can be easily accessed and parts are readily available. Exclusively using this strategy for offshore wind O&M activities is however unfavorable, because weather windows can be scarce, especially during the winter. Parts and craft can also have significant lead times, leading to long downtime periods and production losses (Kang et al., 2019; Ren et al., 2021; Shafiee, 2015).

2.2.2 Preventive Maintenance

Preventive maintenance is maintenance performed to prevent component or system failure. Preventive maintenance is therefore less urgent and can be planned further ahead of time. The advantage of preventive over corrective maintenance is that in theory there is only downtime due to the maintenance itself and not due to weather delays or lead time of parts/craft (Ren et al., 2021). Preventive maintenance has two sub-strategies: calendar-based and condition-based maintenance.

Calendar-based Maintenance

Calendar-based maintenance is done for components or systems of which the deterioration rate is more or less known. Inspections and maintenance are scheduled before failure of the system or component is expected. This can be either at a specific time or power generation interval (Ren et al., 2021; Shafiee, 2015). The intervals are based on general deterioration profiles but do not take into account local phenomena that affect the deterioration rate or possible manufacturing defects in components causing premature failures. Periodic maintenance can therefore never be used as the sole maintenance strategy, corrective maintenance will still have to occur if failures occur earlier than the planned maintenance visit. Calendar-based maintenance is the primary maintenance strategy currently employed by the offshore wind O&M industry [1].

Condition-based Maintenance

Condition-based maintenance is a strategy where maintenance is only performed when it is deemed necessary. So somewhere between when a component is in a good state but before it has failed causing unwanted downtime. Condition-based maintenance combines data-driven reliability models, with condition monitoring systems to determine a component's position in its service life and predict how much service life is left before failure (Rinaldi et al., 2021). A planning is made based on the information from the model(s) and the sensor(s) so a maintenance visit occurs at the optimum time, which will, when done correctly be at longer intervals than with a calendar-based strategy. This maintenance strategy requires a thorough understanding of complex system dependencies and dynamics (Rinaldi et al., 2021), which is one of the reasons why this strategy has not yet been employed as the primary strategy in the offshore wind industry. The sensors, data collection, and data processing equipment that is used when employing this strategy is CAPEX intensive but has been proven to be cost-effective compared to calendar-based maintenance strategy by Kang et al. (2020) and Walgern et al. (2017). Alternatives to suppress the CAPEX-intensive nature of this strategy are being researched. For example using a set of turbines that can be seen as representative of the whole wind farm, instead of installing the sensors on all turbines (Rinaldi et al., 2021).

2.2.3 Opportunistic Maintenance

Opportunistic maintenance is a way of coupling corrective with preventive maintenance. This strategy uses corrective maintenance visits as an occasion to also perform preventive maintenance, to reduce the amount of visits to a turbine (Ren et al., 2021). The status of other components are checked when a corrective visit to a turbine is required and preventive maintenance is performed on the components that are below a certain threshold. This strategy is currently being researched in literature but has not yet been employed in the field[1]. Literature does however show that opportunistic maintenance can be beneficial for (offshore) wind turbine maintenance compared to the classic preventive maintenance strategy (Abdollahzadeh et al., 2016; Zhang et al., 2019). Opportunistic maintenance can be combined with either of the two preventive maintenance strategies.

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[1] From conversations with SGRE employees between May and August 2023

2.3 Maintenance Strategy of SGRE

SGRE currently uses a preventive maintenance strategy, where corrective maintenance is performed whenever required. There are currently five types of maintenance visits that are done to service the scope described in section 2.1, these are shown in table 2.1. Each of these maintenance categories will be described below. The descriptions cover what is done and needed on the turbine. There is, therefore, no prescribed wave limit, because the waves only impact the transfer to and from the turbine and the limits for transfer are determined by the capabilities of the vessels. The waves have no impact on the work once on the turbine. The information in this section is specific to SGRE, although the information from competitors will likely be similar. This information has been gathered during several conversations with employees from SGRE in June and July 2023.

Table 2.1: Maintenance visit types

	Maintenance types
Preventive	• Annual service • Lift inspection
Corrective	• Unplanned maintenance • Major component exchange
Miscellaneous	• Evacuation

2.3.1 Preventive

Annual Service

The annual service should in principle be the only visit where actual maintenance is performed. The statutory inspections that are part of this annual service are currently required by law to be performed within 13 months of the last statutory inspection. The annual service has a set list of items that have to be completed every visit and items that change based on the age of the turbine. The aim for all wind farms is to perform the annual service on all turbines in the summer months when access to the turbine is easier due to better weather. Delays can result in some annual services being performed in months that typically have worse weather. Alternatively, some sites have a limited amount of annual services planned in the winter. This has to do with the capacity of the vessel(s) at the site and the amount of turbines.

The duration of an annual service is also dependent on the vessels that bring the technicians and parts to the turbine. A craft that can accommodate technicians overnight can deliver more ‘time on turbine‘ because the technicians only start working when they transfer to the turbine. Technicians that are based out of port have less time on turbine because their work hours include the transit time to the turbine. The duration of an annual visit is also influenced by the number of technicians that can simultaneously work inside the turbine. This number is dependent on the size of the turbine and how many evacuation devices are present in the turbine. An annual service might take two days, dependent on the number of hours required for the annual service and the size of the turbine. This is normal for most wind farms, however, tighter planned, so-called, ”pitstop service” is making it possible to perform an annual service in one visit. The annual service typically requires between 0 and 300 kg of spare parts and equipment to be delivered to the turbine, with a total average of around 40 kg. This is the same across all maintenance categories except major component exchange. The operation is limited by the maximum wind speed at which it is safe to operate the nacelle crane. An overview of the annual service is shown below.

Table 2.2: Annual service summary

• Scope	Annual Turbine Service, Annual Statutory Inspections, High Voltage, Lift and Crane Maintenance and Retrofits
• Interval	1x per year, retrofits ad hoc as required
• Timing	Aim in favorable summer months, can be year round being less intense during winter
• Duration	6 - 11 hours for 1 or 2 days, dependent on transfer vehicle and turbine size
• Resources	Technicians: turbine size dependent Cargo: 0 - 300 kg
• Limit	Wind speed: 14 m/s 10m above Lowest Astronomical Tide (LAT) for nacelle crane

Lift Inspection

An inspection of all man-ridden equipment is required by law in most countries. This typically has to happen every six months but some countries require this inspection to happen every three or twelve months. Exceptions can be made to increase the time between inspections but six months is typical. The first inspection is included in the annual service. The second lift inspection, which typically has to be performed six months after the annual service will therefore typically occur in the winter months. The inspection requires a relatively small weather window however because the inspection takes between two and three hours. The visit might be longer if problems are discovered. The inspection requires 3 technicians and between 0 - 300 kg of equipment and parts dependent if any faults are discovered. The operation is limited by the maximum wind speed at which it is safe to operate the nacelle crane if necessary. An overview of the lift inspection is shown below.

Table 2.3: Lift inspection summary

• Scope	Lift and Crane Inspection
• Interval	1x per year (dedicated visit), first time included in annual service
• Timing	6 months after annual service (typically), so typically during winter
• Duration	2 - 3 hours, longer if a problem is discovered
• Resources	Technicians: 3 Cargo: 0 - 300 kg
• Limit	Wind speed: 14 m/s 10m above LAT for nacelle crane

2.3.2 Corrective

Unplanned Maintenance

Unplanned maintenance is normally purely corrective and therefore requires an urgent response to limit production losses and reduction of the fatigue life of the turbine. The fatigue life of an offshore turbine is quickly reduced when the turbine is stopped because the excitation by wind and waves becomes larger due to the absence of the aerodynamic damping that the rotating rotor provides. Some visits can however be triggered by alarms or in limited cases based on the condition monitoring system or predictive models. These visits are less urgent because the turbine has not yet stopped and can be planned ahead of time. This is still called unplanned maintenance because the maintenance that is required for this visit is not part of the original maintenance plan. The work can be as small as a turbine restart or as big as replacing a heat exchanger for example.

The number of unplanned maintenance visits changes significantly between sites and turbine types. The number of unplanned visits is highly dependent on turbine age. Turbines follow the classical bathtub curve with more failures during the first stage of their operational life, followed by a steady period of fewer failures, ending with an increased failure rate due to wear out of parts. Turbine OEMs typically maintain the turbines during the first phase with more failures and during the steady state period. Most unplanned maintenance cannot be planned and therefore occurs year-round. The visits typically require between two and four technicians and 0 - 300 kg of parts and equipment. This group of technicians is usually deployed further away from other technicians because a sudden failure can be on the opposite side of the wind farm form where preventive maintenance is performed. The operation is limited by the maximum wind speed at which it is safe to operate the nacelle crane if it is required to use it. An overview of the unplanned maintenance is shown below.

Table 2.4: Unplanned maintenance summary

• Scope	Can be any component except for entire major components
• Interval	Varies significantly between sites and turbines
• Timing	Year round
• Duration	30 min - 3 days, typically 4 -5 hours
• Resources	Technicians: 2 - 4 Cargo: 0 - 300 kg
• Limit	Wind speed: 14 m/s 10m above LAT for nacelle crane

Major Component Exchange

Major component exchange needs to happen when one of the major components is damaged to a point where repairing without a heavy-lifting crane is no longer possible. The major components are blades, gearbox (if present), generator, or main bearing. The major components are designed so they do not have to be exchanged during the lifetime of the turbine, but failures can still occur due to various reasons. The interval at which major component exchange occurs is highly dependent on site-specific parameters and turbine types. Additionally, these intervals are one of the core challenges in this industry making them highly confidential and unable to be disclosed in this thesis. The failure of the component can occur at any time during the year, but the exchange itself is dependent on the availability and weather limits of the heavy lifting vessel used for the exchange. These weather limits are typically relatively low due to the heavy lifting and jacking operation. The critical weather limits are around 11 m/s wind speed and 1.5m Hs respectively. It can therefore be the case that a turbine has to be stopped for a significant number of days or weeks. The amount of technicians that are needed for each exchange can vary but the amount of technicians onboard the vessel is always the same because it will perform several different major component exchanges when it sails out. There are usually around 20 to 25 technicians on board. The amount of cargo it needs to carry depends on the number of exchanges it should be able to do without returning to port and the types of exchanges. A major component exchange typically takes between three to five days. An overview of the major component exchange is shown below.

Table 2.5: Major component exchange summary

• Scope	Blades, (gearbox), generator or main bearing
• Interval	Industry sensitive information
• Timing	Failure occurrence year round. Activity depends on availability and weather limits of heavy lift vessel
• Duration	3 - 5 days
• Resources	Technicians: 20 - 25 onboard, number of technicians changes per exchange Cargo: 4500 tons Heavy lift crane, capable of reaching the required height
• Limit	Wave height: 1.5m Hs (jacking) Wind speed: 11 m/s 10m above LAT (lifting)

Evacuation

Regardless of all the safeguards and procedures in place, an incident or fire can occur. The technicians deployed on a turbine should therefore always be able to be evacuated. They should be evacuated from the structure and be able to be brought to a safe place (with medical care) as soon as possible. It is not possible to rely on the coast guard, because an offshore wind farm has to be self-sufficient by law in most countries. The time between an incident and the evacuation to a safe place is not prescribed by laws but is assessed in the safety plan of each site. These times tend to vary between thirty minutes and two hours, dependent on the location and craft available to the wind farm. An evacuation of a turbine is very rare happening about once every 10 years, but can occur year-round. The evacuation should at least be possible in all weather conditions in which technicians can be deployed. An overview of the evacuation is shown below.

Table 2.6: Evacuation summary

• Scope	Evacuation of technicians to safe space
• Interval	Once every 10 years
• Timing	Year round
• Duration	As fast as possible, typically 30 min - 2 hours
• Resources	Enough space for all technicians that need to be evacuated
• Limit	wind speed: Could be necessary in all conditions, but technicians are usually not deployed when predicted wind speeds are above 20 m/s 10m above LAT

2.4 Maintenance Developments

The information in this section has been gathered during several conversations with employees from SGRE in June and August 2023. Offshore wind farm O&M is centered around technicians visiting a turbine and doing work on the turbines. This means that they have to be transferred from, usually a vessel, to the turbine, which is dangerous and expensive. **The number of visits should therefore be reduced as much as possible, to make O&M safer, less expensive and to improve availability**.

The condition-based and opportunistic maintenance strategies, mentioned in section 2.2 will play a part in reducing the number of turbine visits. SGRE and other companies in the industry are working on incorporating more sensors and predictive models to only intervene on the turbine when required. Some of the modeling methods used for this are machine learning and artificial neural networks to create models from real-life condition monitoring data (Rinaldi et al., 2021). In addition, digital twins are being developed. These are high-fidelity models that can replicate a system to such a high degree that real-life decisions for, for example, maintenance activities, can be based on the analysis of the digital twin.

It is however not cost-effective to do this on all components. It is SGRE's opinion that this can only be done for the major components, with vibration sensors and around 10% of the remaining scope. The reason for this is that most of the other failures occur due to the failure parts that cost just a few euros. The nature of these parts is that they work until they break, without significant warning. Condition monitoring systems could be applied to these parts but the expected notice that this will provide is estimated to be a few hours. This would require a large investment for likely negligible results and will therefore not be applied.

The industry is however looking into more opportunistic strategies to reach its goals. Literature has also recognized that applying an opportunistic strategy is a better overall strategy for the maintenance of these large multi-system machines (Kang et al., 2019). The calendar-based-opportunistic maintenance strategy will use the information from the sensors and models that can be applied cost-effectively and reduce the hours required to inspect components. These extra hours can then be used to perform activities that may prevent corrective visits later in the year. Thereby, when done effectively, reducing the number of corrective visits to a turbine. There are ideas to increase the hours used for an annual service visit to increase this effect further. Additionally, centralizing the information about the work done on turbines can reduce unnecessary inspections or work. Therefore further cutting down the hours required to perform the preventive maintenance scope. These developments mostly affect the way maintenance is performed on a turbine and how the tasks during a visit are planned. **The logistics of transporting technicians and parts to the turbines will remain the same**. So, these developments do not have a significant influence on the work of the O&M fleet.

The operations of the O&M fleet would however see a significant impact if condition monitoring systems and predictive models could be applied to more components. Transfer limits of the maintenance craft could for example be lowered if a significant portion of the corrective visits could be predicted ahead of time. The transfer limit of the maintenance craft could possibly be lowered because the extra time to plan the visit would make it more probable that a weather window with milder environmental conditions will occur. The industry is also working on robotics to decrease the number of turbine visits or to remove people from the most dangerous tasks. Mainly rope access jobs, such as blade inspection and repair. Some examples are:

Blade Bug The Blade Bug is a crawler robot that can traverse turbine blades to perform inspections and repairs if needed (Offshore Magazine, 2022a).

Watereye Watereye is a monitoring system that will use a drone that flies inside the turbine tower to monitor the corrosion levels of the tower (Watereye, 2023).

MIMRee MIMRee stands for Multi-Platform Inspection Maintenance and Repair in Extreme Environments and is a platform using drones to deploy the Blade Bug in a fully autonomous way (Z. Jiang et al., 2023).

2.5 Concluding Insights

Sub-question 1: What maintenance needs to be performed at offshore wind farms and how will this develop in the future? Is answered in this chapter. The answer to this question and other conclusions from this chapter are discussed below.

The maintenance scope for turbine OEMs, such as SGRE, is normally limited to work on the turbine and occasionally items on the TP that are easy to include in the turbine maintenance schedule. This means that the foundation type is irrelevant to the maintenance activities that need to be performed. Floating turbines might however see faster deterioration of components due to larger motions of the entire structure causing more corrective visits. The maintenance scope is currently tackled by a preventive-corrective maintenance strategy which requires at least 2 preventive and a variable number of corrective visits per turbine per year. The number of corrective visits is varies significantly site to site. Corrective visits often require technicians to be deployed further away from each other than preventive maintenance. **The evacuation requirement however restricts the technicians deployment area.**

Major component exchange requires the use of a large heavy-lifting crane which is not used in the other more common maintenance categories. **Major component exchange is therefore not included in the scope of the mother-daughter concepts.**

The goal for future developments in offshore wind farm O&M is to reduce the number of turbine visits. This will be done by implementing a calendar-based-opportunistic maintenance strategy. An opportunistic strategy is better suited to these complex multi system machines than a condition-based maintenance strategy. It is however possible to cost-effectively apply condition monitoring systems and predictive models to the major components and around 10% of the remaining maintenance scope. These two tools will be used to perform health checks of these components, so the hours spend performing inspections during the annual service can be reduced. This freed up time will be used to perform activities that will prevent the need for some corrective visits later in the year. These changes will mostly affect the activities on the turbine but will not have a significant impact on the logistics of the technicians, apart from the possibly lower number of corrective visits.

3 Offshore Wind Farms Developments

This chapter will discuss the parameters of currently operating offshore wind farms and how these parameters are expected to develop in the future. Hereby answering sub-question 2: How will offshore wind farms develop in the future? This is first discussed on a global level in section 3.1, followed by an analysis of the regional differences in section 3.2. The ”Global offshore wind power project database” from Wood Mackenzie (Wood Mackenzie, 2023) is used to make this analysis. This database contains all offshore wind projects that are currently operational or under development. The relevant environmental differences cross all offshore wind development sites around the world are discussed in section 3.3 and this chapter concludes with some concluding insights in section 3.4.

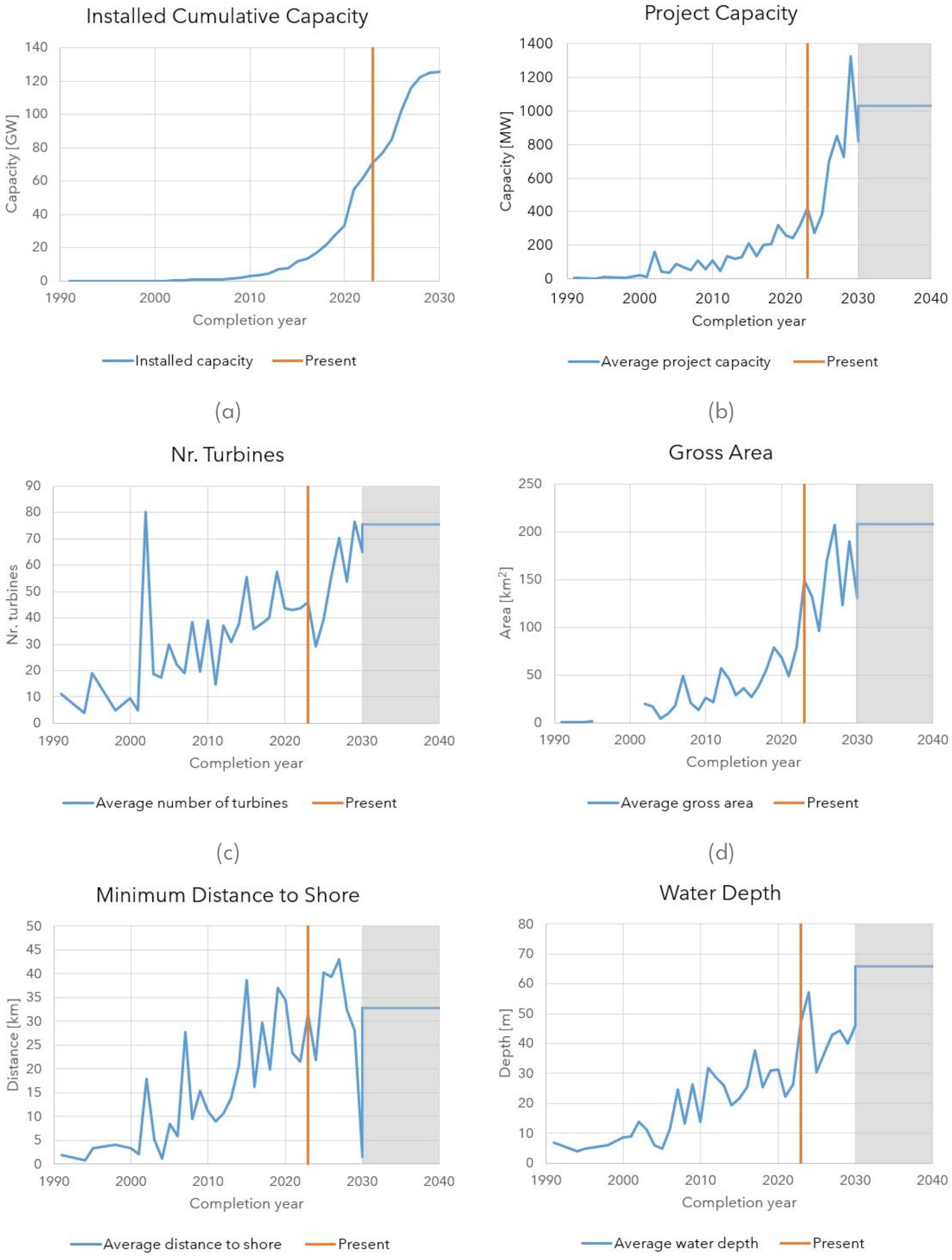
3.1 Global Analysis

The database has records of 2712 projects, 742 of these projects are no longer active, meaning they did not get past the planning stage and are no longer being worked on. 1538 projects equal to 1425 gigawatts (GW) are still in the planning phase and have no completion date planned yet. Most of these projects also do not yet have permits. These numbers make it clear that this market is planning rapid expansion. This large proportion of projects still in the early phases of planning, lack a significant amount of information. These missing values can however be ignored since, on average around 50% of the values are recorded and this analysis focuses on large-scale trends in the market. The averages being calculated to show these trends will simply not include the zero values. An overview of the amount of missing data is given in Appendix A. Some of the projects that lack a set completion date will likely not be completed. The data from these projects is however still useful because it indicates where the market is headed.

3.1.1 Offshore Wind Farm Parameters

The global average values of several wind farm parameters as well as total installed capacity are shown in Figure 3.1 on the next page. The graphs show the average value of projects completed in that year. All ‘no longer active‘ projects have been removed from the data for this analysis. Projects without a set completion date are pooled together and shown as the value in the grey area between 2030 and 2040. This gives an indication of projects that are planned to be completed in the future. Figure 3.1a shows that this market is growing rapidly and will continue doing so in the near future. The growth does however seem to taper off towards 2030, this is just a result of plotting the graph over the year in which projects are completed. There are simply very few projects that have their completion date set close to 2030 because most of the projects that will be finished by that time are still in the planning phase.

The other sub-figures in figure 3.1 clearly show that the size, minimum distance to shore, and water depth have been increasing and will keep rising until 2030. The growth in size and distance to shore will increase the transit times to the farm but also inside the farm. The minimum distance to shore seems to drop to near zero in 2030, this is caused by the fact that just one project has a completion date in 2030 so this value is misleading and will likely



(a)

(b)

(c)

(d)

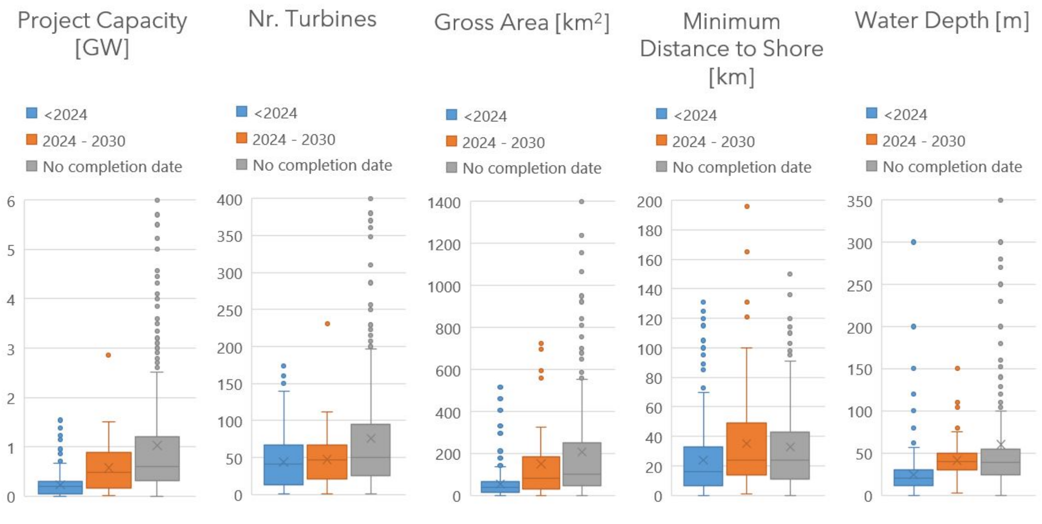
(e)

(f)

Figure 3.1: Global offshore wind farm parameter averages developments

not be representative. The minimum distance to shore is shown in figure 3.1e instead of the distance to the O&M port, due to the limited availability of that parameter. An analysis of the commercial projects that do report this distance shows that the ratio between the distance to the O&M port and the minimum distance to shore is typically between one and two for projects with a minimum distance to shore greater than 20 kilometers. The ratio tends to increase when the minimum distance to shore decreases. This analysis is mostly based on projects from Europe since only five project from outside Europe had reported the O&M port. This analysis is shown in Appendix A. The increase in water depth has no significant influence on regular maintenance since all vessels simply float. This is however a crucial factor for jack-up vessels used for major component exchange. Figure 3.4 shows that the maximum water depth for bottom-founded wind farms will be about 80 meters, which is the maximum of currently operating jack-up vessels (Jan de Nul Group, 2022). The range of water depth for floating farms is much larger with farms installed in waters much deeper than 100 meters. An alternative to a jack-up vessel must therefore be developed to perform major component exchange for these projects.

The projects that do not have a set completion date show that the growth in farm size will, on average, slow down or even stabilize, see figure 3.1b. The variance in park size is, however, a lot larger in the future, with parks up to 10 GW proposed where 3 GW is the largest project installed before 2030, see figure 3.2a. Most parks will however not be greater than 3.15 GW, with 45 projects larger than 3.15 GW. The value of 3.15 GW does not match the whisker of the box and whisker plot, because the whisker does not give a completely representative maximum value (outlier boundary). The value of 3.15 GW has been obtained from the violin plot in figure 3.3. The other plots have also been checked in this way, but the other values of the whiskers are representative. The violin plots from the other box and whisker plots are shown in Appendix A. The other size metrics: nr. turbines and gross area will also grow together with capacity. The average and variance in minimum distance to shore seems to remain broadly the same, whilst the average and variance of the water depth will increase. The increase in water depth originates from the floating projects.



(a) (b) (c) (d) (e)

Figure 3.2: Global offshore wind farm parameter evolution, not all outliers are shown in this figure

As discussed in the previous chapter, the foundation type does not influence the maintenance for turbine OEMs, because the foundation is outside of the scope of the turbine OEMs. An analysis of all floating projects is however made in the following paragraphs to discover if the design of these wind farms differs significantly from their bottom-founded counterparts.

Floating wind is a newer market, with the first demonstration projects being launched in 2009, almost twenty years after the first bottom-founded offshore wind park. The largest operational floating wind farm is Hywind Tampen, which was completed this year (2023) and has a capacity of 95 mega watt (MW). This is significantly smaller than bottom-founded farms that are currently being completed. The project provides electricity for oil and gas platforms in the

North Sea and also serves as a test bed for the technology. There are currently no projects planned with a set completion date that have a capacity as large as to the Hywind Tampen project.

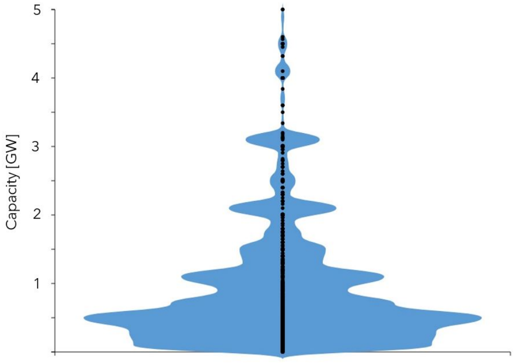
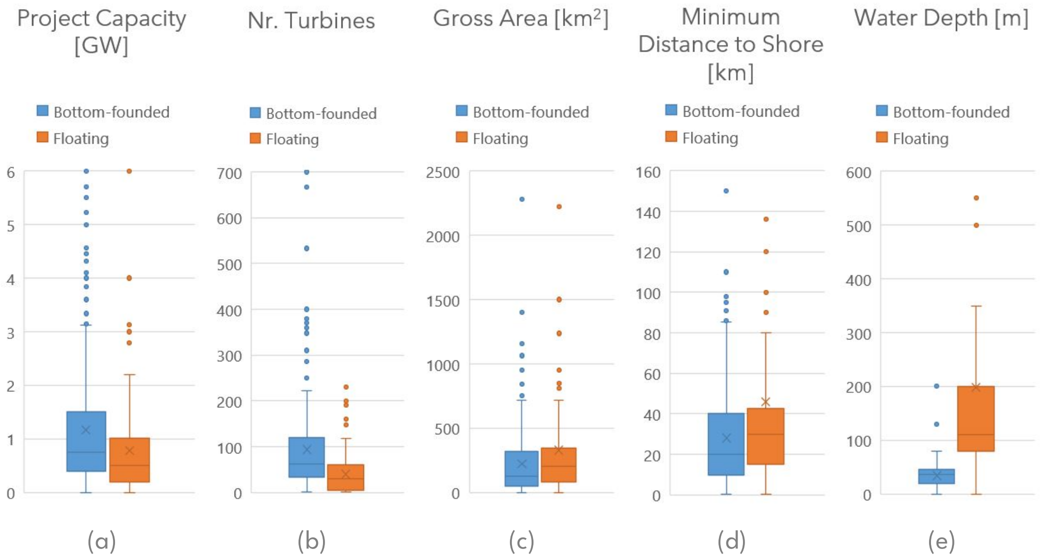


Figure 3.3: Violinplot of project capacity, no completion date

The projects with no set completion date are however more ambitious, with 243 projects each with a capacity of more than 100 MW. The average capacity is relatively close to the bottom-founded farms with 1100 MW compared to 860 MW for floating. The variance in wind farm size is also similar with the reasonable maximum is around 2.2 GW, with outliers up to 10 GW, as can be seen in figure 3.4. The physical size of bottom-founded and floating farms seems to be similar, the number of turbines per farm is however significantly lower for floating farms. **This results in fewer turbines per square kilometer indicating a larger space between turbines, which decreases the number of turbines within the evacuation radius.**

The minimum distance to shore for floating farms is, on average, higher compared to bottom-founded wind farms, the variance is however very similar, see figure 3.4. There is however a significant difference in water depth. This difference is to be predicted since that is the main reason to choose a floating foundation.



(a) (b) (c) (d) (e)

Figure 3.4: Fixed vs floating comparison (projects with no set completion date)

3.1.2 Increasing Turbine Size

The rated power of turbines has risen steadily in the last two decades and will keep rising, see figure 3.5. Accelerating to an average of around 15 MW by 2030, with the aim to increase the profitability of the turbines (van Zinderen Bakker, 2023). Figure 3.5 shows however that this rise in rated power will halt based on the projects with no set completion date. This is however misleading since 81% of projects that have listed a maximum power rating of the turbines use the specs of announced turbines, which have a maximum power rating of 15 MW, with just 19% listing higher power ratings. It is therefore expected that turbine size will keep increasing in the foreseeable future. The increase in size also increases the number of technicians that can work in a turbine at the same time, making it better possible to service a turbine in one shift. There are currently no significant regional differences concerning power ratings. There are however discussions to limit turbine sizes in the future to focus on reducing strain on the supply chain, increasing efficiency and reducing waste (Hill, 2023; Lee, 2022; van Zinderen Bakker, 2023). The Dutch government has already enacted standard that prescribes a maximum tip height for turbines at 1000 feet (Hill, 2023; van Zinderen Bakker, 2023).

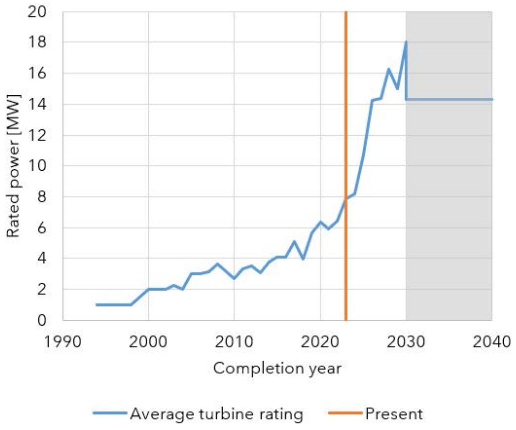
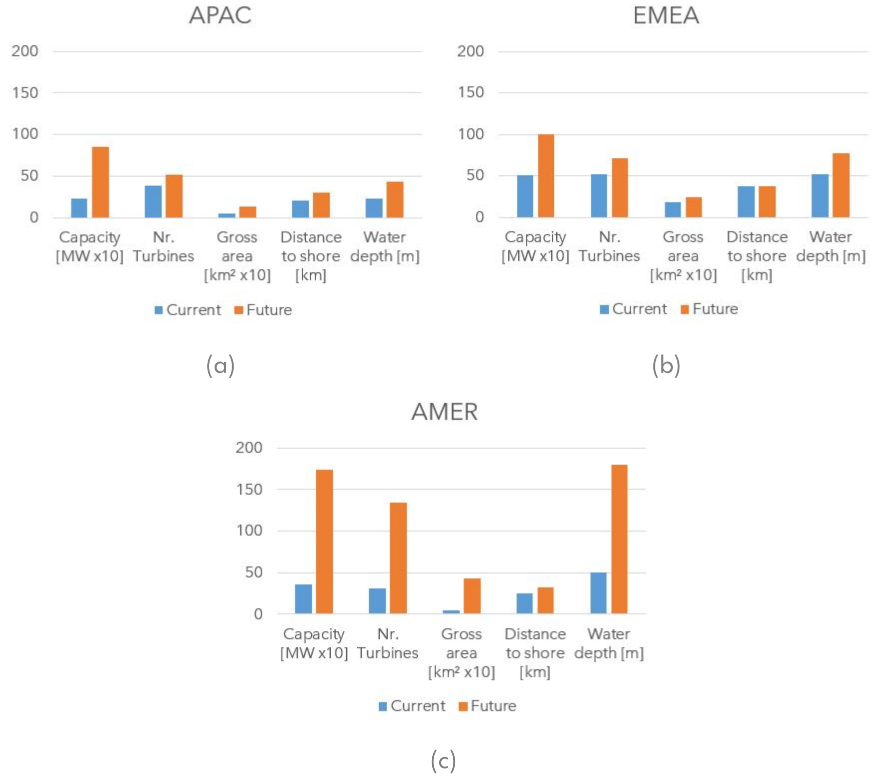


Figure 3.5: Turbine rated power

3.2 Regional Analysis

Globally three regions are defined for the offshore wind market: Europe, Middle East, and Africa (EMEA), Asia-Pacific (APAC), and North, Central, and South America (AMER). Figure 3.6 on the next page shows the differences in average wind farm parameters across the different regions currently and for the projects completed in the future (>2023). The values for the current columns are the weighted averages of all the projects in that region with a completion date between 2021-2025 and the future columns are the weighted average values for all projects completed after 2023, this includes projects with no set completion date.

When looking at figure 3.6 it is immediately clear that the AMER region is significantly different from the APAC and EMEA regions, which are relatively similar to one another. This is due to the significantly smaller number of projects currently installed, with just four projects completed before 2024 and 150 projects in the planning phase. Compared to the APAC and EMEA regions with 184 and 150 projects currently installed respectively and 819 and 664 planned. The AMER region also has a relatively large amount of floating wind projects planned in deep waters, causing the difference in average water depth compared to the APAC and EMEA regions. The AMER region also does not have as many sub-GW projects planned as the other regions, 65% of the projects in the AMER region are larger than one GW compared to 22% and 34% for the APAC and EMEA regions, causing the average capacity and number of turbines per farm to be significantly higher.



(a) (b)

(c)

Figure 3.6: Regional comparison of current and future offshore wind farm parameter averages

The APAC and EMEA regions are and will be similar in size in the future, with currently 34 and 36 GW installed respectively, and 643 and 586 GW planned. Their wind farm characteristics are and will also be more similar to each other than compared with the AMER region. The EMEA region has and will have more challenging characteristics, with on average larger farms, situated further offshore and in deeper waters. A significant difference between these two regions is the difference in the number of planned floating wind projects, as can be seen in figure 3.7, with the APAC region planning significantly fewer floating projects while the other parameters show similar proportional differences compared with figure 3.6. Figure 3.7 also depicts the severe difference in average maximum water depth between the APAC, EMEA, and the AMER region. This is due to most projects with a specified water depth being located in the pacific ocean, where there is no extensive continental shelf.

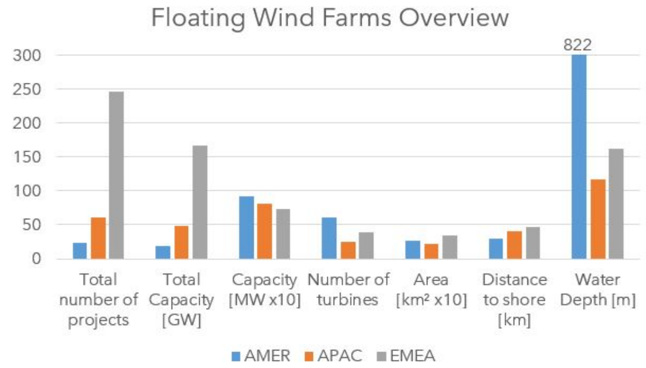


Figure 3.7: Floating wind farm overview per region for projects with a completion date after 2024

The APAC region is dominated by the Chinese market, with 30 of the 34 GW currently installed in the region originating from China. This is highly important since all turbines installed in Chinese waters are also from Chinese OEMs. This causes the opportunities for European OEMs in this region to be slim. The other countries in the region are however planning on installing at least another 9.6 GW before 2030 and the total capacity of projects without a completion date is also larger with 350 GW, compared to 283 GW in China. It is expected that competition with Chinese OEMs will remain fierce and entrance in this market will likely require formal Joint Ventures with Chinese parties. It is also likely that western countries will impose limitations on how much information is shared with these parties[1].

3.3 Environmental Conditions Around the World

The environmental conditions at sites around the world differ significantly. This allows different craft with varying requirements to be effective in different places around the world. The most important environmental factor is wave height because this impacts the most dangerous stage in the O&M process, the transfer of technicians to the turbine, the most.

Significant wave height is the most important variable in operational planning. This is the average height of the highest one-third of waves. This metric does however not provide a complete picture, as swell and wind waves can come from different directions, creating complex wave patterns. The wave direction is also important since the ways vessels can be oriented during transfers are limited to a few sets of headings[1]. This metric is however used in this section to provide a quick overview of the differences in wave conditions around the world.

Wind speed and current are also important factors to be considered when determining the feasibility of offshore operations. Wind speeds are however most restrictive for the operation of the nacelle crane and not for the operation of the maintenance craft. The current is important for the dynamic positioning systems onboard vessels but generally has a less profound impact on workability than wave heights[1]. These environmental factors are therefore not discussed further in this section. The main areas where offshore wind farms are operational or being planned are Asia, Brazil, the Mediterranean, North America, Northern Europe, and Oceania (4COffshore, n.d.-a). The mean significant wave height of each of these areas in January and July is shown in table 3.1. These two months are shown because they feature the highest and lowest mean wave heights for all areas. Figures showing the mean significant wave heights in these months across the entire areas are shown in appendix A.

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[1] From conversations with SGRE employees between May and August 2023

Table 3.1: Highest mean significant wave heights (obtained from the Wavewatch III model in (MetOceanView, n.d.))

Area	Sub-area	January	July
Asia	Vietnam	2.3m	0.7m
	Other	1.5m	0.7m
Brazil		1.8m	2.3m
The Mediterranean		1.8m	0.9m
North America	East Coast	2 - 2.4m	1.3m
	West Coast	3.5m	1.9m
Northern Europe	North Sea	3.1m	1.3m
	Norway	3.7m	1.4m
Oceania	Bass Straight	1.7m	1.8m
	Other	2.6m	3.7m

The west coast of the USA and the western/southern coast of Australia show the highest mean significant wave heights. These areas are however mostly exposed to swells with relatively long wave periods (DNV GL, 2017). Northern Europe features slightly lower wave heights but the wave periods are typically shorter causing steeper waves that result in more severe vessel motions.

Northern Europe features some of the toughest environmental conditions and largest volume in the offshore wind industry.

3.4 Concluding Insights

Sub-question 2: How will offshore wind farms develop in the future? Is answered in this chapter. The answer to this question and other conclusions from this chapter are discussed below.

Offshore wind farms will keep increasing in size, in conjunction with turbine size. This means that distances between turbines will increase as well. There are however conversations about limiting the maximum size of a turbine and there is already a maximum size for turbines in the Netherlands. The distance to shore will stop increasing and stabilize on an average of around 40 km with a maximum distance to shore of around 100 km. There are no significant differences between bottom-founded and floating wind farms apart from the foundation, distances between turbines, and the water depth in which they are installed. The EMEA region has the majority of the world's floating projects planned and on average sees the largest distances to shore. The wind farm parameters in the APAC region are relatively similar to the EMEA region, however, are usually not as deep or far away from shore. This region currently mostly consists of wind farms in China, with 88% of the installed capacity in this region originating from China. This percentage will likely drop to around 50% in the future, as other countries build more offshore wind farms. The AMER region is significantly different from the other two regions. Opting to almost exclusively build/plan wind farms larger than one GW and having on average very deep floating projects. The environmental conditions vary significantly between these regions and between areas within these regions. The most challenging areas appear to be the west coast of the USA, the western/southern coast of Australia, and Northern Europe.

4 Maintenance Craft

This chapter discusses the craft currently used in offshore wind farm O&M and the mother-daughter concepts discussed in literature, hereby answering sub-questions 3: Which craft are involved in offshore wind farm maintenance and what mother-daughter concepts are discussed in literature? Section 4.1 discusses all the currently used craft in offshore wind O&M and section 4.2 discusses the literature that discusses mother-daughter type concepts for offshore wind O&M. Section 4.3, concludes this chapter with the concluding insights.

4.1 Currently Used Craft

This section discusses all the vessels currently being used in the O&M phase of an offshore wind farms life cycle. An overview table of the different vessels along with some of their characteristics is shown in table 4.1. Here it is visible that most craft have a much larger cargo capacity than is required for an annual service visit for example. Part of the reason is that the maximum of 300 kg is the weight of the items that are taken to the turbine, so, this excludes the weight of the 10 or 20 ft container in which they are transported for example. These containers weigh one to two tons.

Table 4.1: Overview of currently used maintenance craft design characteristics

	CTV	SOV	DC	SATV	Helicopter
Length [m]	12 - 34	57 - 96	10 - 15	36 - 40	≈ 14
Beam [m]	4 - 10	14 - 22	3 - 4	10 - 12	≈ 12
Speed [kn]	15 - 39	7.5 - 14	25 - 45	16 - 25	≈ 140
Transfer limit [m Hs]	1 - 2.2	2.8	1 - 1.2	2	2.5 - 6
Technicians [pax]	12 - 24	25 - 50	8 - 10	8 - 12	<10
Cargo capacity [ton]	1 - 15	800 - 2300	1	<15	0.3 - 0.7
Port calls	Daily	2 - 4 weeks	NA	1 - 2 weeks	Multiple time per day

4.1.1 Crew Transfer Vessel

A crew transfer vessel (CTV) is a relatively small vessel typically between 12-34 meters long and is mostly used to service wind farms where the transit time with a CTV is shorter than 90 minutes[1]. CTVs are based out of a port and typically bring 12-24 technicians and 1-15 tons of tools, spares, or equipment at high speed (up to 39 knots) to the wind farm (Dewan & Asgarpour, 2016; Hu & Yung, 2020). This high speed is typically required because a technician's working hours start when the ship leaves the port, so fast transport is required to maximize the use of the technicians' working hours. Once in the wind farm, technicians are transferred to the turbines using a push-on maneuver. During this maneuver, the CTV pushes itself against the turbine's boat landing, which partially arrests the vertical movement of the bow of the

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[1] From conversations with SGRE employees between May and August 2023

vessel, making it easier to jump onto the ladder that leads to the working platform. The CTV retrieves all the technicians after the work has been completed and returns to port. A typical shift length is 12 hours after which the CTV either stays in port overnight or goes back out with another crew and technicians[2]. There are five types of CTVs, based on their hull form. Pictures of all the CTV types are shown in figure 4.1.

Monohull The monohull was the first hullform used for CTVs. These are mostly vessels that were already used as pilot tenders boats. Their main advantage is low cost and scalability however their seakeeping performance is relatively poor, being able to transfer technicians to turbines at sea states with a Hs up the 1-1.2m (Hu & Yung, 2020).

Catamaran Most CTVs currently in use are catamarans. This is due to their good seakeeping behavior and high transit speed. Catamarans typically have a transfer limit between 1.2-1.5m Hs (Hu & Yung, 2020).

Trimaran Trimarans are similar to catamarans, however, their seakeeping behavior is better, with transfer limits between 1.5-1.7m Hs (Hu & Yung, 2020).

SWATH Stands for Small Waterplane Area Twin Hull (SWATH). A SWATH is a catamaran-like design but the hulls have a small waterplane area causing changes in buoyancy forces due to waves to be small resulting in low ship motions. The buoyancy of the vessel comes from submarine-type hulls under the water's surface. This hullform allows for comfortable transit and safe transfer at higher Hs. The limit for safe transfer is between 1.7-2m Hs (Hu & Yung, 2020).

SES A Surface Effect Ship (SES) is also a catamaran-like design. It has two hulls with an air cushion between the hulls. The air is kept between the hull by hovercraft-like skirts. This hullform enables high transit speeds and has good seakeeping performance. The safe limit for transfer is between 1.8-2.2m Hs (Hu & Yung, 2020).

It is important to note that the transfer limits stated above, are the transfer limits usually disclosed by the manufacturers of the vessels. Operators find the maximum transfer limit for the most capable CTVs to be around 1.75 - 1.8m Hs[2].

(a) Monohull CTV (b) Catamaran CTV (c) Trimaran CTV

(d) SWATH CTV (e) SES CTV

Figure 4.1: Different CTV types, (a) (J. Jiang, 2020), (b) (Dixon, 2021), (c) (Snyder, 2023), (d) (Bluebird Electric, n.d.), (e) (Cooke, 2015)

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[2] From conversations with SGRE employees between May and August 2023

As discussed above, CTVs are typically the main O&M craft used for wind farms relatively close to the coast. Transit times longer than 90 minutes are too long, since it decreases technicians' useful working hours and also decreases their performance. Long transits in a high-speed vessel that encounters waves, can also cause fatigue and/or nausea, decreasing the performance of the technicians and further decreasing their effective working hours[3](Dewan & Asgarpour, 2016). This makes utilizing CTVs as the primary way to transport technicians inefficient and typically not cost-effective for farms further offshore[3]. CTVs can however be used for corrective maintenance at farms further offshore, where they are then stationed in the wind farm with just the crew of the CTV onboard. Technicians are then picked up from a vessel or structure in the wind farm and deployed to the turbine[3]. Preventive maintenance can also be done by CTVs if there is an accommodation platform close to or in the wind farm[3].

CTVs are increasing in size due to the increase in size of the turbines. Larger turbines require larger tools and parts (4COffshore, n.d.-b; Dewan & Asgarpour, 2016). The increased size also improves the seakeeping behavior, increasing the length and occurrence of weather windows, especially in winter.

4.1.2 Service Operation Vessel with Daughter Craft

SOVs are used as the primary vessel to service large wind farms located far offshore, where transit times between port and the wind farm make the daily trips of CTVs inefficient[3](Dewan & Asgarpour, 2016; Hu & Yung, 2020). SOVs, therefore, act as an offshore maintenance hub with a large workshop and accommodation. Being able to house between 25 and 50 technicians, for two to four weeks (Hu & Yung, 2020). Most SOVs return to port after two weeks, however, in line with the rotation schedule of the technicians. These added facilities compared to CTVs mean that SOVs are significantly larger than CTVs, being typically between 57 and 96 meters long. SOVs need to be deployed in larger wind farms, or sets of wind farms to keep them occupied and justify their higher day rate, which is typically 8-10 times higher than that of CTVs, and can operate year-round due to their better seakeeping behavior (Hu & Yung, 2020). SOVs do need to return to port in bad weather if waves become too large. This is always the master's decision and depends on the duration of the adverse weather and the time too the next port call for example[3]. The conditions in which an SOV returns to port are therefore quite variable. SOVs are usually monohull designs, a SWATH SOV has however been developed by SGRE in combination with DEME. The advantages of a SWATH SOV are increased comfort (vibrations, noise, and motions) and flexibility in the layout design of the vessel, due to its square deck space[3]. An image of both types of SOV is shown in figure 4.2.

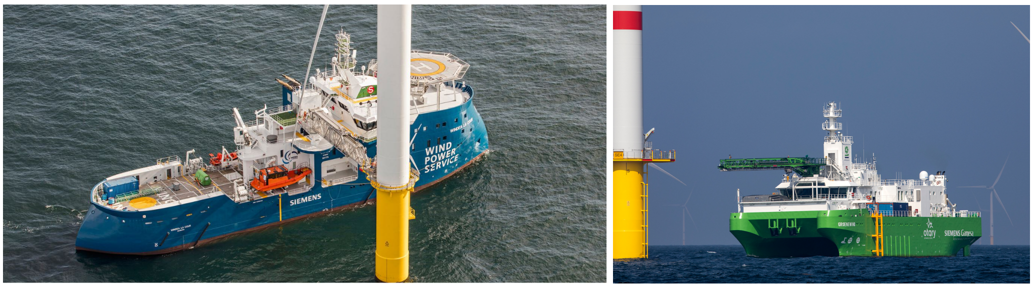
(a) Monohull (Ulstein Group ASA, n.d.)　(b) SWATH (VUYK Engineering, n.d.)

Figure 4.2: Service operations vessels

A fully supplied SOV usually sails to the wind farm during the night, so the technicians can start their work the next morning. The working hours of the technicians only start when they start working, so, when the day briefing starts onboard after which they transfer to the turbine[3].

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[3] From conversations with SGRE employees between May and August 2023

The transit time to the turbine is therefore not included in the technicians working hours and technicians can therefore have more time on turbine. This means that the transit to the wind farm can be performed at a slower speed, between 7.5 and 14 knots. This, in addition to its larger size, reduces the fatigue and nausea experienced by technicians (Hu & Yung, 2020). An SOV uses a dynamic positioning (DP) system when entering a turbine's safety zone to be able to maneuver accurately close to the turbine and prevent collisions. The safety zone of a turbine is usually a radius around the structure that can only be entered by O&M craft that aim to service the structure[4]. A walk to work (W2W) system is used to transfer technicians to the turbine, these systems can theoretically allow for safe transfer in waves up to 4.5m Hs (Ampelmann Operations B.V., n.d.; Hu & Yung, 2020). In practice transfer to the turbine is usually done in waves up to 2.8m Hs[4]. W2W systems can be integrated in a 'step less' way to enable spare parts and equipment to be wheeled over the gangway using trolleys, further improving access to the turbines. Some of the W2W systems can also double as a motion-compensated crane, with a capacity of one to six tons(Hu & Yung, 2020). SOVs can deploy technicians around the clock using different shifts to maximize its utilization. After two weeks the SOV usually returns to port during the night and spends one day resupplying before returning to the wind farm. SOVs can also be used to service multiple farms, possibly closer to shore. This has not gained significant traction in the market yet, because the service schedule of multiple wind farms need to sync up, which is difficult in practice[4].

SOVs mostly perform preventive maintenance. An SOV can also perform corrective maintenance but has slower response times due to its low transit speed and busy schedule when having multiple teams of technicians deployed on several turbines that all have to be retrieved before a certain time[4]. Some corrective maintenance can however be performed by the SOV's DC. This is a small vessel, 7 to 15 meters long that is usually stored and deployed from the SOVs side. DCs are mostly used for urgent unplanned tasks, such as resetting a turbine, but DCs can also be used to send technicians to turbines ahead of the SOV to prepare the turbine (Brans, 2021). They can also be used to increase the range at which technicians can be evacuated, this is however limited to times when wave conditions allow for the deployment of the DC[4]. DCs can transport 8-10 technicians and up to one ton of cargo at high speed, between 25-45 knots, from the SOV to a turbine (Brans, 2021). The technicians are transferred to turbines with a push-on maneuver, similar to that of CTVs. DCs have limited seakeeping capabilities due to their small size, being able to transfer technicians to turbines at waves up to 1-1.2m Hs[4]. This limits the deployability of the DC, especially in winter. An image of a DC is shown in figure 4.3 below.

Figure 4.3: Daughter craft (ESVAGT A/S, 2015)

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[4] From conversations with SGRE employees between May and August 2023

The planning of SOV operations is significantly restricted by the evacuation requirement if no other craft is available to perform the evacuation. All technicians must be deployed within a predetermined range. This will be called the evacuation radius in the rest of this report. The DC is not a reliable asset to perform this duty due to its low transfer limit and the SOV itself can be too slow to reach everywhere within the farm to evacuate technicians. A CTV is therefore sometimes used to increase the deployable range of technicians around the SOV. The CTV is then stationed in the wind farm with just its crew onboard and it picks up technicians from the SOV when maintenance has to occur at a turbine that is not within range of the SOV.

The industry has recently also developed so-called CSOVs, which stands for construction service operation vessel. These vessels are typically larger than SOVs and are normally exclusively used in the construction/commissioning stage of a wind farm's life cycle. These vessels are therefore not within the scope of this thesis.

4.1.3 Service Accommodation Transfer Vessel

A service accommodation transfer vessel (SATV) is a way to fill the gap between CTVs and SOVs. A way to service wind farms that are too far offshore to be serviced by CTVs efficiently but too small for SOVs to be kept occupied (Hu & Yung, 2020). A SATV is essentially a CTV that can accommodate crew and around 8-12 technicians for several days to two weeks, thereby removing the need to return to port every day and therefore being able to work cost-effectively at farms further offshore. The extra space needed for cabins increases its size relative to CTVs with the length of SATVs being typically slightly shorter than 40 meters. The operation of a SATV is very similar to that of an SOV, the transfer to the turbine is however usually performed with a push-on maneuver as with CTVs. Although the increased size of an SATV does allow for the installation of a W2W or bring to work (B2W) systems to increase the safety of the transfer operation (Foxwell, 2018). The increased size of the SATV also increases its seakeeping behavior relative to CTVs with SATVs being able to perform safe transfer in waves up to 2m Hs (Foxwell, 2018). SATVs typically operate at slower speeds than CTVs due to their overnight abilities, however, SATVs are usually faster than SOVs. SATVs typically operate between speeds of 16-25 knots. An image of an SATV is shown in figure 4.4 below.

The name SATV has not gained significant traction in the sector. Sometimes they are simply called large CTVs, but the name SATV is used in this report to make a clear distinction between vessels with CTV-like performance but that do and do not have the capability to accommodate technicians overnight.

Figure 4.4: SATV (Baird Maritime, 2019)

4.1.4 Helicopter

Helicopters are currently mostly used as a last resort when access by vessel is not possible or not fast enough[5]. Helicopters are therefore mostly used for corrective maintenance but can also be used for preventive maintenance or transport of parts. When to use helicopters depends on what the job is, how many technicians are required, and the parts needed for the job. The main advantage of a helicopter is its speed and the capability to deliver technicians and parts directly to the nacelle[5](Hu & Yung, 2020). Removing the need for further lifting operations, further speeding up the process. This speed does however not come with the same technician fatigue as with the CTV and the operational limits of a helicopter are also better than that of the vessels. Being able to operate in waves up to 6m Hs, which is the limit for ditching the helicopter in the sea in case of an emergency and wind speeds up to 23.5 m/s[5], allowing the helicopter to be used as a last resort. Helicopters do however have some extra weather limits. They cannot operate in freezing or thunder conditions and have to have a visual range of at least 2 km[5].

Helicopters currently always operate from an onshore heliport[5]. Technicians and parts are loaded and possible changes to the helicopter, such as taking out the seats are made, after which the helicopter flies to its destination. There it drops off its parts and/or technicians by hoisting them from a hover down to the hoisting deck, it then either flies to its next destination or back to base. The technicians and/or parts are then picked up by a later flight. The cargo capacity of a helicopter also includes the technicians, fuel, and even the weights of the seats. This means that fewer technicians can be flown in if heavier parts or more fuel is required. The total capacity depends on the air temperature, wind speeds, and the way the cargo is transported[5]. Either inside the helicopter, hanging in the hoist, or as an underslung load. The total capacity varies between 350 and 800 kg[5]. A helicopter used for offshore wind O&M is shown in figure 4.5 below.

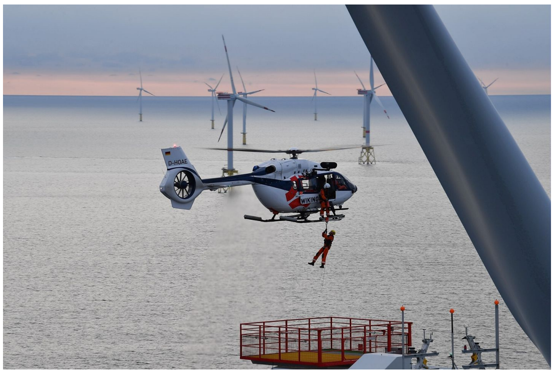

Figure 4.5: O&M Helicopter (SAS, 2018)

Helicopters are contracted in three different ways. Either with a monthly standing charge with a fixed minute rate; only with a minute rate (normally more expensive) or a committed number of flying hours[5]. An important addition to contracts is exclusivity. Since helicopters are often seen as a last resort they are usually shared with other clients, meaning the helicopter might not be directly available. Minute rates currently vary significantly from tens of euros per minute to more than one hundred euros a minute[5].

Offshore wind O&M is typically seen as a maritime endeavor and the use of helicopters is therefore often seen as a secondary, high cost, addition that is not considered to its full potential when creating the maintenance plan for a site. Some industry experts however think that helicopters could be a more beneficial asset to offshore wind O&M if they are better integrated

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[5] From conversations with SGRE employees between May and August 2023

with the use of vessels[6](WIND, n.d.). No literature researching this improved integration was however found.

4.1.5 Maintenance Craft Decisions

The choice of which maintenance craft are used at a specific site is made in a relatively simple way at SGRE. A site is typically seen as a CTV or an SOV site, based on the distance to the O&M port[6]. This works for most sites, however, some sites are too small for an SOV but too far offshore to service with CTVs so these sites are SATV sites. Employing helicopters is usually somewhat of an afterthought, either being required by law or seen as a last resort that needs to be arranged in a flexible manner. The decision between specific vessels is made based on the vessel's specific restrictions and the number of working hours required to complete the entire O&M scope. A slight overcapacity is planned to prevent large delays due to unforeseen events[6]. The vessel restrictions mainly include the compatibility with the W2W system if present and the general workability[6].

4.1.6 Push to Zero Emission O&M

Offshore wind is considered a low-carbon energy source, producing between 6-40 gCO2-eq/kWh (Bruckner et al., 2014) even though producing energy from the wind with a wind turbine does not produce any emissions. The aim of renewable energy sources is to be completely carbon neutral, so improvements still have to be made. The emissions produced by the offshore wind energy sector originate mostly from the phases before the O&M phase, such as manufacturing and installation (Siemens Gamesa Renewable Energy, n.d.; Spyroudi, 2021). The O&M phase has a smaller but not insignificant contribution, with most of the carbon emissions originating from the vessels used in this phase which burn fossil fuels. This also compromises the image of offshore wind since vessels are typically seen as severe polluters that are in this case servicing a 'clean' energy source.

There is therefore a drive to develop O&M vessels that use renewable fuels. O&M vessels are also relatively well suited to renewable fuels, due to the limited size of their working area and vicinity to renewable energy sources. The proposition to produce hydrogen at offshore wind farms plays a significant role in this respect. Hydrogen, ammonia, and methanol fuelled O&M vessels are therefore being developed and starting to get used (Buljan, 2023; Offshore Magazine, 2022b; OffshoreBIZ.com, 2022). Battery-powered vessels are also being developed with varying levels of battery power from, smaller battery packs used for peak shaving to vessels exclusively using the battery pack for its energy (Bureau Veritas, 2021). These renewable fuels or batteries are less energy dense than fossil fuels and therefore require either more space onboard and/or a higher bunker frequency. This can impact the operation of the vessels significantly, especially from a planning standpoint. Implementing alternative energy sources into the mother-daughter concepts is however not the focus of this thesis.

4.2 Mother-Daughter Concepts in Literature

This section will discuss the different craft proposed in literature and the service concepts in which they are proposed to be used. As discussed in section 2.4 there are a plethora of unmanned or even autonomous vehicles being developed to service wind farms in the future. These are however craft that aim to reduce the need for humans to be transferred to structures or even be present in a wind farm and therefore try to accomplish a completely different goal than this thesis. Additionally, these craft will likely have to be launched from a vessel operating in the wind farm for the short to medium-term future, still requiring more traditional O&M vessels to be present.

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[6] From conversations with SGRE employees between May and August 2023

All of the literature that proposes the use of new types of craft focus on creating an offshore base of some kind that typically deploys CTVs to perform the maintenance. These CTV type vessels meet the definition of a DC, according to the definition in section 1.1 and will therefore be called DC. These ships are however not to be mistaken for the DC that operates from an SOV as these are smaller boats that perform similar actions.

Enlarged SOV DC

The work of Kamerbeek (2022) and Almat (2015) propose the use of an enlarged DC onboard an SOV. The work of Almat (2015) only states the concept of using a enlarged DC deployed from a stern dock inside the SOV to transfer as many technicians as possible in the shortest amount of time. Thereby decreasing the time in which a wind farm can be serviced. It does not evaluate the performance of this concept but goes into the design of the enlarged DC. The work of Kamerbeek (2022) does look into the performance of this concept, although the concept is slightly different. In the work of Kamerbeek (2022), the enlarged DC is only used for corrective maintenance events, and the storage location of the enlarged DC is considered. Three main concepts are evaluated: storing the enlarged DC onboard the SOV (like a normal DC), towing the enlarged DC behind the SOV, and mooring the enlarged DC to several buoys in the wind farm. Kamerbeek used a direct simulation of weather over 21 years of hindcast data of three different wind farms. The model calculates all the weather windows to compare the accessibility of each concept and uses average number of transfers to turbines, number of turbines, and number of port calls based on the weather limits of the concepts to calculate the economic performance. All three concepts perform better than a conventional SOV with a DC, but the enlarged DC stored onboard the SOV performs best in the three wind farms considered.

Permanent Offshore Base and Multiple DC SOVs/Motherships

Avanessova et al. (2022) compares the performance of a normal SOV with a permanent offshore base for a floating wind farm, with 66, 15 MW turbines located 100 km from the service port in 100m water depth. The offshore base can accommodate three DC and the SOV has one conventional DC. Both concepts perform both preventive and corrective maintenance. The performance of the concepts is simulated using the COMPASS tool developed by ORE Catapult. It performs a time domain simulation with set failure rates for preventive and corrective maintenance that are used in a Monte Carlo simulation to determine the timing of failures. The results of the study show that the SOV has better financial and farm availability performance than the offshore base when it uses a separate foundation. An offshore base could potentially perform better when it is integrated with the wind farm's substation, thereby reducing foundation costs. The offshore base does produce lower CO_2 emissions than the SOV concept.

Dewan and Asgarpour (2016) analyzes the performance of several concepts for near and far offshore wind farms. The nearshore concepts are conventional but the far offshore concepts are more novel: an SOV capable of deploying two DC and a permanent offshore base capable of deploying three DC. Both concepts perform both preventive and corrective maintenance. The first concept is evaluated on a wind farm with 100, 8 MW turbines, located 150 km offshore. The second concept is evaluated on a wind farm with 200, 4 MW turbines, located 150 km offshore. The performance of the concepts is calculated using the ECN O&M Access tool, a commercially developed tool that was used in consultancy for the Borssele wind farm tenders. The tool translates wave conditions using hydrodynamics of the vessels to vessel motions, technician fatigue, and therefore operability. The results of this study show that the SOV has a lower cost per kWh and higher farm availability than the permanent offshore base.

Dalgic, Lazakis, Dinwoodie, McMillan, Revie, and Majumder (2015) has compared the performance of three concepts to a CTV concept baseline, including different chartering durations, for a wind farm with 150, 3.6 MW turbines located 50 nm offshore in 250m water depth. The three concepts are a permanent offshore base, a hotelship, and a pro-active mothership. The permanent base does not accommodate the DC but they can moor alongside it. This is also the case for the hotelship but the pro-active mothership also has three DCs if the CTVs are all in use. The study uses the StrathOW-OM planning tool and stochastic weather (wind and waves) and turbine failures to calculate the availability of the wind farm, the travel time and utilization of the CTVs/DC, and the financial performance. The results show that a permanent base has the best financial performance, closely followed by the two floating concepts when operating year-round. The differences in the availability ranges between the concepts are not very significant. All concepts use a corrective maintenance strategy. This strategy does not reflect current or future O&M activities since this strategy has been proven inferior to preventive or condition base maintenance. No firm conclusions can therefore be drawn from this article, only an indication that a permanent offshore base could be effective.

McCartan et al. (2015) proposes a vessel designed to deploy 4 DC from a SWATH mothership that can store the DC onboard. The work of McCartan et al. (2015) focuses mostly on the spatial design of the mothership and the construction of the lifting mechanism to bring the DC onboard. The performance of this concept is not evaluated.

4.3 Concluding Insights

Sub-question 3: Which craft are involved in offshore wind farm maintenance and what mother-daughter concepts are discussed in literature? Is answered in this chapter. The answer to this question, other conclusions from this chapter and the research gaps that have emerged are discussed below.

CTVs, SOVs with their DC, SATVS, and helicopters are used in offshore wind farm O&M. CTVs are used to transfer technicians and parts for maintenance to nearshore wind farms. SOVs are used for large far offshore wind farms and act as a maintenance hub with a workshop and storage space of parts. SOVs often have a small DC that can be used to assist it. The seakeeping capabilities of the DC are however very limited due to its small size. This causes the workability of the DC at far offshore sites, in for example the North Sea, to be so limited that its value at these sites is debatable.

The SOV without a DC or other assisting craft is limited in its activities due to its small evacuation radius and is therefore poorly suited to perform corrective maintenance, especially at newer wind farms with larger turbines. A CTV can be used to assist the SOV, thereby increasing this range. The CTV can in this case stay offshore for longer periods but still has to make the trip back to port for crew changes or bad weather, which can occur often in the winter. An SATV is also used at far offshore wind farms but these vessels are used to service smaller wind farms. Helicopters are currently mostly used as a last resort, being used when access by vessel is not possible or too slow. These craft are seen as an add-on after the logistics plan has been set up, based on the marine-based options. Experts however think that helicopters could provide extra benefits if they are better integrated. Literature has however not researched this.

Several studies have evaluated the performance of mother-daughter concepts. All the concepts in these studies use CTV-type vessels as DC. The motherships are more diverse however, with some being able to perform maintenance whilst some can not. The number of DC also varies. The concepts however appear to be randomly chosen. It is at least not obvious if these concepts are the most optimal mother-daughter concepts for these wind farms. Nor is this stated. The wind farms that are used to evaluate these concepts are also not as large as some wind farms will be in the future or use smaller turbines that have smaller distances between them.

The following research gaps are identified based on this research:

- No other craft than a CTV-type vessel has been considered as a DC in a mother-daughter concept.
- It appears that no optimization has taken place to see what an optimal mother-daughter concept is.
- No mother-daughter concept has been evaluated in the larger wind farms of the future.
- Better integration of the helicopter in the O&M activities has not been considered in literature.

5 Fleet Evaluation Method

This chapter will discuss the method that has been created to explore the design-space of mother-daughter concepts for offshore wind farm O&M based on the findings of the previous chapters and therefore answer the main research question:

What method can best be used to explore the design-space of mother-daughter concepts for offshore wind farm O&M?

Section 5.1 starts by evaluating the various modeling methods that have been used in literature for similar analyses and provides an overview of the method proposed in this thesis. The input for this method is discussed in section 5.2, followed by an explanation of the workings of the model in section 5.3. Section 5.4 discusses the number of simulations that are required to obtain reliable results from the model. This chapter concludes with a discussion on model improvements and alternative uses in section 5.5. An example of the application of this method is shown in chapter 7 based on a case study. This example is also used to determine the sensitivity of the model to input changes and to draw some preliminary conclusions of the performances of fleets.

5.1 Methodology

The previous chapters have established that using an SOV together with its DC will no longer be able to deliver the required performance when the footprints of wind farms and the spacing between turbines increase. Literature study has shown that:

- Only the performance of a handful of new concepts has been evaluated without any clear reason why only those concepts are proposed.
- No study has evaluated the usage of helicopters for far offshore wind farms in this context.

The methodology created in this thesis should therefore be able to evaluate the performance of a large number of fleet configurations to explore the design space. **The most important factors to take into account are the weather conditions and the restrictions caused by the evacuation requirement.**

This section starts by providing an overview of the modeling methods used in literature for studying similar problems to that of this thesis. A modeling method is then selected based on the specific demands of this problem. An explanation of the method proposed to answer the main research question is then given in section 5.1.2.

5.1.1 Performance Assessment Methods - Literature Review

Modeling Method

Assessing the performance of fleet configurations and finding the best-suited fleet for the application is a well-known problem. So-called fleet size mix problems have been researched extensively for the application of offshore wind farm maintenance. Many articles have tackled this problem and some software packages have been created to calculate the operational expenses of different fleets (Sperstad, Stålhane, Dinwoodie, Endrerud, et al., 2017). Most of these packages are however not publicly available. The articles either use deterministic optimization modeling, stochastic programming modeling, or simulation modeling to determine the optimum fleet. The software packages all use the simulation approach. The three approaches are briefly discussed below.

Deterministic and stochastic modeling uses an analytical formulation and objective functions (usually cost) solved by either a mixed integer programming or a mixed integer linear programming approach to find the optimum fleet. The stochastic approach however incorporates uncertainty in variables such as weather, electricity prices, or charter rates. The advantage of this modeling method is that the problem is reduced to a clear mathematical formulation, which speeds op computational time. The drawback of this is that the scheduling of visits becomes a more abstract process, this has so far however not been an important issue. Halvorsen-Weare et al. (2013) and Gutierrez-Alcoba et al. (2017) use a deterministic approach and Stålhane et al. (2016, 2019, 2020), Bolstad et al. (2022), Gutierrez-Alcoba et al. (2019) and Gundegjerde et al. (2015) use a stochastic approach to find the optimum fleet.

The simulation approach consists of making a model that makes multiple fleet configurations carry out the same operational events to determine the best-performing fleet, based on any of the output parameters. This approach is more flexible in how behavior is modeled but does require more computational time. Dalgic, Lazakis, Dinwoodie, McMillan, Revie, and Majumder (2015), Dalgic, Lazakis, Dinwoodie, McMillan, and Revie (2015), Dinwoodie et al. (2015), Halvorsen-Weare et al. (2017), and Tusar and Sarker (2023) use a simulation approach to find the optimum fleet. Additionally, the following simulation software packages have been created: NOWIcob, MAINTSYS, ECUME, StrathOW-OM, MARINTEK, COMPASS, Shoreline, and DTO Ocean +. Many of these packages have been created by the authors of the previously mentioned articles (Sperstad, Stålhane, Dinwoodie, Endrerud, et al., 2017). Non of these packages are however publicly available and can therefore not be used for the purposes of this thesis.

It is important to note that all these modeling methods focus on uncertainties caused by weather or prices. **None of the above-mentioned studies discuss the limitation caused by the evacuation requirement, however.** Probably because this did not used to be a significant restriction. Including this new constraint can more easily and accurately be done using the simulation approach because the modeling freedom of this method enables the algorithm to closely mimic the real-life process. The magnitude and complete behavior caused by this constraint are not well known because this is the first time that this is being modeled. Making an accurate abstract reduction for the deterministic/stochastic approach of the influence of this constraint is therefore more difficult.

The incorporation of the evacuation requirement is therefore the reason why the simulation approach is chosen for this study. The following simulation methods were considered to model the transportation of technicians through the wind farm: Queuing Theory, multi-agent modeling, and Discrete-Event Simulation (DES). These three are discussed below.

Simulation Approaches

Queuing theory can be used to determine the capacity of certain systems, such as the number of cash registers at a supermarket based on the waiting times (The Investopedia Team, 2023). These models consist of customers and servers. The servers can complete tasks that the customers require to happen. This service takes time however which is why queues are formed. The servers would in this case be the maintenance craft and the customers would be the turbines. Queuing theory uses stochastic inter-arrival times of customers to trigger the service process (The Investopedia Team, 2023) but is not able to let the work of the server wait until a certain condition is met, for example, if there is a weather window. Queuing theory is therefore not suitable to model the transportation process of technicians through a wind farm.

Multi-agent models are models that use autonomous agents in an environment that make decisions under specific predetermined policies (The Alan Turing Institute, n.d.). These models are used to solve dynamic transport problems, such as the dial-a-ride problem, which is a problem where X number of passengers need to be transported to different locations at different times with Y number of vehicles in an efficient manner (Van Lon et al., 2012). This bears resemblance to this problem, where the technicians are the passengers and the locations are the turbines and the vehicles are the maintenance craft. Multi-agent models require significantly more time to set up correctly, however, making them less suitable to use for this thesis.

DES is a simulation method that uses events to trigger system state changes instead of simulating every time interval, to save computational time (SoftwareSim, 2022). A DES consists of entities that flow through the model, generators that generate these entities, and resources that are used to complete the tasks of the entities (SoftwareSim, 2022). DES has been used for multiple tools that have been created to determine the optimum fleet for offshore wind turbine maintenance (Sperstad, Stålhane, Dinwoodie, Endrerud, et al., 2017) and is very flexible in registering output variables.

The flexibility, ease of modeling, and the fact that this is a proven modeling methodology for this purpose are the reasons why a DES is used to assess the performance of the different fleet configurations. Multi-agent modeling would also be a useful method, especially to see the combined effects of planning policies and different craft (characteristics) but this requires significantly more time to set up and provides a level of detail that is not required for this purpose.

5.1.2 Performance Assessment Approach

The method proposed in this thesis uses a DES that simulates the transport of technicians throughout the wind farm to execute maintenance visits. A large range of fleet configurations and wind farms can be input into the model to explore the design space and investigate the influence of wind farm layout parameters. The performance of the different fleet configurations is assessed based on the metrics listed below. The secondary metrics are recorded and used to further support decision-making.

- **Primary metrics**
    - Availability/cumulative turbine downtime

      To assess O&M performance of the fleet configuration.

      The calculation of the turbine downtime for corrective maintenance assumes that the turbine has stopped at the visit inception time and starts when the visit has been completed. This is in reality not always the case since not all issues on the turbine directly cause the turbine to stop. This time is therefore more a reflection on how quickly a visit has been executed since. This is therefore a simplification, but this metric does provide meaningful insight into how quickly a fleet can perform the required maintenance and allows for fair comparison between fleet configurations. The downtime calculated by this model should therefore also not be directly compared to the downtime of operational wind farms.

  - CO_2 emissions

    To assess the future viability of fleet configuration, considering carbon taxes and energy requirements for adaptation of cleaner energy sources.

    The emissions are calculated using the estimated fuel consumption of each craft, the carbon factor of the fuel each craft uses, and the number of hours each craft has operated. A more detailed explanation is given in section 5.3.7.

- **Secondary metric**
  - Craft utilization rates

    To assess the usage of all craft

    The utilization rates are the number of hours each craft is used during the simulation divided by the total number of hours that the technicians could have worked.

The financial performance of these fleet configurations is not directly estimated, because some of the craft within these fleets have not yet been developed.

The model simulates both planned and unplanned maintenance visits, excluding major component exchanges because these require a heavy lifting crane which is outside of the scope of the mother-daughter concepts. **Whether visits can be executed is determined based on weather, available technicians, and craft availability, and are constrained by the evacuation requirement.** The planning algorithm aims to show the true performance of each fleet configuration without optimizing the planning.

Each fleet configuration-wind farm combination should be run a set number of times (see section 5.4) with annually varying weather conditions and workloads to obtain an accurate estimation of the downtime and to evaluate the robustness of each fleet configuration. The number of runs is determined based on the level of accuracy of the estimated total downtime and fleet rank position. The weather and workload are however the same for every fleet configuration in the same run. Fleet A will therefore be confronted with the same circumstances as Fleet B during run one. Run two will then have different weather and workload compared to run one. The simulation itself is however deterministic because the duration of each event is set in the input. This is done to limit the complexity of the planning algorithm and aids in the comparability of the results of different fleet configurations. This removes the effects that delays have on performance. These effects are however mostly relevant and dealt with using good planning. The goal of this thesis is however to create a method to evaluate the performance of different fleet configurations, not to create the best possible planning algorithm. A planning algorithm is however required to assess the performance of the fleets.

Using a DES for a deterministic simulation may seem unnecessary because the schedule that the planning algorithm makes should represent what happens in the simulation, but it has several advantages. The functions in the DES library (SimPy) in Python provide the infrastructure on which the simulation is built. The DES environment is also able to incorporate effects that are not taken into account in the planning algorithm for example. The added value of this is explained in section 5.3.6. Using a DES instead of a pure planning tool also allows for easier and more diverse future development of the model. The potential downside of using a DES over building a planning tool is extra computational time, assuming that the planning tool can be built efficiently in a relatively short time.

The results of the model need to be graphically analyzed to determine the best types of fleet configurations because the financial performance of each configuration is not estimated. Simply selecting the fleet with the highest availability will likely result in choosing the most expensive or complex configuration, which will most likely not be the most efficient fleet when taking into account financial performance later on. The fleets are divided into groups that use the same crafts to understand the performance differences between each group. A relatively easy selection can then be made based on common sense to select the most promising fleets. An example of this analysis based on a case study is shown in chapter 7.

5.2 Model Input

This section will discuss the input required to run the model. The model requires 8 input groups. The input groups are divided into fleet configurations, site dependent input, and default input. The default data can still be altered but is presumed to be general for all simulations.

5.2.1 Exploratory Set of Fleet Configurations

The fleet configurations input into the model can be varied but a standard exploratory set has been created to cover most of the design space. This exploratory set is discussed in this section. Each craft is described using the following parameters:

- Number of technicians (only mothership)
- Number of craft present (always only one mothership)
- Transfer limit
- Transfer time
- Transit speed

The goal of this exploratory set is to evaluate significant portion of the possible configurations. Most of the fleet configurations will feature relatively normal craft characteristics to evaluate the possibilities available today. Some configurations that have more extreme values are considered to indicate where investing in innovation might be beneficial. SATVs are not included in this set, since it does not make sense to have technicians sleep onboard a CTV-type vessel while a larger mothership is in the area. Additionally, larger vessels that can transport multiple technician teams are not included in this set due to the limitations of the simulation. The number of fleet configurations that can be evaluated is however limited by the computational time of the model. Table 5.1 shows the different craft and their characteristics that have been evaluated. The number of unique fleet configurations based on this table is 1200.

Table 5.1: Craft characteristics

	Number of craft	Transfer limit	Transfer time	Speed
Mothership	1	0, 2, 2.5 or 3m Hs	30 min	6 knots/12 knots
DC	1 or 2	1.5, 2 or 2.5m Hs	17 min	20 knots
CTV	0 or 1	1.5, 2 or 2.5m Hs	17 min	20 knots
Helicopter	0 or 1	3000m visibility	7 min	130 knots

The minimum visibility requirement is set to 3000 m, based on helicopter operations using one pilot[1]. In reality, helicopter operations are sometimes also conducted with two pilots which lowers this requirement to 2000 m[1]. The difference in number of hours in which this criterion is met is low, so the limit of 3000m is applied to simplify the model and be conservative in the hours the helicopter can be used. The speeds and transfer times are determined in collaboration with company experts and include time to carefully approach and depart the turbine exclusion zones.

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[1] From conversations with SGRE employees between May and August 2023

Every configuration in the model has one mothership. This ship serves as the offshore home of the technicians. Only one mothership is present in each configuration to limit the complexity of the planning algorithm. The assessment of using two motherships on the same farm can still be done using this approach by dividing the wind farm in half and assigning one mothership to each half. The mothership can accommodate 30, 40 or 50 technicians overnight. The lower and upper bounds are chosen based on the capacity of currently operating SOVs. The transfer limit range of 0, 2, 2.5, and 3m Hs is chosen to evaluate a similar range to current SOVs. Increasing the transfer limit further is likely to be ineffective since technicians do not feel comfortable transferring in conditions with significant wave heights higher than 3m Hs [2]. The transfer limit of 0 is chosen to evaluate the performance of a mothership that is fixed at one location and does not transfer technicians to turbines. This configuration can be seen as an offshore platform.

The maximum of two DCs and one CTV is determined based on the number of unplanned visits that could be completed by a 50-person mothership with a day and a night shift. One CTV is added instead of a third DC because it is expected that this worst-case scenario will not occur often, so it will most likely not be cost-effective to increase the size mothership to accommodate another DC. The range of transfer limits is chosen based on what might be necessary. A transfer limit of 2.5m Hs might however be very difficult to achieve for a DC without becoming too big to be recovered by the mothership. This transfer limit is however included to see if further innovation in this area would be useful.

One helicopter operating from the mothership is included to see how it will be used and what effect its presence has on the performance and characteristics of the mothership and DCs. A helicopter operating from shore is also relevant to evaluate. However, this would require additional modeling efforts while the effects will be largely similar to the helicopter operating from the mothership. The operating criterion for the helicopter is visibility since this is its most restrictive weather parameter. It is assumed that all craft can transport enough technicians and equipment to perform all types of maintenance visits, see section 4.1.

5.2.2 Site Dependent Input

Wind Farm Layout

Any wind farm can be put into the model: real or fictional. The layout of the turbines used to calculate the sailing distances can either be the turbine coordinates of a real farm or a grid layout based on the number of turbines, number of rows of the grid, and the inter turbine distance. A wind farm is therefore defined by the following parameters:

- Real Wind farm
    - Turbine coordinates
    - Distance to port
- Fictional Wind Farm
    - Number of turbines
    - Number of grid rows
    - Inter turbine spacing
    - Distance to port

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[2] From conversations with SGRE employees between May and August 2023

Weather Data

The weather should be a time series containing the significant wave height in meters and the visibility in kilometers. Hind cast data can typically be used as input with no modifications. The length of the time series should be slightly longer than simulated time to prevent the simulation from running out of weather data.

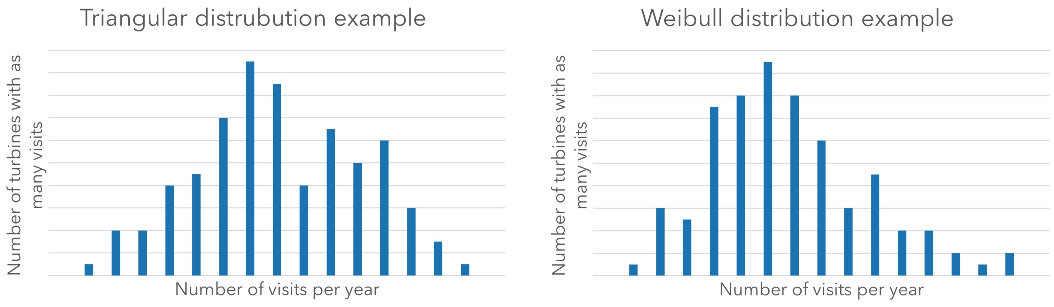
Visit Agenda

The visit agenda is a table that contains the visit information for each turbine visit, both preventive and corrective. Each visit has the following parameters:

- Visit inception time (Time at which it is known a visit is required)
- Visit duration
- Required number of technicians
- Turbine ID
- Maintenance type (either preventive or corrective)

Each simulation run has a different visit agenda. These agendas are generated using probability functions. The shape of these probability functions is based on those seen in real-world data of ten operational wind farms, five CTV sites, and five SOV sites. Exact copies can however not be used in this thesis due to confidentiality. The visit agendas are made by first assigning how many times each turbine is visited for corrective maintenance. Each turbine visit is then assigned an inception time, duration, and number of required technicians.

The distribution for the number of corrective visits per turbine show two general shapes. Either resembling a triangular or Weibull distribution. Some examples of what the actual data looks like are shown in figure 5.1. The triangular distribution is used to generate the visit agenda's. The minimum and maximum of this distribution can be changed based on site specific parameters.



(a) Triangular distribution

(b) Weibull distribution

Figure 5.1: Visit distributions

The distributions for the visit duration are more varied. Four out of five CTV sites have two humps while the distributions for every SOV site are different. Some examples are shown in figure 5.2. A flat distribution from 0.5 to 10.5 hours is chosen to generate the duration of each visit, because of the variability in the shapes. The other visit parameters are also generated with a flat distribution, because the distribution of these parameters is unknown. The minimum number of technicians for a visit is 2 and the maximum is 6. These numbers typically do not change per site.

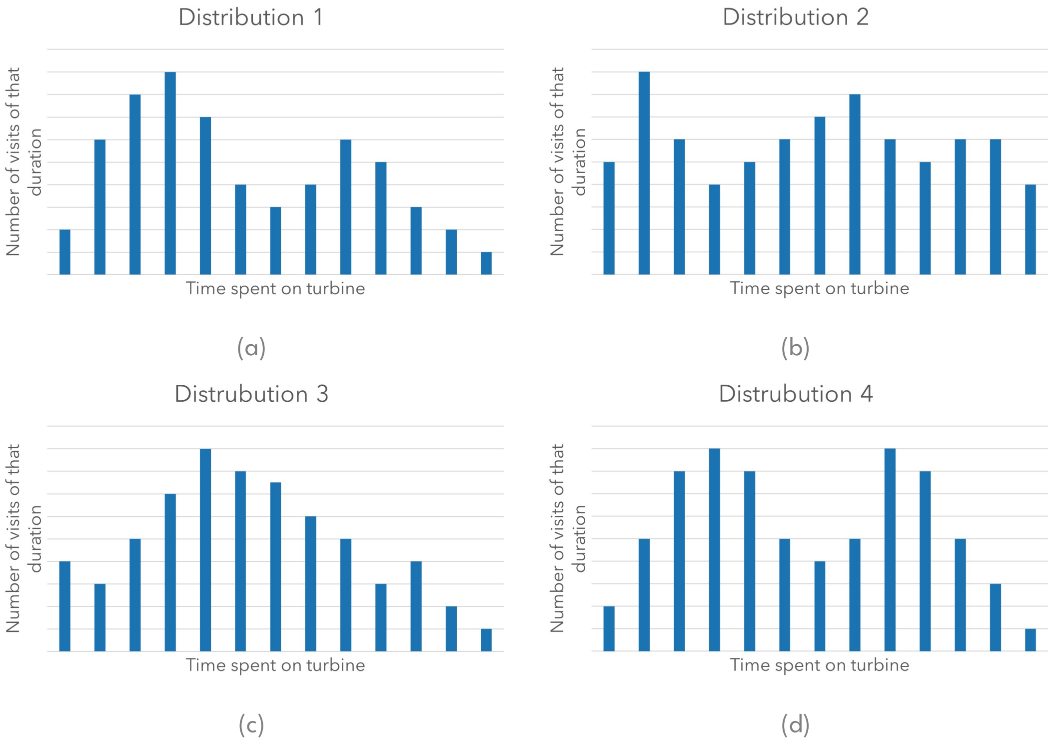


Figure 5.2: Visit duration distributions

The preventive maintenance visits are divided into two kinds, the lift inspection and annual service. Not all sites require a dedicated lift inspection visit and the contents of the preventive maintenance visits may vary based on the turbine type and operational year. The number, type, and duration of preventive visits is therefore input for the model. The order in which these visits are performed is however typically roughly the same from site to site. this is typically done in a column by column fashion. So, the first two visits are performed on the first two turbines in the first column of the wind farm grid, followed by the second two, and so on, see figure 5.3. An overview of the input for the visit agenda is shown below:

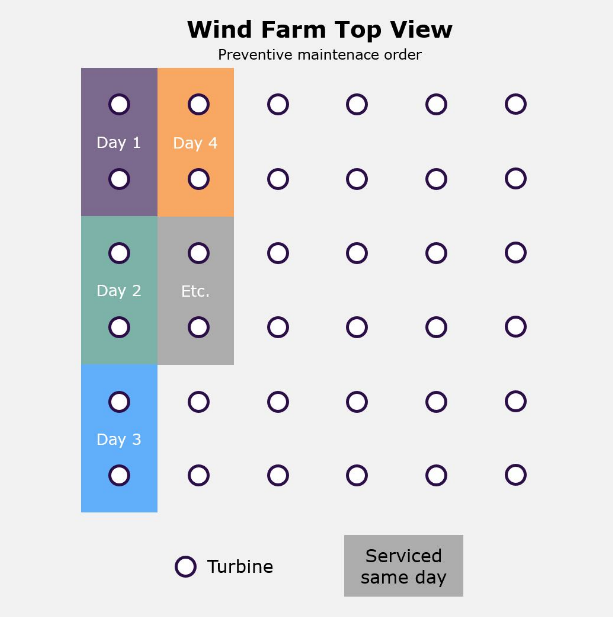


Figure 5.3: Preventive maintenance order

- Preventive visits
  - Number of lift inspections/annual services
  - Number of technicians required for lift inspections/annual services
  - Duration of lift inspections/annual services
- Corrective visits
  - Minimum and maximum for number of visits per turbine distribution

5.2.3 Default Input

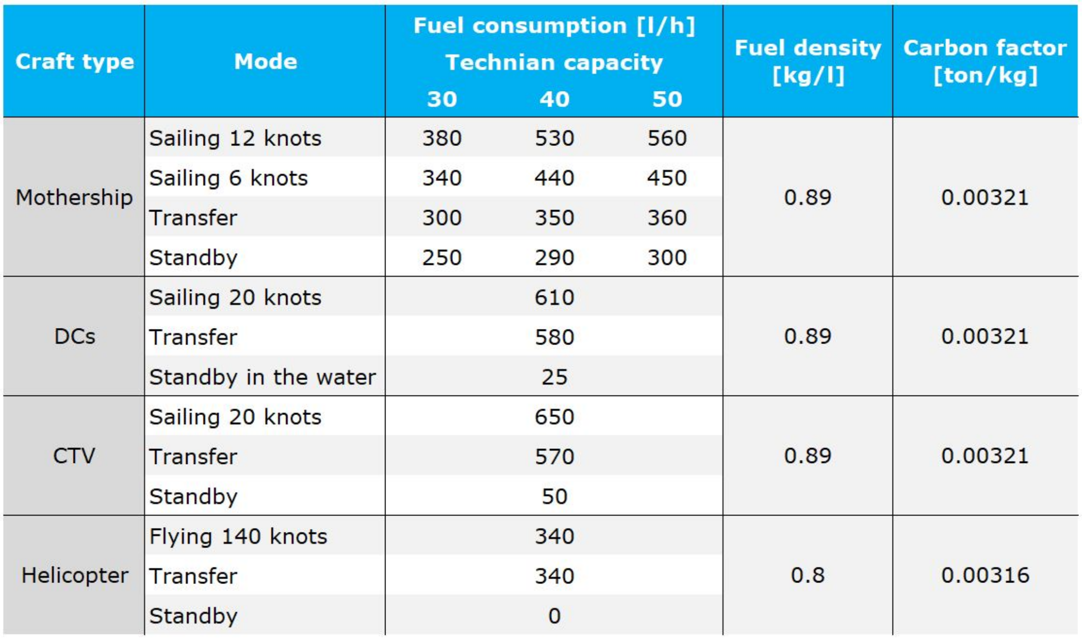
Technician Shifts and Port Calls

Technicians are typically allowed to work 12 hours every day. In some countries the shifts are scheduled during the day and night, however, in most countries maintenance is only performed during the day due to the added regulations for working during the night [3]. The technicians therefore only work during the day in this simulation. The technician pool is divided into three separate shifts that start separated by one hour. This is done to prevent overloading the craft at the start of the shift, meaning that technicians have to wait until the first round of technicians is deployed to other turbines. Port calls are scheduled once every 2 weeks and take one day. This is a typical port call interval and duration for an SOV.

Emission Calculation Data

The emission calculation uses the hourly fuel consumption of the craft and the carbon factors of their fuels to estimate the CO_2 emissions of the fleet. This calculation is explained in more detail in section 5.3.7. The fuel consumption, fuel densities, and carbon factor input values are shown in table 5.2 below. The fuel consumption figures are based on operationally observed values from different classes of craft by SGRE.

Table 5.2: Emission input data



Craft type	Mode	Fuel consumption [l/h] Technian capacity			Fuel density [kg/l]	Carbon factor [ton/kg]
		30	40	50		
Mothership	Sailing 12 knots	380	530	560	0.89	0.00321
	Sailing 6 knots	340	440	450		
	Transfer	300	350	360		
	Standby	250	290	300		
DCs	Sailing 20 knots		610		0.89	0.00321
	Transfer		580			
	Standby in the water		25			
CTV	Sailing 20 knots		650		0.89	0.00321
	Transfer		570			
	Standby		50			
Helicopter	Flying 140 knots		340		0.8	0.00316
	Transfer		340			
	Standby		0			

The fuel consumption of the motherships is expected to be close to that of SOVs but not the

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[3] From conversations with SGRE employees between May and August 2023

same due to the extra space and equipment onboard required for the storage of the larger DC. SGRE divides SOVs into three classes based on the number of technicians it can house (24, 40, and 90 technicians). The fuel consumption varies significantly between these classes due to the difference in the physical size of the vessels and HVAC loads. The fuel consumption figures of the motherships will therefore be different for different size motherships. The fuel consumption figures for each SOV size class are shown in figure 5.4. The fuel consumption figures for the different-sized motherships are derived from linearly interpolating these fuel consumption figures based on the number of technicians. SOVs typically reduce their speed when within the wind farm to 6 knots. This operational mode is however not present in the data. The fuel consumption values for this operational mode are derived from linearly interpolation of the values of the transfer and sailing at cruise speed. This is most likely an overestimation since the relation between power and speed is cubed. This overestimation will therefore increase the difference in emissions of the fleet configurations with a sailing mothership compared to the ones that have a motherplatform. This however does not influence the interpretability of the results since there will always be a distinct gap in emissions between these two groups, caused by the total absence of any motherplatform emissions (assumed to be powered by the electricity from the wind farm).

The operational fuel consumption values of the CTVs are used for both the CTV and the DCs since the design of these vessels are very similar vessels in this study. CTVs are divided into five classes by SGRE, see appendix B. The values for the DC are taken as the CTV class with a transfer limit of 1.75m Hs and an autonomy of 0 days since the DC will be recovered by the mothership every evening. The CTV values are taken as the class with a transfer limit of 1.8m Hs and 7 days of autonomy since it needs to remain in the wind farm for multiple days.

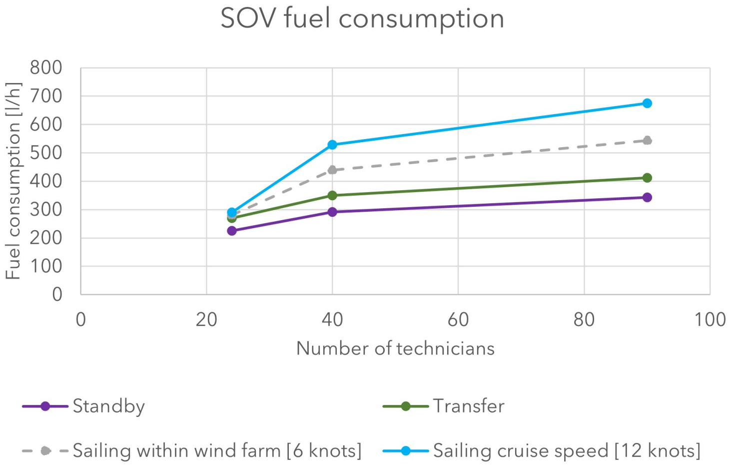

Figure 5.4: SOV fuel consumption

The fuel consumption of helicopters in the different operational modes is not as well known as for the vessels. The assumption is made that the fuel consumption is roughly the same in all modes. This is a simplification but is not as influential as for the other craft since the time spend in each operational mode is much smaller per visit. The fuel consumption value is based on the consumption at cruising speed of several helicopters used in offshore wind O&M.

The vessels and helicopters burn different fuels. The ships in the model burn Marine Diesel Oil (MDO) while the helicopter burns jet fuel. They therefore have a different fuel density carbon factor.

Evacuation Criterion

Laws for evacuating offshore turbines vary worldwide and even within Europe. Most countries however require evacuation teams to reach the turbine's TP platform within around half an hour. This response time can however vary from site to site based on the emergency response plan of each site, which takes into account the specific circumstances and challenges of the site. The evacuation criterion is therefore set to half an hour. This includes transit to the turbine and transfer to the TP.

Craft Selection Order

The planning algorithm uses a particular order in which it checks if the craft are available for a particular drop off or pick up operation. The first craft for which all conditions are satisfied will then be selected. There are three selection orders, one for preventive visits, another for corrective visits, and one for which craft will perform an evacuation if necessary. The selection order for preventive maintenance is based on which craft can provide the most time on turbine and overall ease to perform the annual service. The selection order for corrective maintenance and the evacuation is based on the speed of the craft, since reducing transit time is crucial for an evacuation and increases to potential time on turbine for technicians. It is however interesting to see what effect the selection order for corrective visits has on the downtime so two different orders can be used. The priority orders are shown below. The position in the order of the mothership is not adjusted because performing more corrective maintenance with the mothership is unlikely to be more effective. The order of the other vessels is also not changed because operationally they are not any different to one another.

Preventive maintenance order	**Corrective maintenance order 1**	**Corrective maintenance order 2**	**Evacuation Selection order**
1. Mothership	1. DC 1	1. Helicopter	1. Helicopter
2. DC 1	2. DC 2	2. DC 1	2. DC 1
3. DC 2	3. CTV	3. DC 2	3. DC 2
4. CTV	4. Helicopter	4. CTV	4. CTV
5. Helicopter	5. Mothership	5. Mothership	5. Mothership

5.3 Model Architecture

This section will explain how the fleet evaluation model works and which assumptions were made to construct it. Sections 5.3.1 - 5.3.3 together with figure 5.5 provide an overview of the model. The functioning of the individual parts is then explained in more detail in subsections 5.3.4 - 5.3.7.

The model aims to evaluate the performance of the different fleet configurations. It uses the wind farm layout, weather conditions, and workload (visit agenda) to calculate the resulting downtime and CO_2 emissions. The model is a DES that models the process of a maintenance visit, from inception to completion. It consists of three sub-processes: The drop-off, work, and pick-up process. The drop-off process contains a relatively simple planning algorithm, used to schedule the visits and assign the craft to perform the drop-off and pick-up of the technicians. It also contains the DES of the activities that are required to drop the technicians off at the turbine. The planner by no means creates the most optimum visit schedule, since this is a complete line of research on its own, but delivers a reasonable schedule that allows the different fleet configurations to be compared to one another. The planning algorithm used in this model aims to find the first opportunity that the visit can be scheduled. It therefore does not try to optimize any other parameters. The corrective visits are planned based on a first come first serve bases, while the preventive visits get priority over the corrective visits.

The work process simulates the work done by the technicians on the turbine and the pick-up process consists of all the activities required to pick the technicians up from the turbine and bring them back to the mothership.

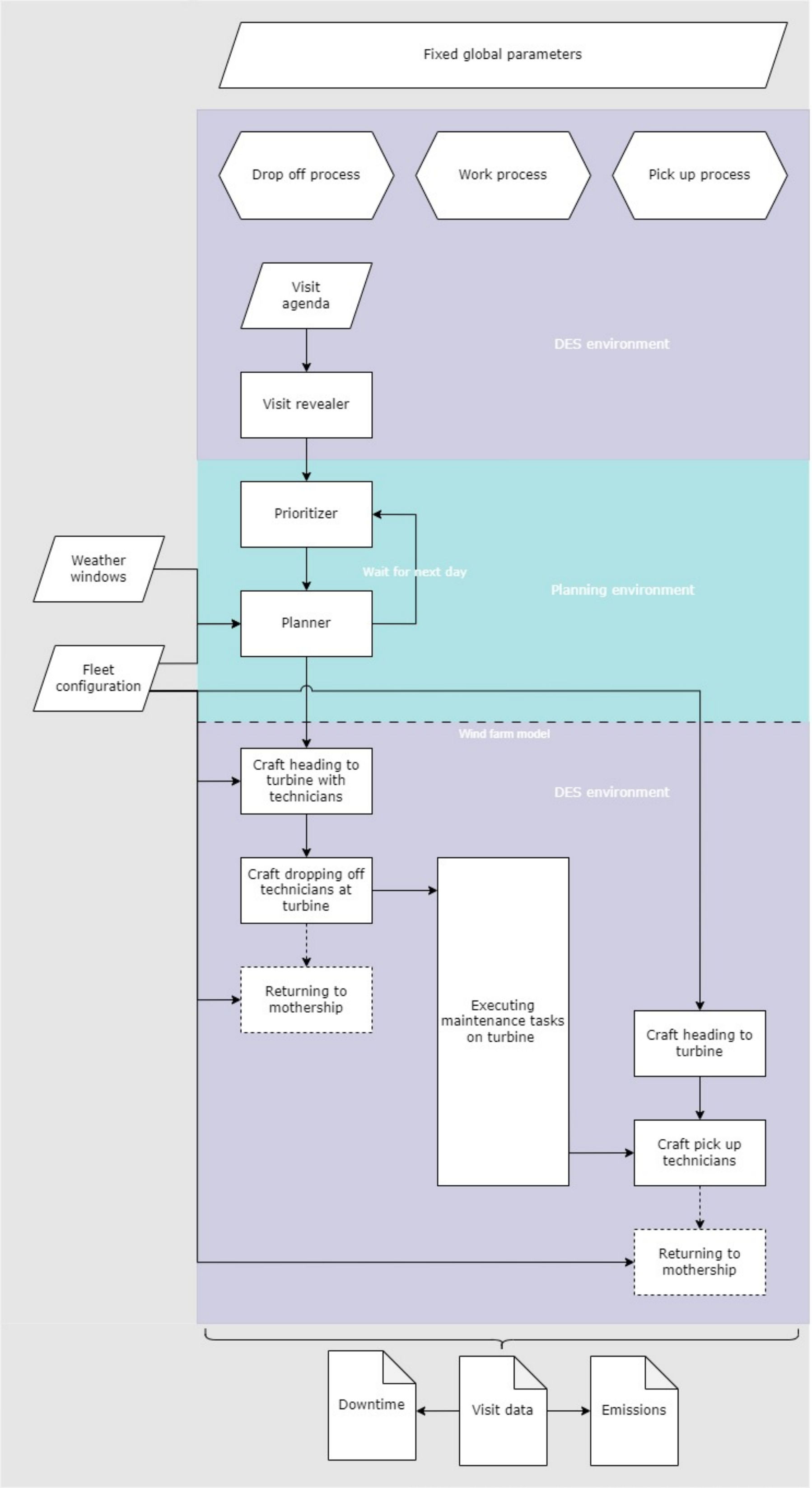

Figure 5.5: Model overview

5.3.1 Assumptions

This subsection describes the assumptions on which the model is built. These assumptions are divided into three different categories. General assumptions, assumptions around the processes of the technicians and craft, and assumptions used to construct the planning algorithm.

General

- All corrective jobs have the same level of priority
- The turbine has stopped producing power once it should be visited for a corrective visit and starts producing power after the work on the turbine is completed
- Preventive visits only cause the turbine to stop for the duration of the visit
- All technicians have the same competencies
- Technicians always deliver the same performance (e.g. are never sick)
- Craft do not suffer mechanical or other issues
- All craft are conventionally fueled (MDO or jet fuel)

Process

- There is no variability in the duration of events (e.g. a visit that should take 6 hours, takes 6 hours, or sailing from turbine 5 to 10 with the same craft always takes 15 minutes)
- The support craft drop-off/pick-up one set of technicians at a time and therefore always only transfer to/from one turbine and return to the mothership
- DC(s) and CTV follow the mothership when not used for drop-off/pick-up operations
- a DC is stored onboard the mothership when the significant wave height is larger than its transfer limit and during night
- The CTV has the same timing of port calls as the mothership (so, no visits can be completed during a port call)
- The CTV is in the wind farm when the significant wave height is lower or equal to its transfer limit, otherwise it is in port/traveling to or from port.
- All craft follow the routing plan shown below:

Planning

- Significant wave height and visibility are the only weather criteria because these are the most restrictive
- Weather predictions are 100% accurate
- Take-off/landing of the helicopter is not affected by the activities of the mothership
- The helicopter can perform heli-hoist operation irrespective of the orientation of the nacelle and blades of the turbine.
- If a technician is deployed until 1 minute past the whole hour then it is reserved for the entire hour (e.g. technician is deployed until 6:01 then it cannot be deployed until 7:00)

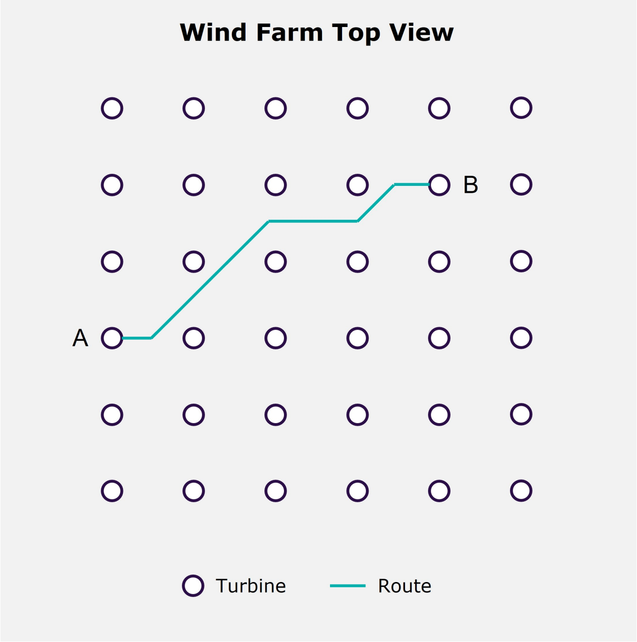

Figure 5.6: Craft routing

5.3.2 Environments

The entire model can be split up into two parts. The planning environment and the DES environment. The planning environment receives the revealed visits, takes into account all the other input parameters and schedules each drop-off and pick-up activity. This information is then relayed back to the DES environment which contains the actual simulation of the craft and technicians in the wind farm. The main difference between these two environments is that the planning environment only uses normal Python code, whilst the DES environment uses a special DES library, that keeps track of the simulation time and events. The planning environment crucially also does not receive any information back from the DES environment except for the simulation time. Unforeseen delays of visits inside the DES environment can occur due to effects that are not taken into account in the planner. These are however not communicated back to the planner to make adjustments to simplify the planner and therefore simply cause certain visits to be delayed. How these unforeseen delays can occur will be explained in section 5.3.6.

5.3.3 Model flow

The model follows the process of a maintenance visit. From the moment a visit is created, due to the detection of a fault on the turbine, until the completion of the visit and the return of all technicians to the mothership. The model runs until all visits have been completed. The visit revealer sets the model in motion by starting this process for all visits. The visits do not all start at the same time but get revealed throughout the simulation, based on the occurrence times stated in the visit agenda. This simulates the spontaneous occurrence of corrective visits.

A visit continues to the priority queue once it is revealed. The priority queue checks if the visit has occurred during the working hours of the technicians or during the night. The visits that occur during the night have to wait until three hours before the start of the working hours of the technicians because the planning for the coming day is made three hours before the start of the first shift. Preventive maintenance visits are planned first (get priority) to ensure that the preventive maintenance plan is adhered to as much as possible. Preventive visits can therefore only be delayed due to weather.

The planner checks the weather, availability of technicians, location of deployed technicians, and the availability and performance of the craft and plans the visit at the earliest opportunity. The planner outputs the planned times for drop off and pick up and selects craft for both activities. The required number of technicians is also reserved for the duration of their work. This information is used inside the planner to take into account for the next visits that need to be planned and is given to the DES environment to instruct the craft. A visit can be returned to the priority queue if the planner cannot find a way to plan the visit on that day.

The drop-off process in the DES environment then consists of requesting the craft and technicians and determining when the craft should start heading to the turbine. It then transfers the technicians to the turbine and in case of all the craft except the mothership, returns to the mothership. The technicians then start working on the turbine. The pick-up craft then calculates the time it has to set off to be just in time to pick the technicians up when their work has been completed. The technicians then transfer to the craft and in case of all the craft except the mothership, return to the mothership. The visit is complete when this entire process is completed.

5.3.4 DES Environment - Visit Revealer

The visit revealer starts the process for each visit in the visit agenda. The visit revealer waits until the simulation time reaches a visit inception time, creates a visit with all the information that belongs to that visit, and starts the drop-off process for that visit.

5.3.5 Planning Environment

As explained in section 5.3.2, the planning environment receives the visits and all the input and creates a schedule that the wind farm model needs to execute. The planning environment consists of the priority queue and the planner. The planner can only handle one visit at a time so, the priority queue collects all the revealed visits and dispatches one visit at a time to the planner. Visits are only dispatched to the planner either 3 hours before the first shift starts or during the hours that technicians work. This is done to simulate the way the daily planning is made at the start of the day and this allows the preventive visits to be the first to be scheduled. This is done to ensure that the preventive visits have the highest chance of being executed on the day they were scheduled in the long-term planning made at the start of the year. This is important because of the statutory time constraints associated with these activities.

The planner takes each visit and finds the first opportunity in the day that this visit can be scheduled, taking into account the weather, availability of technicians, location of deployed technicians, and the availability and performance of the craft. The planner incorporates a four-stage process designed to make the planning as computationally efficient as possible. The four stages are shown in figure 5.7. The content of each stage is discussed in detail in the following sections. The order of the checks is dictated by the computational time of each check to avoid performing time-consuming checks that could be prevented by simpler ones.

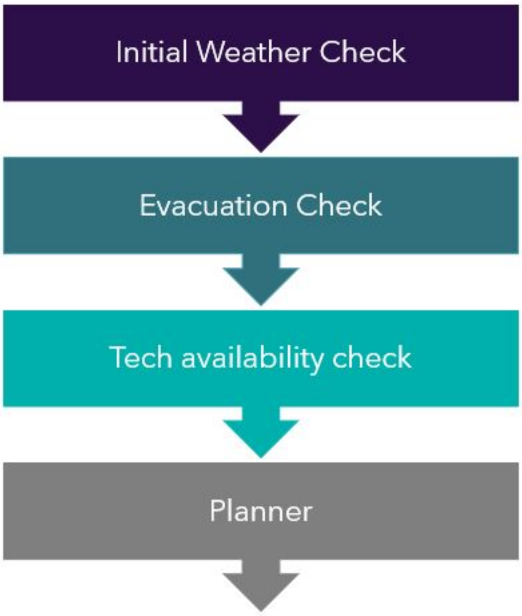

Figure 5.7: Four planner phases

Stage 1 - Initial Weather Check

The first stage evaluates the weather for that day. The planner starts every day with a blank schedule. The number of hours during which visits can be executed is dependant on the technician working hours and the weather conditions. The first and last moment visits can take place is called the start/end of the plannable window (SPW/EPW). An illustration of this is shown in figure 5.8 on the next page. The initial weather check looks at two types of weather parameters, the significant wave height and the visibility. This initial check evaluates the hours during which the vessel with the highest transfer limit and the helicopter (if present in the fleet) can operate. The start of the first and the end of the last hour are taken as SPW and EPW.

It can occur that the significant wave height and visibility windows do not overlap causing a set of hours in the middle of the day to be unworkable. This does not mean that visits will be planned during that cap because this is taken into account in stage four. Visits are sent back to the priority queue if the plannable window is shorter than the duration of the visit.

Stage 2 - Evacuation Check

The evacuation requirement check ensures that the visits that are executed at the same time are all within each other's evacuation radii. The evacuation radius is dependent on the craft that is used for evacuations and is therefore dependent on the craft present in the wind farm and the weather conditions. A fleet that contains a helicopter will in most cases use the helicopter due to its speed advantage but will have to use a vessel on a day with fog for example. This will decrease the evacuation radius.

The check starts by evaluating which craft are available to perform an evacuation at the start of the plannable window. This availability only considers the weather. The availability does not include if the craft is already performing a drop-off or pick-up operation since a craft would stop its current task and immediately head to the turbine that needs to be evacuated. The fastest craft that is available throughout the visit is selected as the evacuation craft. The visit will be delayed to a later time if no craft can be available during the entire visit starting at the start of the plannable window. The visit is pushed to the next day if no craft is available for a sufficient duration of time.

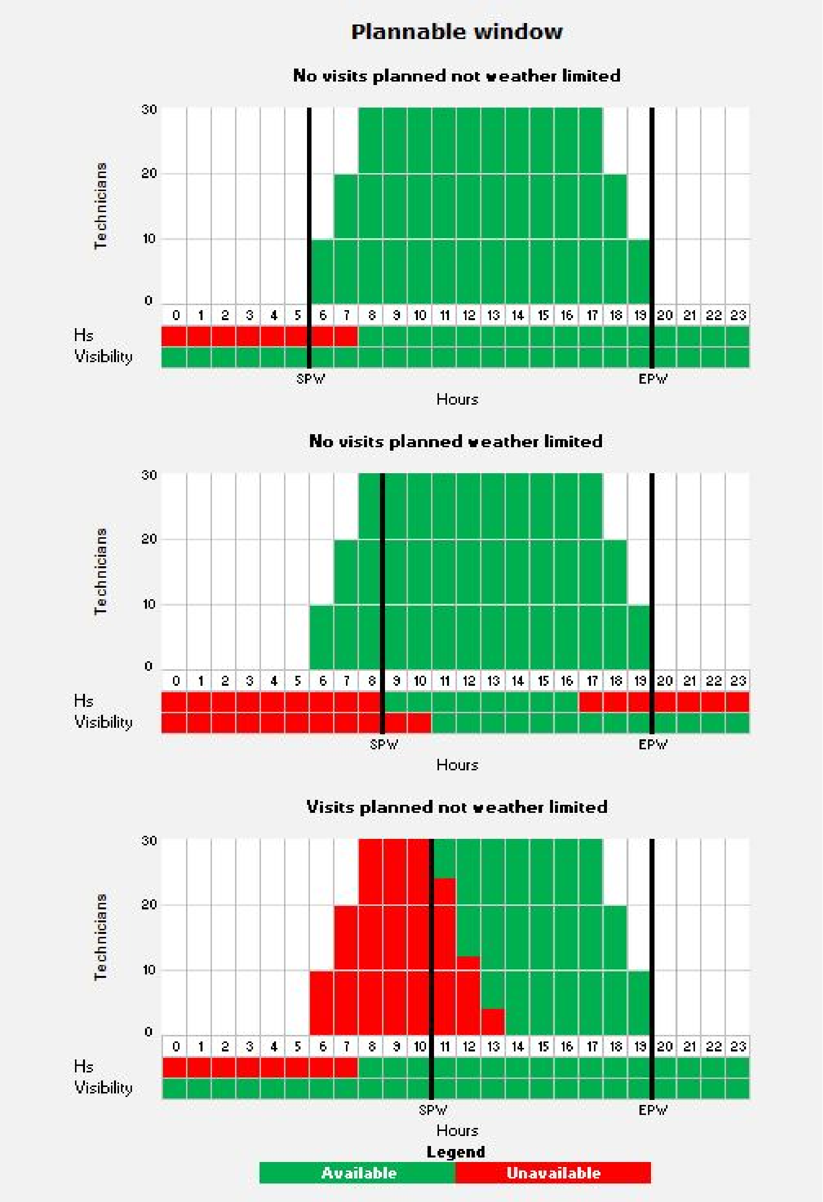

Figure 5.8: Plannable window

The evacuation radius is based on the time it takes to reach the TP of the turbine that needs to be evacuated. The time it takes to reach that turbine is dependent on the position of the evacuation craft, its speed, and its transfer time. The worst-case scenario is when this craft is at the furthest away turbine at which technicians are deployed. This would require some time to abort the transfer and would have the longest transit time. An evacuation cycle therefore consists of the transit duration and one transfer to reach the TP of the evacuation turbine.

The evacuation check is deemed successful if the sailing times from the turbines where technicians are working to the designated visit turbine are all shorter than the maximum evacuation time minus half the craft's transfer time. The normal transfer time of the craft is halved because this always includes the transfer of equipment and multiple people whilst this is not necessary within the evacuation time. All transfer times reduce by around half when this is considered[4]. The start and end time of the period in which the criterion are met are denoted as the start and end of the visit window. This window is used because it is at this stage in

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[4] From conversations with SGRE employees between May and August 2023

the planner not exactly known when and how long the drop-off and pick-up are. In cases where this criterion is not initially met, the start of the visit is rescheduled to align with the technicians' completion of work on another turbine. The sailing times are then recalculated to evaluate if the evacuation criterion is possible at that time. A visit is pushed to the next day if the evacuation criterion can never be met with any of the craft on the day that is being planned.

Stage 3 - Technician Availability Check

The technician availability check evaluates when enough technicians are available to execute the visit. It takes a list where each entry is the number of technicians deployed within that hour and adds the required number of technicians to perform the visit to see if this number does not exceed the number of technicians that are available during those hours. Figure 5.9, shows an illustration of this process. The visit window is adjusted based on this principle. This method only checks for the number of technicians that should be available each hour and not how long each technician has already worked. This method is slightly conservative since the technicians are reserved for an entire hour whilst they may only work for half that hour. This method could also result in technicians working more than 12 hours, which is usually not permissible by law. Keeping track of all the exact times would however be more computationally expensive, while the influence on the planning would not be that great and was therefore deemed too inefficient for the purpose of this simulation.

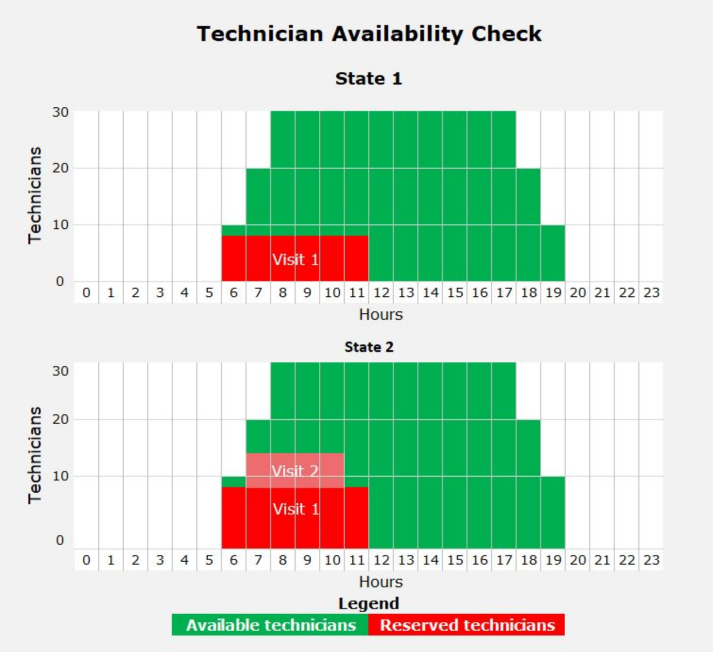


Figure 5.9: Technician availability check

There may already be too many technicians working during some hours within the visit window. In that case, there could be two or more visit windows in one day, as depicted in figure 5.10. This check marks the visits where this occurs. The last stage will perform an extra check if this is the case to make sure that the visit is performed in one of the windows.

Port calls are modeled as days where there are no technicians available, this causes no visits to be scheduled during this day. These port calls are scheduled based on the port call interval and duration and always occur on those days. This schedule is more flexible in reality, based on weather conditions and maintenance to the vessels but the effect of this on the simulation results is small and the same across all simulations.

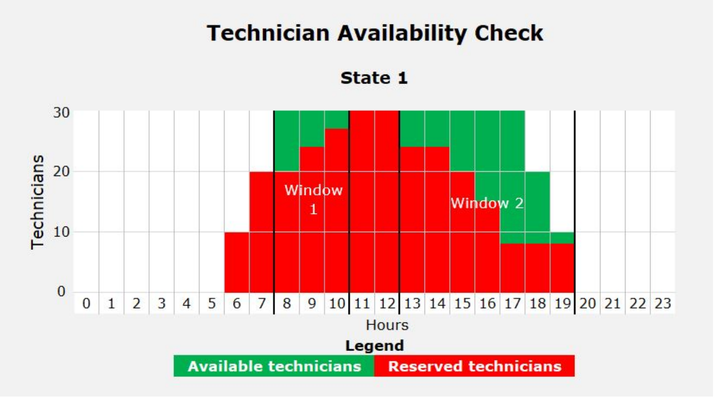


Figure 5.10: Multiple visit windows

Stage 4 - The Planner - Drop-off planner

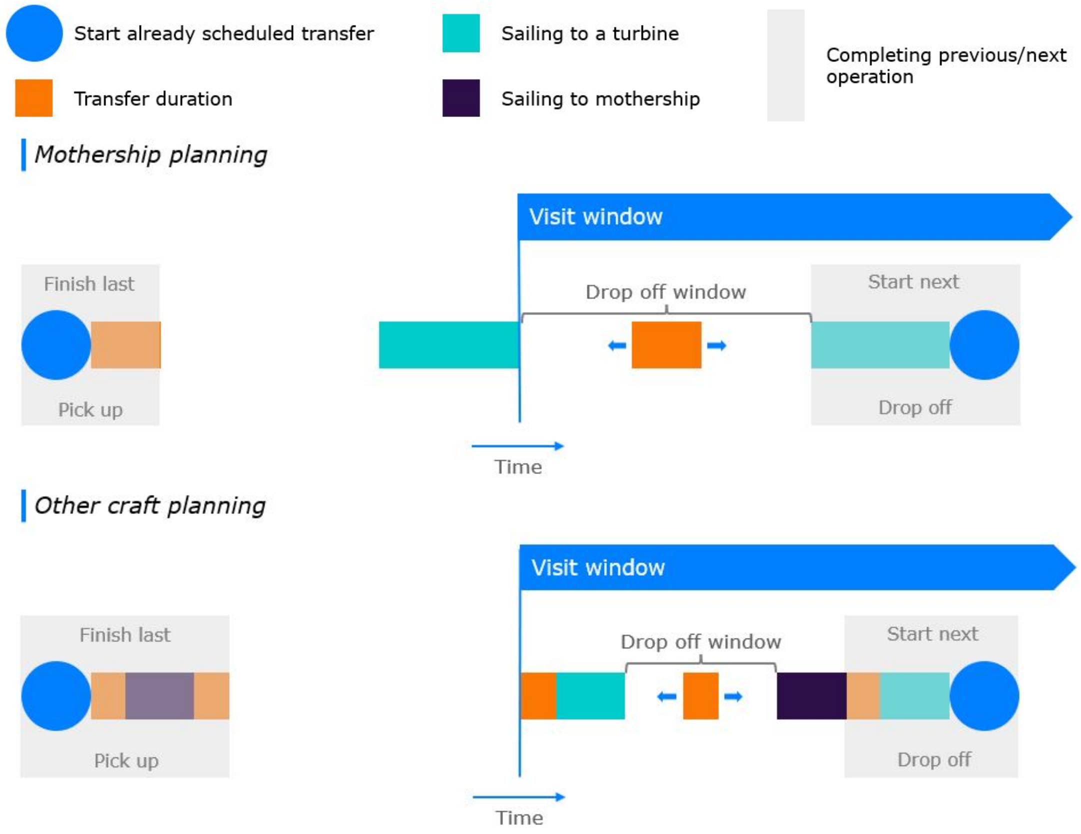
The planner searches for the first opportunity to perform the visit within the visit window and consists of two parts: the drop-off planner and the pick-up planner. Each schedules its respective operation. The drop off planner starts by evaluating which craft are available (based on weather) during the visit window. The planner then takes these craft and puts them in the correct craft selection order. The drop-off planner then starts with the most preferred craft and checks if that craft can be used at the start of the visit window.

To achieve this, the planner evaluates the craft's already scheduled transfers and identifies the two transfers between which the start of the visit window occurs. Subsequently, the planner calculates the time needed to transport technicians from the preceding transfer to the planned turbine visit and the time required to bring technicians to the next scheduled transfer. The path of going from one turbine to the next is different for the mothership compared to the other craft because the mothership can go directly from turbine to turbine, whilst the other craft have to return to the mothership to get a new group of technicians.

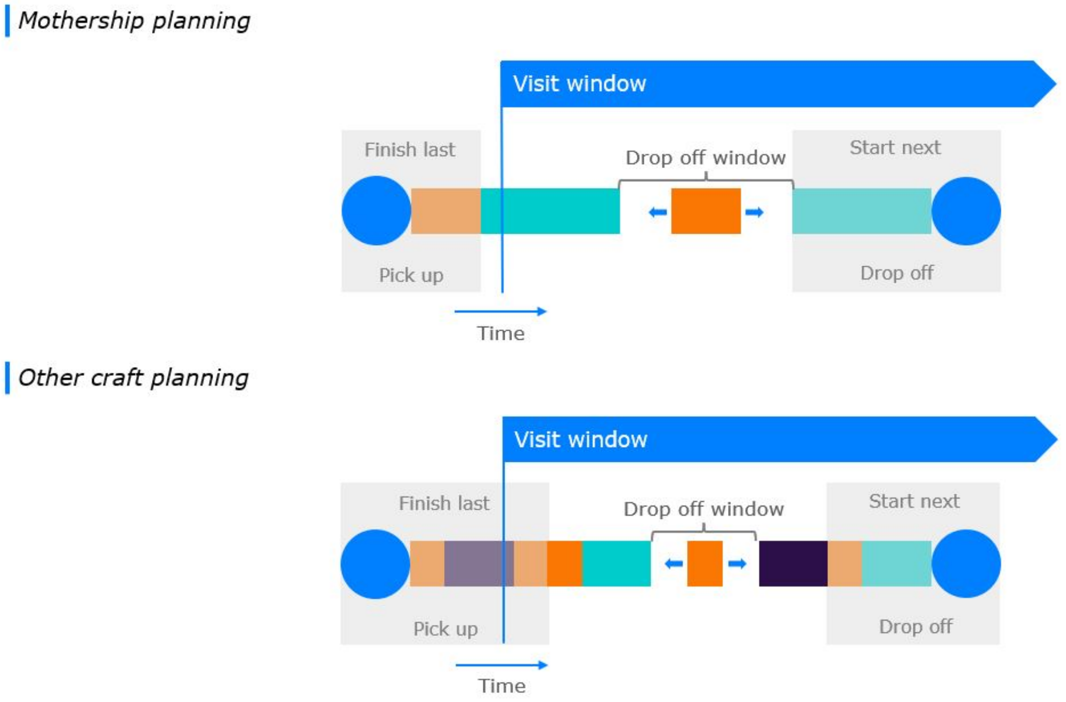
The planner also takes into consideration that the technicians can only start working at the start of the visit window. This means that the mothership can already sail to the new turbine even though the technicians are not yet available (read section 4.1.2), whilst the other craft have to wait until the technicians are available before they can depart and head to the turbine. A visual representation of this process is shown in figures 5.11a.

Comparing figure 5.11b with 5.11a shows that the start time of the drop off window is delayed if the previous transfer is planned closer to the start of the visit window. Similarly, the end of the drop off window is brought forward if the following transfer operation is scheduled earlier than in figure 5.11a. There is of course no limitation of this nature if there is no previous or following transfer scheduled.

It is assumed that the previous transfer was always a pick-up operation and that the following transfer is a drop-off operation because these create the smallest drop-off windows. The length of the window can be further reduced by the weather window of the craft or by the end of the visit window. The end of the drop-off window is also limited by the duration of the work on the turbine and the end of the visit window since the work on the turbine should always be completed on the same day. It is important to note that the availability of the mothership is only assessed based on its own schedule. It does not take into account that relocating to a different turbine has consequences on the schedule of the other craft. This is done to limit the complexity of the planner.



(a) Drop off planning with early previous transfer



(b) drop off planning with later previous transfer

Figure 5.11: Drop off planner visualization

A visit cannot be planned at the start of the visit window if there is no drop-off window. In that case the craft that is being assessed is deemed not available at that time and the next craft will start this process. The time of the following transfer (i.e. the time of the blue circles on the right of figure 5.11) is saved in case there is no drop-off window for any of the craft at the start of the visit window. The process is then restarted with the start of the visit window set to the first time where the previous and following transfers are different for at least one of the craft.

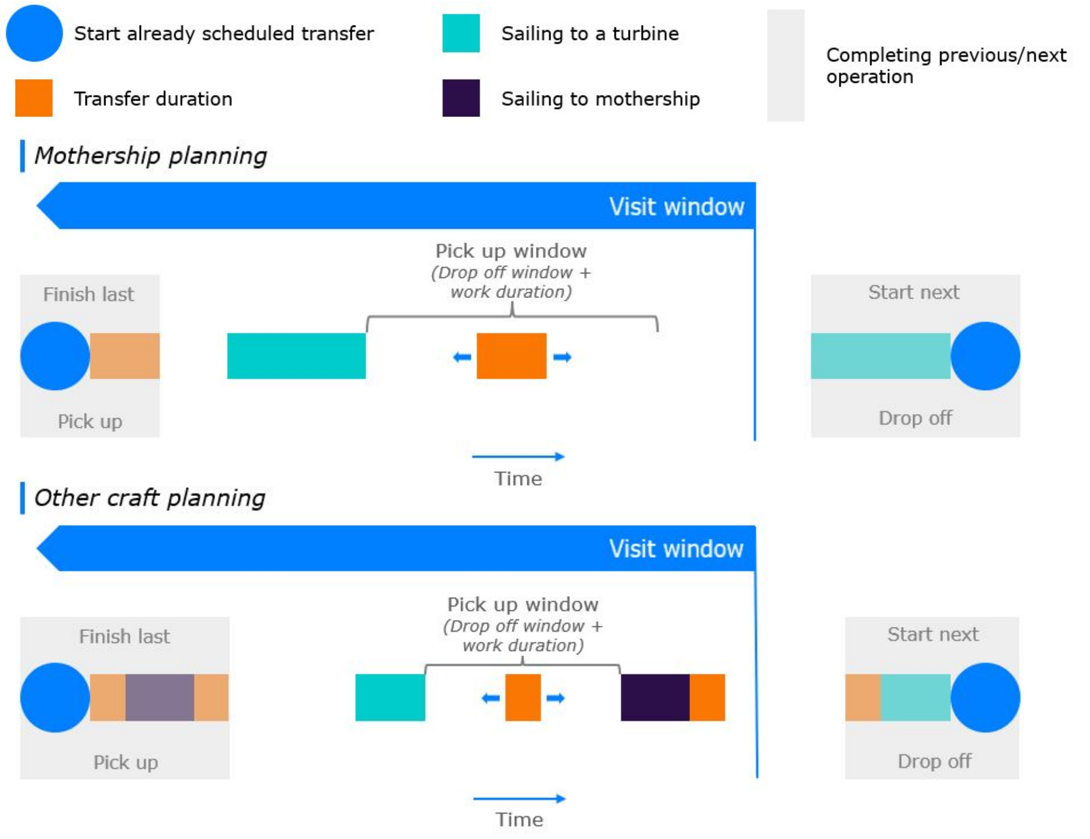
Stage 4 - The Planner - Pick-up Planner

The pick-up planner uses the same check to asses if the craft is able to work and if the craft is available, just as the drop-off planner. It however does not use the start of the visit window to find the previous and following transfers. It uses the start of the pick-up window, this is the drop-off window but shifted by the duration of the work on the turbine. The end of the visit window is an added constraint, because the technicians are not allowed to work later than that time, for this visit. This constraint is however not always present between previous and following transfers, so is usually only a constraint for visits that are being planned at the end of the working day. The influence of this constraint is shown in figure 5.12b, when compared to figure 5.12a on the next page. The pick-up planner also adjusts the pick-up window based on the weather window of the craft, as is done in the drop-off planner. The length of the pick-up window can however never be increased due to the limitation for the drop-off. The start of the pick-up window can therefore only move to a later time and the end can only become earlier.

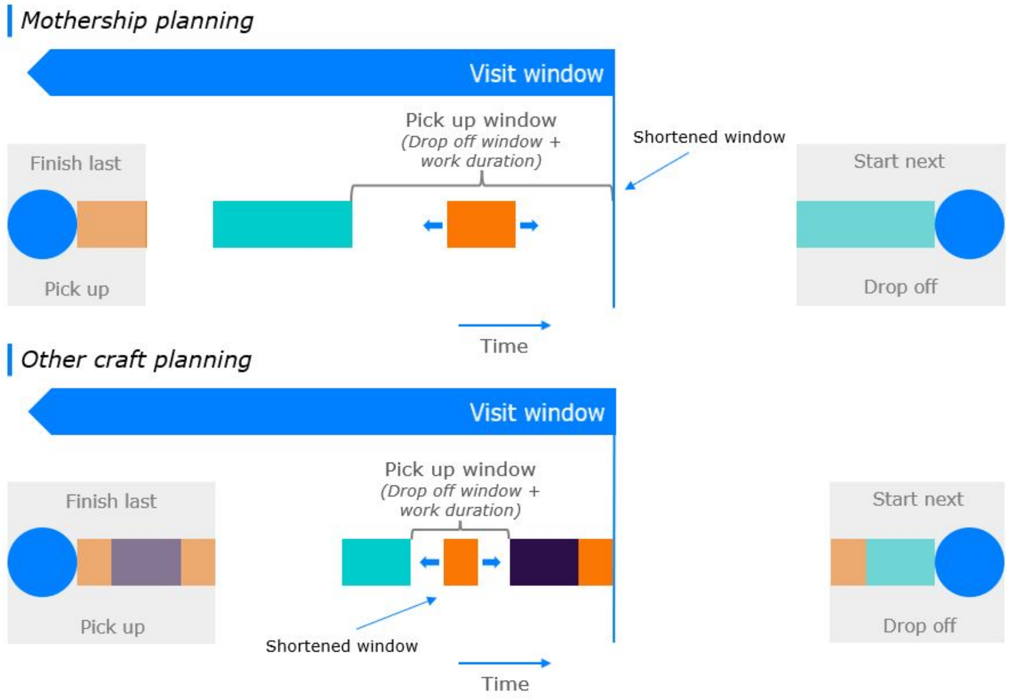
The pick-up planner does two additional checks. The first is only activated if there are not enough technicians available for the entire duration of the visit window, as explained in section 5.3.5. It checks if the visit is entirely planned during the hours when there are enough technicians available. If this is not the case, then The check returns the first time the technicians are available after the period where this was not the case. The drop-off planner is then run again with that time as the start of the visit window. The pick-up is scheduled at the earliest opportunity within the pick-up window and the drop-off is scheduled at the corresponding time (so, the duration of the work on the turbine + a transfer duration earlier) if all the checks are passed. The drop-off and pick-up transfer moments are then recorded in the planning for the respective craft. The required number of technicians to execute the visit is added to the other technicians that are deployed during the hours that the visit and the transport to and from the turbine are scheduled to take at that time. The actual duration of the transport could potentially be different due to later additions the the planning that cause the sailing distances to change. The effect of this on the planning is not that significant because changes in sailing time are usually not very large and the technicians are reserved for the entire hour even if they might only work for the first half hour. The location and timing of the work on the turbine are also recorded to be able to calculate the compliance with the evacuation criteria for visits that are planned next. The drop-off planner is run again with the start of the visit window shifted to a later time if not all checks are passed. This can result in the visit eventually being shifted to the next day if it is never able to be completed within the visit window.

5.3.6 DES Environment - Wind Farm Model

The wind farm model is the section of the model that actually simulates the transport of the technicians through the wind farm by the different craft. It consists of the drop off, work and pick up process as shown in figure 5.5. The visit is completed when the pick up process is completed. The simulation stops when all visits have completed the pick up process.



(a) Pick up planning



(b) Pick up planning constrained by end of visit window

Figure 5.12: Pick up planner visualization

The drop off process is split into two parts. One for drop off operations performed by the mothership and one for the other craft. This subdivision is made due to the different operational cycles, as explained in the previous section. Both sub processes however start in the same manor, because each visit exits the planner at the time it is scheduled. This is however not necessarily the time that the craft also has to start traveling to the turbine/start transferring technicians to the craft. This time is determined by the position of the craft before heading to the turbine. This position can change due to new drop offs or pick ups being scheduled before the execution of this drop off process. The process therefore recalculates the time to depart every time a new visit is planned within the window that the craft might need to depart. This way the craft always departs at the right time if no earlier delays have occurred.

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The DC, CTV, or helicopter might however not always be available at this departure time. This can occur if another transfer with the mothership is planned at a turbine that is further away. This causes the sailing/flying times of the DC, CTV, or helicopter to increase, possibly to the point where it will not have returned before the required departure time for the next operation of the craft.

This will then result in that next operation being delayed. This however does not occur very often en does not result in scenarios where the pick-up operation is executed before the completion of the work on the turbine. The processes of sailing/flying and transferring then follow the steps shown in figure 5.5 and 5.11.

Sailing to and from the turbine for a very short visit is unpractical. Therefore DCs and CTV stay at the turbine and wait until the visit is completed. This is done if the visit takes less then one hour, the drop off and pick up is scheduled to be performed by the same craft and no other transfers are planned in between drop off and pick up. The absence of a landing platform and the limited fuel capacity of a helicopter means that it cannot wait at the turbine until the work is done. This is also of less concern due to the short travel times that the helicopter provides.

The pick-up process is identical to the drop-off process. The pick-up time is however adjusted based on the possible delay that occurred during the drop-off process, ensuring that the pick up does not occur before the finishing of the maintenance on the turbine. The work process simply waits until the predetermined visit duration has passed.

5.3.7 Data Logging and Emissions Calculation

All the important information about a visit is logged in a dataframe. This dataframe contains all the visits performed in the simulation. It logs the data points shown in the list below for each visit. This dataframe is reduced to one row containing the total downtime, emissions, and utilization percentages of all the craft in post-processing.

- Name of the visit
- Turbine number
- Duration of the visit
- Time the turbine stops (visit inception time)
- Times the craft starts and finishes working for drop off and for pick up
- Times the technicians have been dropped off/picked up
- Times the craft finishes the drop off/pick up operation
- Types of craft used for drop off and pick up
- Times work on the turbine has started and ended
- Times the technicians started and ended working
- Turbine downtime
- Craft emissions

Emissions calculation

The emission calculation needs to estimate the emissions of vessels with an unknown design. Only their operational speed, transfer limit, and passenger capacity are known. The most influential of these parameters for the emissions is the operational speeds and these are similar to existing vessels. The transfer limit and passenger capacity only have a secondary influence on the emission due to their impact on the size of the vessel. The fuel consumption of the vessels considered (see table 5.1) will most likely not differ largely from existing vessels. The fuel consumption figures used to calculate the emissions are therefore based on currently existing ships. The figures used for the helicopter emissions also originate from currently operational helicopters in the offshore wind fleet.

Other methods were considered such as estimating the required volume of each vessel based on the transfer limit, passenger capacity, number of overnight cabins, number of DCs stored onboard, etc. Estimating the volume of each vessel is useful because the displacement and hotel load have the largest influence on fuel consumption at the same speed. This method would however need to be benchmarked on existing ships like SOVs and CTVs, so a similar difference in estimated emission levels is achieved. This would cause this method to in the best case deliver similar relative differences in emissions, while having a lot more uncertain factors, due to the rough method of estimating the volume and then transforming that into fuel consumption. The method based on similar operational ships therefore seems a more reliable method to estimate the emissions of the fleets even though the changes to the SOV to become a mothership are not included in this estimation.

The emissions calculation is split up into 5 operational modes: Sailing within the wind farm, transferring, standby, port call, and port call due to weather. Each mode uses the same basic formula, shown below, but with different input.

$$\begin{aligned} Duration\ [hours] \cdot Fuel\ consumption\ [l/hour] \cdot Fuel\ density\ [kg/l] \cdot \\ Carbon\ factor\ [ton/kg] = CO_2\ emissions\ [tons] \end{aligned} \tag{5.1}$$

Not all craft operate in all modes. The DCs do not produce emissions when sailing to/from port nor do they have standby emissions during the night, because then they are stowed onboard the mothership. The helicopter operating from the mothership also does not have any standby, port call, or weather port call emissions, because it is stowed onboard the mothership during these times, in this case.

The duration for the travel time within the wind farm is taken as the travel time by each craft in each drop-off or pick up operation that it is used. The DCs and CTV however also sail to stay close to the moving mothership when they are on standby. These extra hours are also included in the sailing emissions within the wind farm of those craft. The transfer duration is the total duration of all transfers performed by each craft. The duration used in the port call emissions for the mothership and CTV is the number of port calls performed during the simulation multiplied by the sailing time from the port to the wind farm. The duration for the port call due to weather emissions for the CTV is twice the number of times weather windows during the simulation multiplied by the sailing time from the port to the wind farm. The remaining time is used to calculate the standby emissions.

5.4 Model Convergence

All simulations that either have stochastic elements within the simulation or use stochastically generated input should be run multiple times to capture the variance of the system and supply accurate predictions of the output variables (Ritter et al., 2011). The number of required runs should at the same time also not be too high, because this can be computationally expensive and unpractical. This is especially true for this simulation since the computational time of a one-year simulation is around 25 seconds and there are 1384 configurations that have to be run multiple times.

Determining the minimum number of runs to ensure sufficient accuracy in predicting the performance of each fleet can be done on multiple variables and in multiple ways. The goal is that performing additional runs does not significantly change the results. This is usually assessed using statistical tests. One of the most commonly used methods is using confidence intervals. This method calculates the standard error using formula 5.2 and uses a Z-score that corresponds to a confidence level to calculate the required number of runs to reach the set confidence level (formula 5.3) (Ritter et al., 2011).

$$Standard\ error = \frac{Standard\ deviation}{\sqrt{Number\ of\ runs}} \tag{5.2}$$

$$Required\ number\ of\ runs = \frac{Standard\ deviation^2}{(\frac{\pm accuracy}{Z-score})^2} \tag{5.3}$$

5.4.1 Downtime Convergence

The most important output variable is the total downtime. A relatively limited run of 15 years with all fleet configurations was done to obtain an estimation of the required number of runs for each configuration to obtain an accurate prediction of the total downtime. A prediction is deemed accurate if the downtime can be estimated to ± 1 day of downtime/turbine/year with 95% confidence. Figure 5.13 shows the results of this analysis. The value on the x-axis reflects the rank order of the required number of runs.

This figure shows that more than half of the fleets require more than 20 runs to provide an estimate of the downtime to the stated level of accuracy. The required number of runs rises as high as 242,620 but the figure is only plotted up to 200 runs for clarity. These results were to

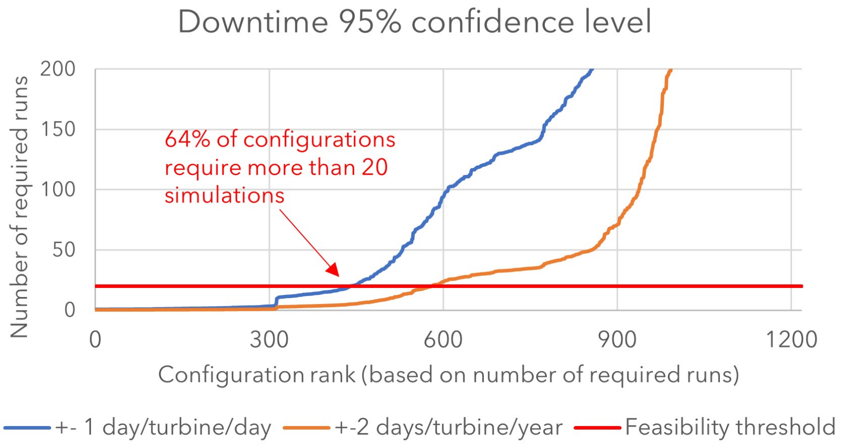


Figure 5.13: Required number of runs based on downtime

be expected since fleets that perform poorer tend to have more variance as well. Performing more than 20 runs per configuration is however infeasible due to the large computational time. The stated level of downtime prediction accuracy can therefore not be obtained for all configurations. Reducing the accuracy to ± 2 days/turbine/year does lower the required number of simulations but not to a feasible level.

5.4.2 Ranking Convergence

The purpose of these simulations is to compare the performance of the different fleets, not to provide the most accurate estimate of the total downtime. The ranking order of the fleets based on downtime is therefore more important. A similar analysis can be performed on the ranking order. The required level of accuracy is set to ± 10 places in the ranking order with a confidence level of 95%. The results are shown in figure 5.14.

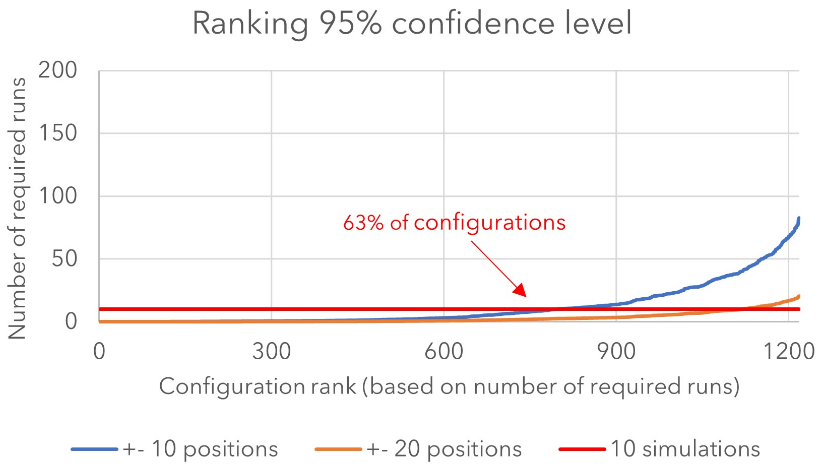


Figure 5.14: Required number of runs based on ranking

The rank of around 63% of all configurations can be predicted to this level of accuracy with 10 runs. This level of accuracy is in certain cases very high when we consider that a change of 1 day of total downtime/turbine/year can in some cases change the ranking order by around 40 places. The ranking order therefore becomes of less importance when the performance of the fleets is very similar. This effect can be seen in figure 5.14 as well since almost all fleets drop below 10 required runs with an accuracy of ± 20 positions. This level of accuracy is therefore accepted. All fleets will be run 10 times, since running it 5 times more does not gain that much accuracy and the computational time using 10 runs is around 27 hours. Which is close to the upper limit of what is practical.

5.5 Model Improvements and Additional Uses

This section will discuss how the model can be improved to increase both its absolute and relative accuracy. The second part of this section will discuss the possible uses of this model within SGRE.

5.5.1 Model Improvements

The fleet evaluation model uses simplifications and assumptions that make the simulations differ from the real-life execution of turbine visits. Removing or improving upon these simplifications and assumptions will improve the model's accuracy. Some of these improvements will increase the accuracy of the model in a meaningful way for the purpose of this study, while others would incorporate some more realistic effects that do not result in significant relative performance changes between fleets. The first category is discussed below.

- **Improving downtime estimation for corrective visit**

  Not all faults or sensor alarms are as important. Some require the turbine to stop while others might only be a broken light and therefore not influence the turbine's productivity. Incorporating these priority levels and changing the downtime is calculation accordingly will increase the absolute downtime estimation of the model. The relative performance of the fleets that do not operate a helicopter would most likely increase because the planner would first perform the high-priority visits, reducing the downtime caused by the evacuation requirement.

  Currently, multiple visits on the same turbine could cause downtime. Resulting in 2 downtime hours on a turbine during 1 simulation hour. This can be changed in post-processing but will most likely have a limited effect if the previous point is implemented because this would significantly reduce the likelihood of this occurring.

- **Planning optimization**

  The current planning algorithm is simplistic, it searches for the first opportunity that a visit can be scheduled and the timing of the visit will not be adjusted once it has been scheduled. The planning algorithm is therefore vulnerable to the order in which the visits are presented to it. A more advanced planning algorithm could aim to maximize the number of visits performed each day or to minimize downtime. This would allow the model to create schedules that more closely resemble those made in real life. The effects of optimizing the planner to the downtime estimation will probably be quite small since the largest improvement will come from the first bullet point. The emissions estimation might however be more sensitive if the algorithm would also optimize the routes of the craft.

- **More realistic and efficient use of support vessels**

  All support craft currently only perform one transfer to/from a turbine before returning to the mothership. The DC and CTV will probably have the capacity to transport multiple technician teams at once, however. It is therefore possible and more efficient to travel to multiple turbines and transfer all the teams before returning to the mothership. This adds complexity to the planning algorithm but will be a more realistic representation of these craft. This change will probably reduce the downtime estimation by a few percent.

- **Integrating helicopter limitations**

  The helicopter on the other hand is currently assumed to be able to always deliver both technicians and equipment at the same time. This will however not always be possible. Some flights to already deliver the equipment to the turbine before the technicians arrive could however be made during moments where the helicopter is not performing transfers. The effects of implementing this extra trip are most likely relatively small and will depend on the number of visits that need to be completed.

  The nacelle and blades should be in a set position relative to the wind and each other to allow for the helicopter to perform a hoist operation. The orientation of the nacelle and blades can however typically not be controlled if the turbine has stopped producing power. It is in reality therefore not always possible to transfer technicians by helicopter to a stopped turbine. Implementing this effect can be done by simply excluding the helicopter for X percent of corrective visits. This percentage is however expected to be low so the effect of this improvement is expected to be small.

The following improvements will increase the realism of the model and will increase its accuracy but these effects will most likely only affect the absolute estimations and not create significant relative changes between the fleets. These improvements are discussed below:

- **Reduce weather prediction accuracy & add stochastic event duration's**

  This will require a more dynamic planning algorithm and would significantly increase computational time. The effects of these changes would also mostly evaluate the performance of the planning algorithm rather than the fleets since their relative performance will remain roughly the same.

- **Remove mothership relocation error**

  This will remove the inconsistencies of the verification checks described in section 6.1 but will only have a marginal effect on the output variables.

- **Incorporate technician competencies**

  This will add a constraint to the planning algorithm but each fleet will have the same restriction as long as it employs the same number of technicians. This will however be usefull to determine the optimum number and composition of technicians for each fleet.

5.5.2 Alternative Uses

The model's setup allows for performance analysis of both the fleet and the planning method. Evaluating the performance of many different fleets, however, requires much fewer modifications than evaluating different planning methods. The types of analyses that can be made using this model are discussed below:

- **Service sales support**

  The service sales team sells service contracts. It therefore looks for the best set of craft to charter to perform the maintenance for a specific wind farm. The different charter options can be run in the model to evaluate their performance. The financial performance of the different charter options can also be evaluated by adding a post-processing step.

- **Personnel transport in other stages of the wind farm life cycle**

  The usage of (C)SOVs, CTVs, and helicopters is not limited to the operational phase of the wind farm. This model can be used to analyze the performance of fleets during these phases as well.

- **Alternative fuel analyses**

  The simulation can already be used to estimate the CO_2 emissions. Estimating emissions of other fuel types is a matter of changing the fuel input parameters. Most alternative fuels also require a higher bunker frequency. In some cases so high that this can become a distinct operational constraint. The consequences of this can be analyzed using this model with no or minimal changes.

- **Test new maintenance strategies/planning algorithms**

  The model can be used to test the effects of new maintenance strategies and how this influences what type of service fleet can deliver the best performance.

- **Scenario testing for the effects of unforeseen events**

  Unforeseen events such as grid faults or a very severe storm can cause a large number of extra turbine visits. This model can be used to simulate these events and run scenarios with different mitigation techniques to evaluate how this can best be dealt with.

6 Model Verification & Validation

Model outputs should not be believed at face value. They can contain errors or underlying assumptions or modeling methods could be wrong. It is therefore important that models are verified and validated. The definitions and methods of Sargent, 2010 are used in this thesis to verify and validate the fleet evaluation model. Sargent, 2010 uses three steps conceptual model validation, computerized model verification, and validation.

Conceptual model verification is used to determine if the theories and assumptions used to make the model are correct. This is usually done by investigating statistical relationships or evaluating if certain criteria are met to use a certain method. This model uses a time-based simulation of events so, the duration and relation of the events should be representative of reality in the case of this model.

Computerized model verification is used to ensure that the programming and implementation of the model are correct. This can be done both statically and dynamically. Static means analyzing the code and checking for faults. Dynamic means running the model and evaluating the results by checking for internal consistency and investigating input-output relations. Both have been done.

Validation is used to determine if the model's output behavior has the required level of accuracy for its intended purpose. This can be done by exploring the model's behavior and comparing the model's results to the data of the real-life system it is trying to replicate. Both have been done.

Sections 6.1 to 6.3 will discuss the work done in each of these steps and answer sub-question 5: How accurately can the method predict the performance of the concepts?

6.1 Conceptual Model Verification

The conceptual model has been verified using face validation. The model has been built using the input of a multitude of company experts from different departments. Two experts have been asked to asses the entire model:

- **Rene Wigmans, Global head of offshore service logistics**

  Rene Wigmans praises the model for its accuracy of the execution of visits (DES environment) but highlights some aspects of the planner that could be improved to replicate the real world even better. These points are listed below. These point would make the model even more realistic but he expects that this model will provide the require level of accuracy.

  - Feedback loop between DES model and planner to adjust planning based on delays
  - Include delays of visits that need to be planned the next day
  - Planning optimization instead of finding first opportunity
  - Taking into account technician competences (e.g. Dedicated HV technicians)
  - Ride sharing
  - Multiple helicopter trips for on transfer

- **Jens Vancoillie, Operational planner**

  Jens Vancoillie finds the flow of the model to be very representative of reality. He also highlights similar items to Mr. Wigmans and added two more:

  - Delay low-priority visits to times with low production, to limit production losses
  - Delays due to delayed permits

  Both of these points would make the model more realistic but would change the outcome of the model minimally. Jens Vancoillie concluded that he expects the model to be accurate enough for its purpose.

6.2 Computerized Model Verification

The computerized model verification has been done both statically and dynamically. The static verification was done using walkthroughs and therefore did not produce any results that can be shown in a report. Some coding faults were however rectified using these walkthroughs. The dynamic verification has been done by analyzing traces and building internal consistency checks. These will be explained below.

6.2.1 Dynamic Verification Methods

Every simulation contains around 2300-2500 visits that have to be performed. Showing a trace of a full simulation is therefore impossible. Analysis of smaller simulations has been done to determine if the individual components of the simulation function as desired. The behavior of the components is as designed. Some verification checks are however written to evaluate if this also holds in complete one-year simulations. These checks are discussed below.

Continuety Checks

Two checks have been written to evaluate if the most critical moments in every visit occur correctly in every simulation. These critical moments are the moments when technicians are dropped off and picked up. The first check checks if the time at which the transfer to the turbine is complete and the time the work on the turbine starts are the same. The second check checks if the time the work is completed is the same as the time transfer from the turbine to the pick-up vessel starts. These checks use the times reported in the results dataframe that each simulation produces.

Scheduling Checks

Two more checks have been written to evaluate if the schedule that is made by the planner is being adhered to in the DES environment. These times use the times reported in the results dataframe and the planning dictionary to see if the drop-off and pick-up times occur at the times scheduled in the planning dictionary. The planning dictionary is a dictionary in the model that contains the scheduled drop-off and pick-up time of every visit.

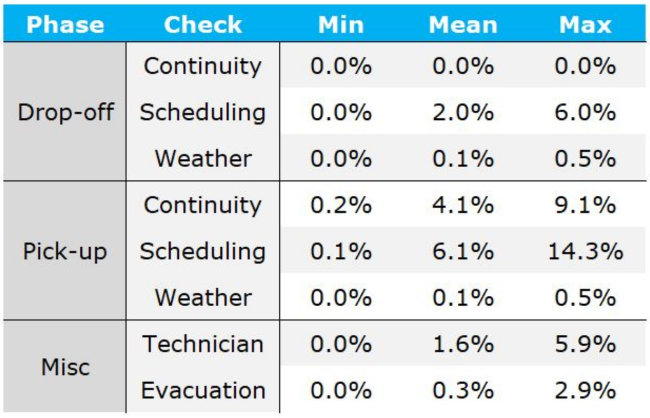
Constraint Checks

Three further checks have been written to determine if the model adheres to its constraints. Meaning that each craft only operates during its weather windows, that the maximum number of technicians that can work at one time is not exceeded, and that no technicians are deployed outside of the evacuation radius. The weather check uses the operational time of each craft noted in the results dataframe. It checks if the start and end of each operation (drop-off or pick-up) are within one of the weather windows of that craft. The technician check uses two lists. One containing the number of technicians that are at work each hour and one containing the maximum number of technicians that are allowed to work each hour. The check is false if the value in the first list is larger than that of the second list during the same hour. The evacuation check uses the start and end time of the work on the turbine of each visit and checks if the evacuation criterion is met for all the other turbines at which technicians are deployed during that time. It also checks if the start and end time fall within the weather window of the evacuation craft.

6.2.2 Dynamic Verification results

The results of these seven dynamic checks for the base case of the sensitivity study are shown in table 6.1 below. The number of failures is shown as a percentage of the number of visits. This table shows that the drop-off continuity is always true. The other checks are not always true indicating improper behavior of the model. These results are discussed in detail below.

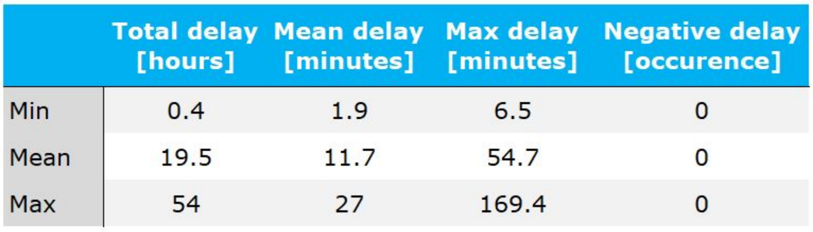
Table 6.1: Verification results



Phase	Check	Min	Mean	Max
Drop-off	Continuity	0.0%	0.0%	0.0%
	Scheduling	0.0%	2.0%	6.0%
	Weather	0.0%	0.1%	0.5%
Pick-up	Continuity	0.2%	4.1%	9.1%
	Scheduling	0.1%	6.1%	14.3%
	Weather	0.0%	0.1%	0.5%
Misc	Technician	0.0%	1.6%	5.9%
	Evacuation	0.0%	0.3%	2.9%

Table 6.1 shows that the pick-up continuity check is always false, however only for 0.2%-9.1% of the pick-up operations. This lack of continuity originates from the mothership relocating to a further away turbine than was initially planned, as explained in section 5.3.6. The delays that this causes are however not that long (12 minutes on average) and crucially no technicians are picked up before the work on the turbine is completed, see table 6.2. The results of this check are therefore not seen as a liability to the accuracy of the model since it is unlikely that the craft will always be exactly on time in reality. The effect of the mothership relocating is also the cause for the other checks to be false. This however results in a very limited number of cases where the simulation weather, technician and evacuation constraints are not met. Changing the model to alleviate this planning error was not deemed worth the effort since the influence of it is so small that it does not significantly influence the conclusions drawn from the results.

Table 6.2: Pick-up continuety details



	Total delay [hours]	Mean delay [minutes]	Max delay [minutes]	Negative delay [occurence]
Min	0.4	1.9	6.5	0
Mean	19.5	11.7	54.7	0
Max	54	27	169.4	0

6.3 Validation

The downtime and emission estimates of the model need to be validated. This is done by exploring model behavior and comparing to model results to real-life data for the downtime. The emissions only use the second method. The downtime validation is discussed first, followed by the validation of the emission estimation.

6.3.1 Downtime

Exploring Model Behaviour

The models behaviour has been explored by varying multiple input parameters and monitoring the output. The model showed the expected direction changes for the variables listed below. These results are shown in chapter 7.

- Number of technicians
- Number of craft
- Transfer limit
- Craft selection order
- Inter turbine distance
- Preventive maintenance order

The magnitude of the downtime estimate cannot be directly compared to real life results due to the way the downtime is calculated, see section 5.1.2. A theoretical lower limit can however be reasoned based on the constraints of the simulation. This reasoning is shown below.

- Night downtime

  Some visit inception times are during the night when no work is done. A flat distribution is used to generate the inception times so there is a 10/24 chance that a visit's inception time occurs during the night. The average waiting time until the visit could be executed is therefore 5 hours. For an average year with 2,400 visits this results in around 5,000 downtime hours.

- Port calls

  No visits are executed during port calls but visit inception times can occur during this time so this results in downtime for those visits. There are 26 port calls each year (one in 14 days) and each visit has to wait at least around 24 hours until it can be executed so this means around 4,100 downtime hours.

- Work on turbine

  The turbine is started again once the maintenance work is completed. Therefore the duration of the work is also included in the downtime. The average duration of a visit is around 5.5 hours. So, the downtime incurred during the work on the turbine is around 11,000.

- Transfer times

  The transfer times also result in extra downtime. Transfers cause downtime because at least one transfer has to occur during the drop-off operation before the visit is completed. The pick-up transfers also cause downtime because this takes up time that could otherwise be used to start the drop-off operation of the next visit. Transfers take between 7 minutes and half an hour so this causes between 1,120-2,400 downtime hours.

- Sailing times

  The time lost due to sailing times is the most uncertain since it is dependent on how the transfers are divided over the different craft and the mean sailing distance. This number can however vary between 6,400-300 if the mean distance is assumed to be half the diagonal distance across the wind farm.

- Weather

  Section 5.2.2 shows that the weather conditions exceed the maximum transfer limits for around 3% of the time. This means that 3% of the visits have to incur downtime for an average of 3.5 hours (half the mean duration of exceedance windows). This results in around 275 downtime hours. This however only includes the visits of which the inception time falls outside of any weather window. Visits that are awaiting planning are however also affected and will be causing downtime. It is however difficult to estimate how large this effect is.

- Other

  There are additional causes of downtime. All craft can be busy causing the drop-off operation for a new visit cannot immediately start. Or certain visits might simply not fit in the schedule causing them to be delayed to at least the next day. The resulting downtime caused by these effects is however hard to estimate.

The above reasoning shows that the theoretical least amount of downtime ranges between 21,795-29,180 downtime hours or 6.3-8.4 days of downtime/turbine/year plus the downtime caused by the more difficult causes to estimate. The best-performing configuration in the simulation has around 8.9 days of downtime/turbine/year (see chapter 7) so the order of magnitude of the results is within expected limits.

Comparison to Real Life Data

The results of the model are compared to a real-life wind farm for further validation. The Rentel, Seastar, and Mermaid wind farms, together called the Rentel Seamade wind farm is used for this validation. These three wind farms are located between 34 and 51 km of the Belgian coast and combined consist of 100 turbines. The following data about this wind farm was gathered and used as input for the model.

- Turbine coordinates
- Technician shift information
  - Start time
  - Shift duration
  - Number of shifts
  - Shift size
- Maintenance vessel parameters
  - Types of craft
  - Transfer limits
  - Number of technicians
  - Speeds
- Hindcast data during March-April
  - Significant wave height
- Executed visits during March-April
  - Visit inception date
  - Execution date
  - Number of technicians that performed the visit
  - Visit duration
  - Preventive or corrective indicator

The turbine coordinates are used to calculate the sailing times for each visit. An SOV with a capacity to house 24 technicians is used in combination with a CTV at the Rental Seamade wind farm. Their respective transfer limits are 2.5m and 1.8m Hs, the operational speeds are the same in table 5.1. This site does not operate a helicopter. The results of the model when using a helicopter can therefore not be validated using the comparison to this wind farm. Some sites use a helicopter to transfer technicians. Data from one of these sites could not be obtained for this study. The helicopters at these sites however do not operate the helicopter from the SOV but from shore. This increases the transit times and changes the logistical setup for the technicians (a group of technicians are then permanently stationed at the heliport). So an exact comparison between the model and one of these sites cannot be made.

The real-life visit data is not exactly the same as is used in the model. The inception and execution are only recorded on a daily basis, meaning that it is only known on which day a visit is executed. Additionally, not all faults/alarms require the turbine to stop operating. This assumption is however made in the model and the real data does not have an indicator that indicates this. It is therefore not possible to directly compare the downtime of the model with the downtime in real life. Comparing the dates at which each visit is executed and assessing how many visits are performed each day is therefore the only alternative.

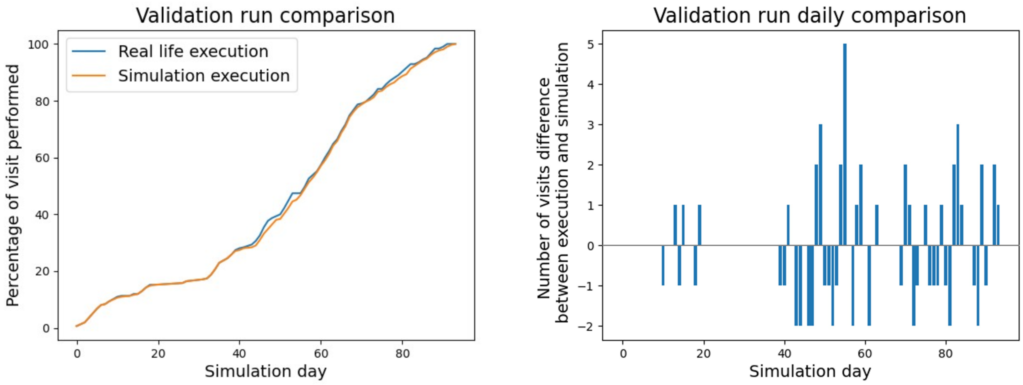
The real-life visit data also features a significant number (around 17%) of corrective visits where the difference between the visit inception date and execution date is large. The cause of these delays between the inception and execution time is that not every visit is as urgent. Some faults or alarm notifications that do not (or by a limited amount) influence the productivity of the turbine are bundled together into one large visit to decrease the total number of visits. These faults can then all be serviced together during a time when there is less wind and there is space in the planning to perform the visit, causing fewer production losses. Only around 10% of visits cause downtime from the inception time of the visit, another 5% requires the turbine to be visited within 4 days. The remained of the visits can be performed within 20 or more days.

These are tactical planning considerations that are not incorporated into the model. The model makes a daily planning and its primary goal is to perform as many visits as the real life fleet is able to perform each day, so the performance of the fleets can be compared. These tactical considerations reduce downtime and spread the workload more evenly over time. The absence of these tactical considerations does not influence the relative performance of the fleet configurations. Only the absolute downtime value which cannot be directly compared to real-life data anyway, as explained in section 5.1.2. The influence of the tactical planning considerations is therefore removed by setting the visit inception time in the model to the day it was executed in real life.

Setting a clear accuracy goal for this validation is difficult because the limitations of the data do not allow for a direct comparison of the estimated downtime. The execution of the maintenance visits in the simulation is therefore compared to those in real life based on the daily volume of visits that is executed. There should not be a continuously increasing difference in total number of visits performed. This would indicate that the simulations execution is not able to deliver a similar level of workload. The number of visits performed by the simulation each day should therefore be close to that of the real life execution.

The results of the validation simulation are shown in figure 6.1 and table 6.3. Figure 6.1a shows the cumulative percentage of visits performed each day, therefore tracking how far behind the simulation is compared to the real-life execution of the visits. Figure 6.1b shows the difference in number of visits that are performed each day. Figures that show the total number of visits each day cannot be shown in this report due to confidentiality. Table 6.3 shows the percentage of visits that are performed later than in real life.

Figure 6.1a shows that the simulation is never many visits behind the real-life execution and is always able to catch up on the backlog in turbine visits. Figure 6.1b shows that the simulation



(a)

(b)

Figure 6.1: Validation results

Table 6.3: Visit delays

Simulation execution delay [days]	0	1	2	3	>3
% visit	76.5%	12.9%	5.5%	1.9%	3.2%
Cumulative % visits	76.5%	89.4%	94.8%	96.8%	100.0%

is able to complete the same number of visits on 47 out of 92 days. The error on the other days is typically one or two visits. This error is caused by the order in which the visits exit the prioritizer. Some days feature visits that have to occur at both the Rentel and Mermaid wind farms for example. These turbines might however not be within each other's evacuation radius so work on these turbines cannot take place simultaneously. Planners in real life would therefore first schedule the visits at turbines at the Rentel wind farm, for example, followed by the visits at Mermaid. The prioritizer does not check for this so in some cases the first visit released to the planner might be for the Rentel wind farm, followed by one at the Mermaid farm. This results in the visit at the Mermaid farm being scheduled directly after the first visit at the Rentel farm has been completed. The other visits at the Rentel wind farm can then typically only be planned on this day if their duration is shorter than that of the first visit because they can only occur while the technicians of the first visit are on that turbine. Otherwise, they are delayed to the next day.

The maximum difference between the simulation and real life is five visits. This difference occurred on a day where no visits were executed in reality, following two days with a notably high number of visits. The reason why no visits were performed on that day is uncertain since the weather conditions did not prevent work from being carried out. This discrepancy could therefore partially be caused by some unforeseen factor. This error is therefore seen as an outlier, especially since it only occurs once in three months.

Table 6.3 shows that 75% of the visits in the simulation are executed on the same day and 90% of all visits are executed with at most a one-day delay. **These results are deemed satisfactory for a model that is only used to compare the results of the simulation with each other.**

6.3.2 Emissions

The emissions of the mothership are compared to that of the SOV operating at the Rentel Seamade wind farm. The fuel consumption data for the CTV is not reported in the data, a comparison can therefore not be made. The results are shown in table 6.4. The simulation has 22% more emissions than were produced in reality. There are two main causes for this difference. The first is that the fuel consumption figures of the SOV at Rentel Seamade are not known per operational mode, therefore the same fuel consumption figures are used as stated in section 5.2.3 for an SOV with 30 technicians. These values will undoubtedly be different from those of the SOV at Rentel Seamade. Second, the schedule that the planner in the model makes is not optimized. It is therefore likely that the SOV in the model sails longer distances. The error will however be similar for all fleets so this does not impact the comparison of the different fleet configurations.

Table 6.4: Emission validation

	Reality	Simulation	% Difference
SOV emissions [ton CO_2]	1222	1494	22%

6.4 Chapter Conclusion

Sub-question 5: How accurately can the method predict the performance of the concepts? Is answered in this chapter. The answer to this question and other findings of this chapter are discussed below.

The verification of the model shows that the conceptual model is a close representation of reality as expressed by the two experts. The computational verification shows that the pick-up of the technicians is delayed in a small percentage of cases, between 0.2-9.1% of visits. The duration of this delay is however only a few minutes and therefore not necessarily unrealistic. This delay is caused by the mothership relocating to a further away turbine than was initially planned. This causes the simulation to not comply with the weather, technician, and evacuation constraints in a limited number of cases. The influence of this is however deemed too small to significantly impact the results of the model.

The model is validated by comparing the results of the simulation with the execution of three months of visits at the Rental Seamade wind farms. This site operates an SOV supported by a CTV but does not operate a helicopter. The results of the model when using a helicopter can therefore not be validated using the comparison to this wind farm. Data from other sites could not be obtained for this study and could not be used for direct comparison because helicopters are currently only operated from shore and not from an SOV.

A direct comparison of the downtime is not possible because of the assumption of the model that turbines stop for all corrective visits. Comparing the dates at which each visit is executed and assessing how many visits are performed each day is therefore the only alternative. This however does make it difficult to establish the exact accuracy of the model. The performance of the model was compared to the real-life execution based on the daily volume of visits that are executed. The simulation showed a close resemblance to the data from the Rental Seamade wind farms and crucially did not build up an ever-increasing backlog of visits compared to those wind farms. The downtime estimation of the model is therefore deemed to be close to the real-life performance for fleet configurations that only use vessels. The accuracy of the fleet configurations that use helicopters could not be established by the comparison and can therefore only be ensured based on the conceptual model verification.

7 Method Demonstration

This chapter uses a case study to show the method to analyze the model's results and to estimate the sensitivity of the model to input changes. The sensitivity of the model is assessed using four cases each focusing on different input variables. The base case will provide insight into the sensitivity to the number of operational technicians, different fleet compositions, and transfer limits. The following cases will focus on the impact of changing the craft selection policy and on the effects of the evacuation criterion. This chapter will first focus on the sensitivity as a results of the aforementioned inputs on downtime, followed by the emissions. The standard analysis of the results is shown in the base case of the sensitivity study. This chapter starts by discussing the input for this case study in section 7.1 and then continues with some post-processing steps in section 7.2. Section 7.3 will then show the analysis to identify the best-performing fleet compositions. Sections 7.4 and 7.5 will then discuss the sensitivity to changes in policy and aspects of the evacuation criterion. The emission results will be discussed in section 7.6 and section 7.7 will provide the conclusions of this chapter.

7.1 Case Study Input

This section will show the model input that is specific to the case study. This is the wind farm layout, weather data and visit agenda generation input data.

7.1.1 Wind Farm Layout

The wind farm parameters for the case study are chosen to emulate the wind farms that are currently in development and that should highlight the shortcomings of current maintenance vessels. These shortcomings are the low transfer limit of the DC, which causes the SOV to be responsible for both preventive and corrective maintenance if the DC cannot be deployed. This significantly reduces the fleets capacity to perform corrective maintenance, due to the SOV's smaller evacuation radius. Resulting in fewer turbines that can be visited each day. Assistance from a CTV can help alleviate this issue but is required to make a long trip back to shore if the weather turns bad. The case study wind farm is, therefore, a large wind farm, with large distances between turbines, located far offshore. A wind farm with 144 turbines, that have a capacity of 8 MW or more, arranged in a square grid, with 1.6 km between turbines, located 100 km offshore complies with these characteristics.

A wind farm with 144 turbines is selected because this is as large as the largest wind farm considered in literature, see section 4.2. That wind farm uses older 3.6 MW turbines, however. This wind farm will have turbines with a capacity of 8 MW or higher. The size of the turbine is given as a lower boundary because this only has a secondary impact on the logistics. Larger turbines require more space between turbines to limit efficiency losses due to the wake behind the turbines. A distance between turbines of 1.6 km is chosen because this is roughly the distance typically used for 11 MW turbines. Therefore being roughly in the middle between an 8 and 15 MW turbine. A distance to shore of 100 km is chosen because this is the furthest offshore wind farms of this size will typically be located in the future, see section 3.1.

There is only one wind farm in the Wood Mackenzie database that meets these criteria. This can be increased to eight if the distance to shore is decreased to 50 km, roughly the maximum

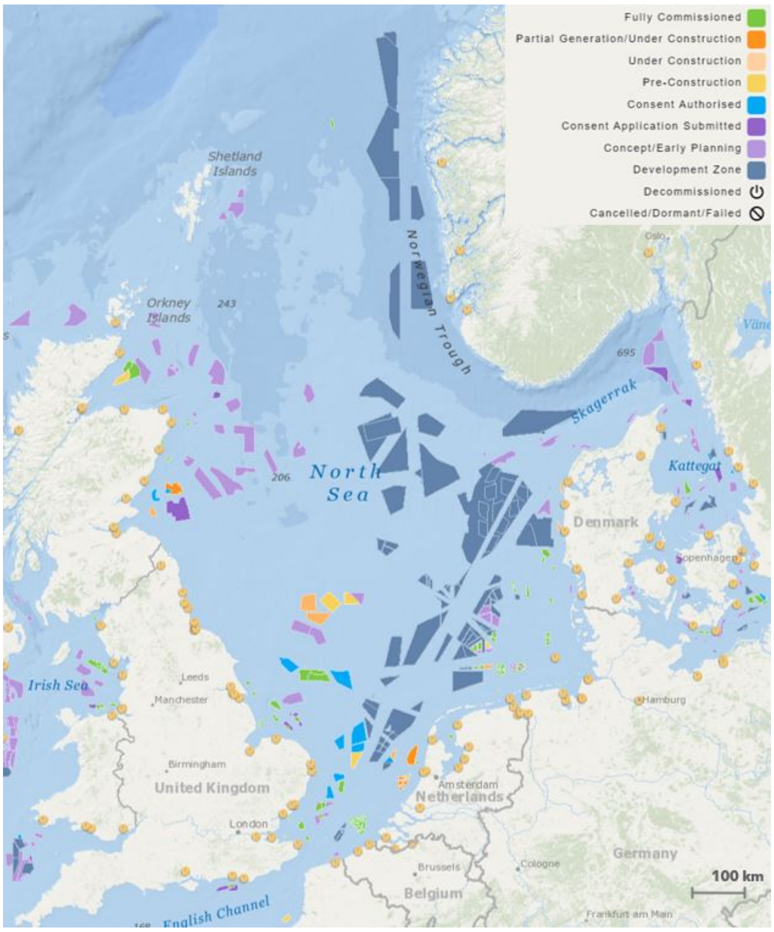


Figure 7.1: Map of all wind farm development areas in the North Sea (4COffshore, n.d.-a)

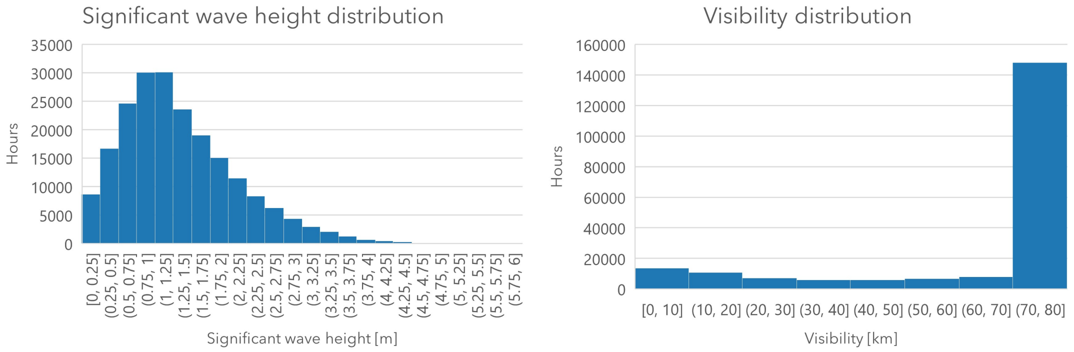
range that can be serviced by CTVs alone. All of these eight wind farms are located in the North Sea (Wood Mackenzie, 2023). This number can be increased to 31 wind farms if the minimum number of turbines is decreased to 60 (Wood Mackenzie, 2023). Almost all of these wind farms are also located in the North Sea and most are also located close together, see figure 7.1. These wind farms could in theory be serviced together by one mother-daughter concept. So, in essence it can be seen as one larger wind farm. None of these farms are currently operational, except one. It is also important to note that only around 50% of the data, concerning the number of turbines and distance to shore was available in the database. So, this number is likely to increase in the future. The wind farm that will be used in the simulation model to compare the different mother-daughter concepts and benchmark them is described in table 7.1.

Table 7.1: Case study wind farm

Wind farm parameters	Value
Nr. Turbines	144
Turbine rating	>8 MW
Distance between turbines	1.6 km
Distance to shore	50 km
Location	North Sea
Layout	Square grid

7.1.2 Weather Data

The weather data used in the simulation is the significant wave height and visibility range from hindcast data of the East Anglia Three wind farm, located 69 km offshore the British coast in the Southern North Sea. The last 23.5 years of hindcast data was available. This dataset was divided into 20 blocks, each with two years of weather data. The first year of this block is the most important since this is used in the simulation. The second year is there to have weather data for the overtime that every sim will make. The most recent years are used first because these are deemed to be the most accurate, due to the effects of climate change. The distributions of both variables for the entire dataset is shown in figure 7.2.



(a) (b)

Figure 7.2: Weather variable distributions

7.1.3 Visit Agenda

One lift inspection and one annual service is planned for each turbine. The preventive visits are scheduled every day from the first of May until all preventive visits have been scheduled. The preventive visit parameters are shown in table 7.2 and are based on the information in section 2.3. The minimum and maximum values of the triangular distribution used to generate the corrective visits are 5 and 25. These values are chosen in cooperation with a company expert to be in the right order of magnitude but do not reveal the actually occurring values.

Table 7.2: Preventive maintenance visits

	Visit duration	Required number of technicians
Lift inspection	3	3
Annual service	10.5	8

7.2 Post-processing

The results of the model are based on assumptions that are not always true in reality. Some post-processing of the results is therefore done to make the results more realistic. The main assumptions that significantly influence the results of the model are discussed below.

7.2.1 Downtime Calculation

The downtime calculated by the model cannot be directly compared to real-life data. The reason for this is twofold. **One**, it is assumed that a turbine is stopped at the visit inception time and only starts again when the work on the turbine is done. This is not true in reality, certain component failures do not or only partially influence the productivity of a turbine. So, this assumption causes there to be more downtime than in reality. **Two**, downtime for corrective visits is calculated as the difference between the visit inception time and the time work was completed at the turbine. This can however cause a turbine to accumulate multiple hours of downtime in one simulation hour if multiple visits are scheduled for that same turbine. This can cause the downtime results of the model to indicate more than 365 days of downtime/turbine/year. These assumptions do allow comparison between the fleet configurations but cannot be used to judge if the configuration is able to obtain 98% availability for example.

The visit data from the Rentel Seamade wind farm however showed that only around 10-15% of visits require the turbine to stop or is expected to stop within the next four days. This means that only 10-15% of visits will actually generate downtime from the inception time of the visit, the other visits only generate downtime during the work of the technicians on the turbine. The downtime values calculated by the model are therefore adjusted. A significant portion of the downtime, around 3.2 days of downtime/turbine/year is caused by the work on the turbine itself. The remaining part is caused by planning or other causes mentioned in section 6.3. This portion of the downtime is multiplied with 15% to take into account that the turbine does not have to stop producing electricity for every visit. The relative performance of the configurations will not change by this post-processing effect but this will allow for comparison of the results with availability goals. The results are however very sensitive to changes in this percentage so it cannot be used to draw exact conclusions on which configurations can deliver the required performance. It does however provide a much better picture than without this post-processing effect. A typical availability percentage goal is 98%, this translates to 7.3 days of downtime/turbine/year.

7.2.2 Helicopter Limitation

Nacelle position limitations

The position of the blades and orientation nacelle is one of the factors that dictates if heli hoist operations can take place. The position of the blades and orientation of the nacelle can typically however not be controlled when a turbine is down. It is therefore not always possible for a helicopter to perform a visit. The percentage of visits where the turbine is not producing any power is however low, around 10%.

Transport capacity

The model assumes that a helicopter is always able to deliver all the technicians and parts at the same time. This is true for most corrective and planned visits but not always. Some visits therefore require multiply flights to complete one drop-off or pick-up operation. Thereby reducing the speed advantage of the helicopter. The utilization percentages of the helicopter do however show that it is not flying all the time so some of equipment drop-off and pick-up flights could be made before or after technicians are flown to the turbine to mitigate this. This could potentially also be done for transfers done by the vessels, thereby shortening the transfer times for those transfers and increasing the performance of the vessels.

SOV take-off and landing limitations

The model assumes that the helicopter can take-off and land on the mothership at any time. It is however uncertain if take-off and landings can/will be allowed to occur while the mothership is performing a transfer. The schedule of the mothership might therefore need to be changed based on the schedule of the helicopter, causing extra planning constraints and limiting the number of transfers the mothership can perform.

The magnitude of these consequences is unknown and should be researched further. The speed advantage of the helicopter is therefore completely removed. This is 2 days of downtime/turbine/year for configurations that only operate a helicopter and 0.5 days/turbine/year for configurations that also feature DC(s)/CTV, see section 7.3.4.

7.3 Base Case - Result Analysis Method Demonstration

The base case is the most standard scenario. Preventive maintenance is performed on a column-by-column basis and vessels get priority when assigning visits as in reality. The evacuation criterion is set to half an hour for the first person to reach the TP. This case is used to demonstrate the result analysis method and also shows the sensitivity of the model to changes in the number of employed technicians, fleet composition, and vessel transfer limits.

7.3.1 Result Analysis Method

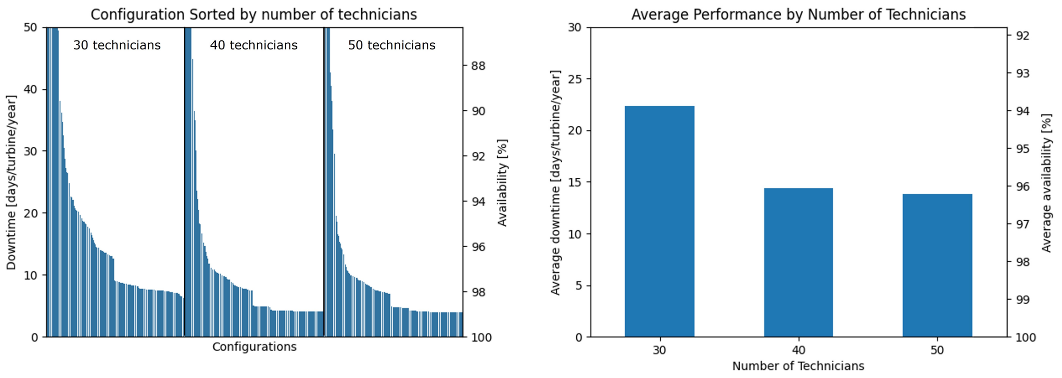
The results analysis method starts by analyzing the optimum number of technicians to perform the analysis. This differs from the operational optimum number of technicians for a specific fleet configuration because operating too few technicians for a configuration will increase the downtime of that configuration. The true performance of the fleet itself can therefore not be observed. The optimum number of technicians for the analysis is the number of technicians that does not significantly restrict the performance of any configuration. This number can be found by increasing the number of technicians to the point where this does not significantly lower the downtime anymore.

The fleets are then divided into groups that hold the same fleet but with different transfer limits. This grouping allows the performance of each type of fleet to be compared to one another. The only performance differentiator within the group is then the transfer limits of the craft, so this will show as the performance range of each group. Analyzing the differences in performance between the groups then allows one to select the number and types of craft. Specific fleets can then be selected based on performance and expected configuration cost. This smaller selection of fleets allows the resolution of the set to be enlarged, meaning that the step size of individual craft characteristics can be reduced if desired. This should be done to determine the optimum number of technicians per fleet configuration. This could be the number of technicians that would result in the fleet delivering a certain contractual availability. An example of this analysis is shown in the following sections.

7.3.2 Optimum Number of Technicians for Analysis

Figure 7.3a shows the downtime of all fleet configurations. The results are sorted by the number of technicians that each configuration uses and its performance. The Y-axis is cut off at 50 days/turbine/year to create a readable figure since the worst-performing fleets have over 269 days of downtime per turbine. Fleets that perform worse than 50 days/turbine/year are also not relevant, since their performance is too poor.

Figure 7.3b shows that operating 30 technicians results in significantly more downtime than operating 40 or 50. Operating 40 technicians lowers the downtime of each configuration on average by around 46% compared to operating with 30 technicians. The difference between operating 40 or 50 technicians is quite small with the difference being 6%. Configurations with 40 technicians are used in the following analyses because these results suggest that 40 technicians are the most optimal for most fleet compositions. The 6% improvement of operating 50 technicians is not insignificant but does not significantly change the relative performance of the configurations.



(a)

(b)

Figure 7.3: Number of technicians

7.3.3 Fleet Composition Analysis

The fleet configurations are divided into groups to see the effects of different craft characteristics on the performance of the fleet. The fleet configurations have been divided into 8 groups based on the different combinations of craft. Each group has received a code name for ease of reading the figures. The formulation of the group codes is explained below. A fleet consisting of a mothership with two DC and a helicopter would therefore be MSDDH for example. A box and whisker plot has been made of all groups and is shown in figure 7.4.

Marine Solutions	MSD	MSDD	MSDDC	
Hybrid Solutions	MSH	MSDH	MSDDH	MSDDCH
Offshore Base	OB...			

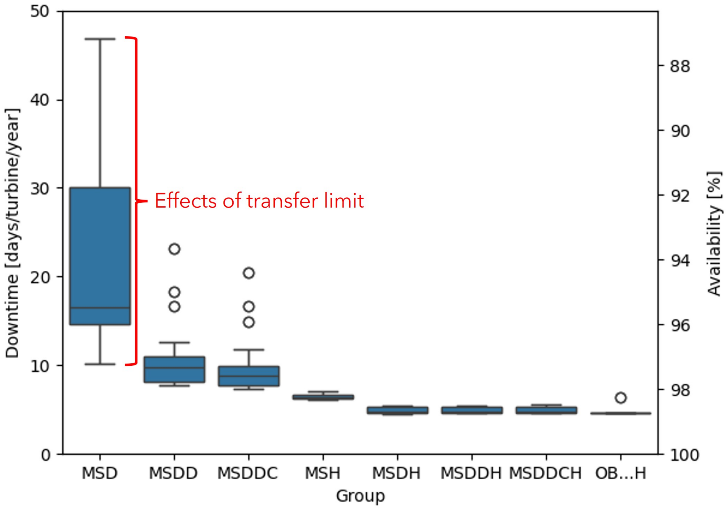


Figure 7.4: Base case - results

Marine Solutions

The results of the marine solutions show that using two DCs results in significantly less downtime when compared to only using one DC. The reduction in downtime is however more severe for the worse performing fleets than for the better performing fleets. This is caused by the fact that the fleets with lower transfer limits have fewer workable days and therefore fewer days within which they can execute the same number of visits. Being able to work with more vessels at once during the limited time they can operate is therefore more beneficial than for fleets that have more workability. The addition of a third support vessel to the mothership, in this case, the CTV, results in a much smaller reduction of downtime. Especially for the better-performing fleets.

Hybrid Solutions

All the hybrid solutions perform better than the marine solutions. The significant reduction in downtime that the presence of a helicopter generates is also clearly visible in figure 7.3a, as the large vertical step in the middle of each of the three parts. This gap between the marine and hybrid solutions can be caused by three factors listed below. Two additional run cases have been done to determine the effects of each of these factors. One run where the helicopter is as slow as a DC/CTV and one where the helicopter is only present to perform evacuations. The results of these factors are in section 7.3.4. The performance of groups MSDH MSDDH, MSDDCH are essentially the same. The performance of the MSH group is only different from these groups due to the post processing effects. This indicates that the helicopter together with the mothership can perform almost all the visits.

- **Increased evacuation radius compared to the DCs and CTV**

  The larger evacuation radius of the helicopter causes no visits to be pushed to the following days due to the evacuation criterion.

- **Increased workablility compared to the DCs and CTV**

  Jumping from 91% workable hours for a vessel with a transfer limit of 2.5m Hs to 96.8% for a helicopter with a minimum required sight line of 3 km.

- **Increased speed and shorter tranfser time of the helicopter compared to the DCs and CTV**

  Causing a drop-off/pick-up operation to be performed faster and therefore being able to perform more visits each day.

Offshore Base

The offshore base group contains all the fleets where the mothership transfer limit is set to 0m Hs and therefore does not transfer technicians to turbines or move within the wind farm. Not all fleets that belong in this group are shown in figure 7.4, because the performance of the configurations that exclusively use vessels is so poor. Only the fleets that use 2 DCs and a CTV fit within the figure having a similar distribution to the MSD group. Group OB...H therefore only shows the fleet configurations that include a helicopter.

These configurations all have essentially the same performance. Indicating that it does not have a significant effect to add more craft. Additionally, an offshore base with a helicopter and one DC with a transfer limit of 1.5m performs better than a mothership with the same supporting craft. The reason for this is that more transfers are being completed by the helicopter when the mothership does not perform transfers to turbines. This is an advantage because the helicopter can perform a transfer faster than the mothership.

7.3.4 Helicopter Performance Breakdown

As discussed above the helicopter performance advantages have three sources: increased workability, speed, and a larger evacuation radius. The advantage that each of these aspects creates is shown using 8 extra groups marked with a asterisk (*). These groups consists of the same fleets as previously used, however the effect of the evacuation criterion is removed or the speed of the helicopter is changed. Figure 7.5 shows the performance of the 16 groups.

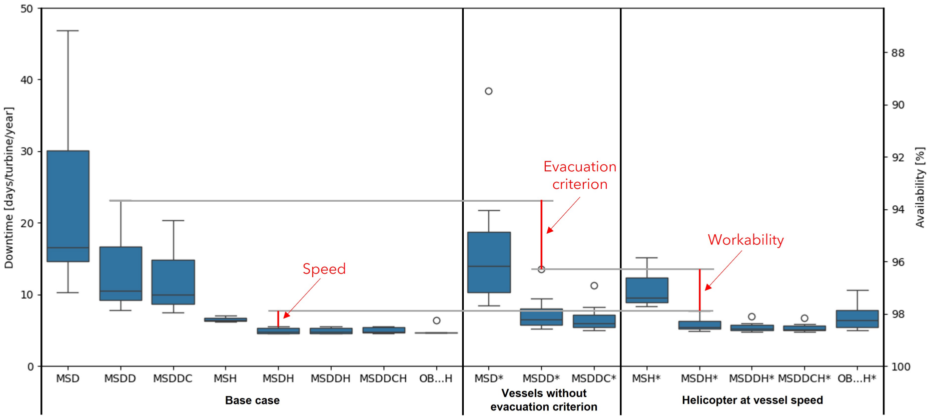
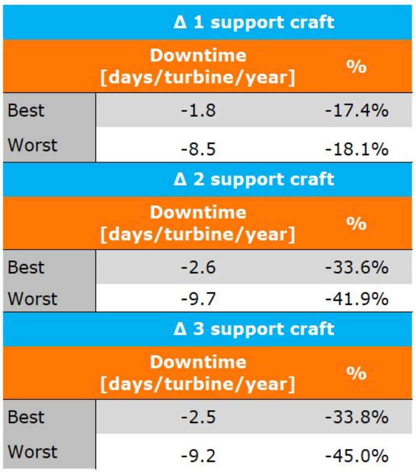


Figure 7.5: Helicopter performance advantage breakdown

Evacuation Criterion

The performance difference between the marine solutions and the marine solutions without the evacuation criterion shows the advantage of the vessels not having to comply with this criterion. This is the main advantage that the use of the helicopter brings. Figure 7.5 and table 7.3 show that most of the performance improvement of the helicopter over the vessels originates from this advantage. The absolute performance improvement is around the same for all three groups. The fleet composition therefore does not influence the size of this advantage.

Table 7.3: Evacuation criterion influence helicopter advantage



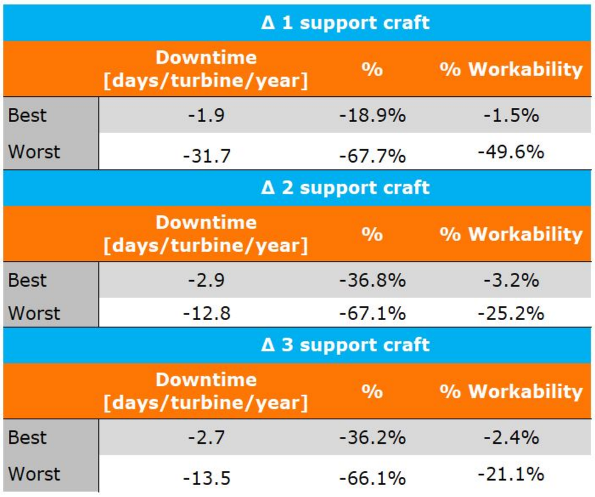
	Δ 1 support craft	
	Downtime [days/turbine/year]	%
Best	-1.8	-17.4%
Worst	-8.5	-18.1%
	Δ 2 support craft	
	Downtime [days/turbine/year]	%
Best	-2.6	-33.6%
Worst	-9.7	-41.9%
	Δ 3 support craft	
	Downtime [days/turbine/year]	%
Best	-2.5	-33.8%
Worst	-9.2	-45.0%

Workability

The added value of the extra workability becomes apparent when comparing the performance the marine solutions without the evacuation criterion with the hybrid solutions where the helicopter's speed is reduced. The cruising speed and transfer time of the helicopter is changed to 20 knots and 17 minutes respectively for these groups. This makes the helicopter equal to a DC or CTV from a workload perspective. Only the workability of the helicopter is better due to it still using the visibility as a transfer limit. The evacuation speed of the helicopter is kept at 240 knots to only see the effect the workability has on the downtime.

Table 7.4 shows the differences between the marine solutions and the hybrid solutions where the helicopter's speed is reduced. The % workability column shows the reduction of the downtime due to the higher workability of the helicopter compared to marine solutions. The table shows that the added workability of the helicopter is between 2-25% for the configurations with two support craft or more, dependent on the transfer limits of the vessels. The improvement for fleets with one supporting craft with a low transfer limit is much larger than for the configurations with 2 or 3 supporting craft. The reason for this is that the configurations with 2 or 3 supporting craft can perform most of the visits during their workable hours. Fleets with only one supporting craft struggle to complete all the work and create a backlog of visits. These configurations therefore benefit more from more workability than fleets with multiple supporting craft.

Table 7.4: Workability influence helicopter advantage



	Δ 1 support craft		
	Downtime [days/turbine/year]	**%**	**% Workability**
Best	-1.9	-18.9%	-1.5%
Worst	-31.7	-67.7%	-49.6%
	Δ 2 support craft		
	Downtime [days/turbine/year]	**%**	**% Workability**
Best	-2.9	-36.8%	-3.2%
Worst	-12.8	-67.1%	-25.2%
	Δ 3 support craft		
	Downtime [days/turbine/year]	**%**	**% Workability**
Best	-2.7	-36.2%	-2.4%
Worst	-13.5	-66.1%	-21.1%

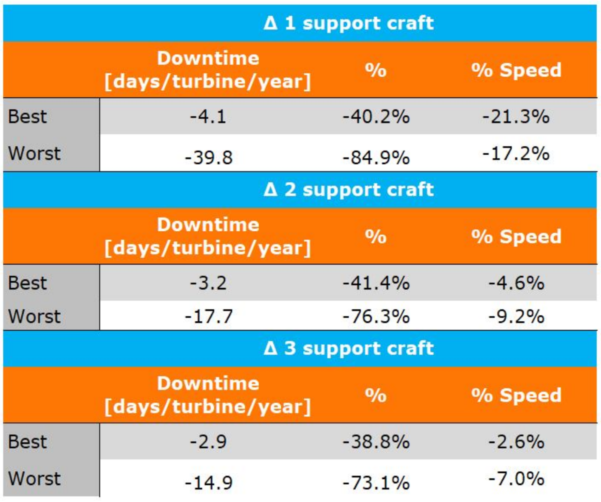
The best-performing configurations show that the relation between extra workability and downtime is not 1 to 1. The maximum transfer limit of the DCs and CTV is exceeded for 9% of the time while the transfer limit of the helicopter is only exceeded 3% of the time. This 6% gain in workability translates to a reduction in downtime of around 2-3%.

Helicopter Speed

Analyzing the difference between groups the hybrid solutions where the helicopter's speed is reduced and the normal hybrid solutions shows the added value of the helicopter's speed. Table 7.5 shows the differences between the marine solutions and the hybrid solutions. The % speed column shows the reduction of the downtime due to the higher speed of the helicopter.

Figure 7.5 and table 7.5 show that fleets with only one support craft are significantly more sensitive to the additional speed than fleets with more than 1 support craft. These only show a marginally higher sensitivity to speed than to workability. The increased speed is more valuable to fleets with one support craft because there is enough time for the fleets with more than one craft to complete all the visits. This is also the reason why the configurations with lower transfer limits gain more from operating faster craft.

Table 7.5: Speed influence helicopter advantage



	Δ 1 support craft		
	Downtime [days/turbine/year]	%	% Speed
Best	-4.1	-40.2%	-21.3%
Worst	-39.8	-84.9%	-17.2%
	Δ 2 support craft		
	Downtime [days/turbine/year]	**%**	**% Speed**
Best	-3.2	-41.4%	-4.6%
Worst	-17.7	-76.3%	-9.2%
	Δ 3 support craft		
	Downtime [days/turbine/year]	**%**	**% Speed**
Best	-2.9	-38.8%	-2.6%
Worst	-14.9	-73.1%	-7.0%

The performance of the best performing fleets overall is more sensitive to extra operational speed than extra workability because the extra operational speed enhances the fleet's maximum workload more. The helicopter is between 64-77% faster within the case study wind farm than a support vessel dependant travel distance. One helicopter can therefore perform a transfer cycle around 70% faster than a DC or CTV. The workability increase of a helicopter over a DC/CTV only lies between 6-49%. Therefore providing between 6-49% more time to perform the transfers. The increased workability of the helicopter therefore increases the performance of the helicopter much less than the operational speed.

7.3.5 Transfer limit Analysis

The same groups used to evaluate the fleet composition are used to determine the influence that changing the transfer limit has on the performance of a fleet. The range that the whiskers indicate in figure 7.4 shows the effect that changing the transfer limits has per group.

Marine Solutions

All three groups show the same trend, where the fleet configuration with the lowest transfer limits scores worst and the one with the highest has the best score. This is to be expected since the fleets with the highest transfer limits have the highest workability and can therefore execute the visits sooner and have more time to execute them. Figures 7.4 and 7.6 show that changing the transfer limits for group MSD has however much more influence than for the other two. This is because the workload is simply too much for a mothership with just one DC, especially when both have a relatively low transfer limit. MSDD and MSDDC therefore show the influence more accurately. The sensitivity of the downtime to changes in transfer limits does become smaller when adding more craft. This occurs because the added value of more workable hours becomes smaller with more capable fleet configurations because the configuration is already able to handle the workload. Figure 7.6 also shows that the marine solutions are more sensitive to changes in transfer limit of the support vessels than the mothership. The sensitivity also depends on the transfer limit itself. The difference in performance between a DC with transfer limit of 1.5m Hs and one with 2m Hs is much larger than between 2-2.5m Hs. This is caused by the difference in extra workability that this step generates. This is 16.5% and

9.6% respectively.

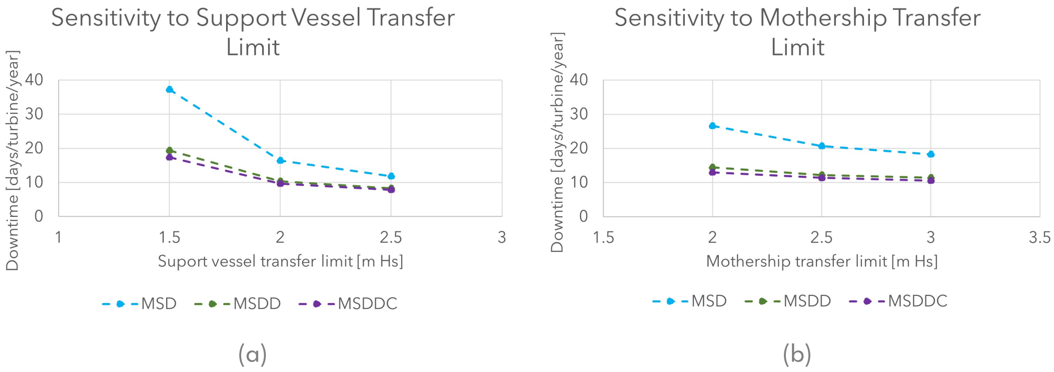


Figure 7.6: Transfer limit influence

Hybrid Solutions

The sensitivity to changes in the transfer limit is much smaller for the hybrid solutions compared to the marine solutions and the sensitivity seems to be constant when adding more vessels, see figure 7.4. This is caused by the high workability of the helicopter combined with its high productivity due to its speed. The workability of the helicopter is higher than that of a vessel with a 3m Hs transfer limit, see section 5.2.2. Increasing the transfer limits of the DCs/CTV therefore does not increase the number of workable days. The only added value of increasing the transfer limit of the vessels is therefore the increased time in which the vessels can transport technicians. This extra time is clearly not required since the gains in performance are almost nonexistent.

The main differentiator within these groups is the transfer limit of the mothership. The transfer limits of the supporting vessels are irrelevant when compared to that of the mothership. Figure 7.7 shows the distribution of the fleets per group. This figure shows that the results are differentiated primarily by the transfer limit of the mothership. With the increase from 2 to 2.5m Hs decreasing the downtime by around 0.8 days/turbine/year. The step from 2.5 to 3m Hs is about 4 times smaller.

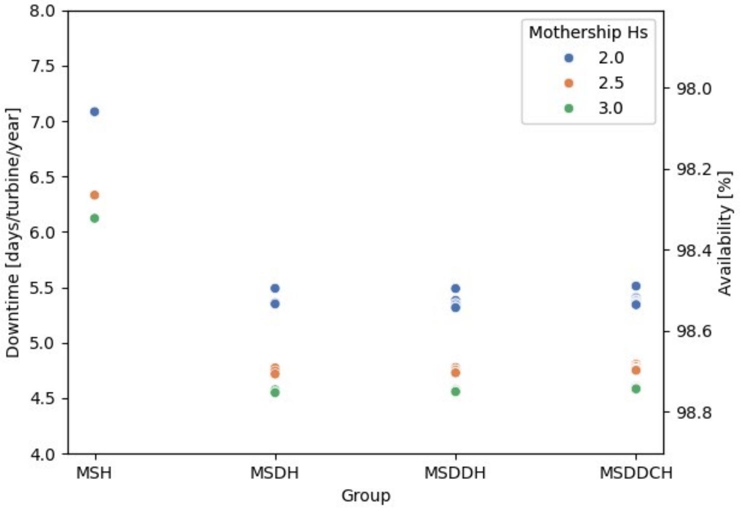


Figure 7.7: Helicopter fleets performance distribution

Offshore Base

The performance of these fleets seems almost completely insensitive to changes in the transfer limits of the DCs and CTV. The difference is only 0.1 days/turbine/year between the best and worst fleets. This is much less sensitivity than is observed for the hybrid solutions. The cause for this could be that the offshore base is always located in the center of the wind farm, while a mothership could be located on the edge of the wind farm causing more travel. This can cause more downtime especially if the mothership is located at the edge of the wind farm during bad weather.

The number of configurations is brought down in the following runs to shorten the computational time. This is done by setting the transfer limits for the DCs and CTV to the same value when they are present in the configuration. This is done because changing the individual transfer limits of the support vessels only has a marginal effect and does not change the output values in an unexpected manner. This level of detail is therefore not required in the following runs.

7.4 Policy - Helicopter prioritization

This case differs from the base case only by the selection order for corrective maintenance. This order is changed to corrective maintenance order 2 from section 5.2.3. The helicopter is selected first in this order. This case is run to see the effects that changing this order has on the performance of the fleets. Figure 7.8 and table 7.6 show the results of this case.

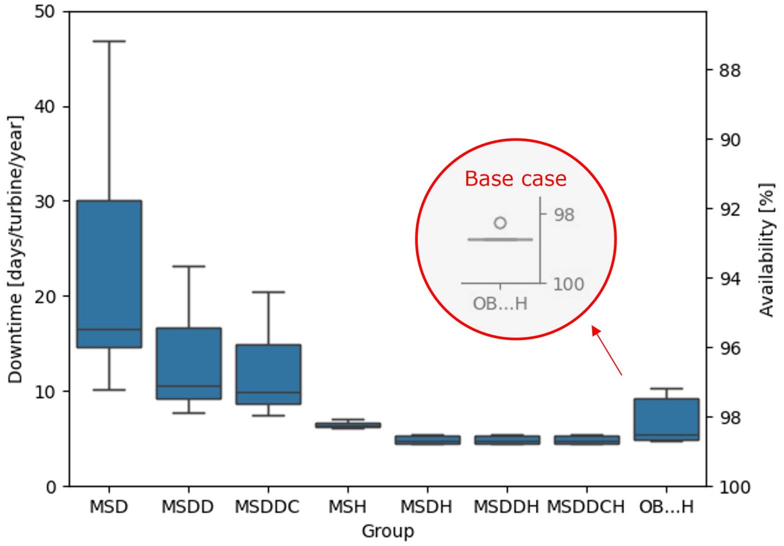


Figure 7.8: Helicopter priority - results

Table 7.6: Policy - Differences compared to base case

Δ% to base case	MSH	MSDH	MSDDH	MSDDCH	OB...H
Best	0.0%	-0.8%	-1.3%	-2.0%	3.2%
Worst	0.0%	-0.5%	-0.9%	-1.7%	61.2%
Range	0.0%	0.9%	0.9%	14.1%	212.8%
Mean	0.0%	-0.5%	-1.0%	-1.9%	40.4%

Figure 7.8 is very similar to the figure of the base case results. The hybrid solutions improve marginally (by around 1%). The configurations with an offshore base do see a significant difference. This could be caused by the fact that the most capable craft is selected first. This could cause visits at the end of the weather window of the vessels to be pushed to the next day. These could normally then be performed by the helicopter but the helicopter could be preoccupied when it is the first craft to be selected.

7.5 Evacuation criterion

The influence of the evacuation criterion on the downtime seems to be significant. Two cases have therefore been run to prove this and to assess possible mitigation techniques. Case one analyzes the sensitivity to the turbine spacing. The second case is run with a different preventive maintenance order is run to see if the performance of the marine solutions can be improved due to tactical improvements.

7.5.1 Sensitivity to Turbine spacing

Reducing the turbine spacing has a twofold effect. One, the transit distances within the wind farm reduce, causing transfer cycles to become shorter. Fleets can therefore handle more workload. Second, the evacuation criterion becomes more restrictive at larger inter-turbine distances. Table 7.7 shows that the performance of groups 1-3 is very sensitive to the turbine spacing. The hybrid and offshore base solutions are not shown in the table because these groups only show a marginal sensitivity to this variable (between 2-7%). The reason for this is that these all use a helicopter, which essentially removes the limitation of the evacuation criterion.

Table 7.7: Sensitivity to inter turbine distance

Inter turbine distance [km]	Evacuation radius coverage	MSD		MSDD		MSDDC	
		Best	Worst	Best	Worst	Best	Worst
1	86.8-100%	5.5	23.9	4.7	14.4	4.6	12.9
		-47%	-49%	-39%	-38%	-38%	-37%
1.3	54.9-100%	7	33.3	5.7	17.7	5.6	15.7
		-32%	-29%	-26%	-24%	-25%	-23%
1.6	38.9-99.3%	10.2	46.9	7.8	23.2	7.5	20.4

Figure 7.9a shows the relation between inter turbine distance and the added downtime that is created by the evacuation criterion. This figure was created by comparing the performance of the marine solutions with and without the evacuation criterion for wind farms with an inter-turbine distance between 1-1.6 km. Figure 7.9b shows the same relation but compared to the minimum evacuation radius coverage percentage. This is the minimum percentage of turbines that is covered by the evacuation radius. The figures show the following trends:

- Every 100m past 800m turbine spacing results in around 6% more downtime (between 800-1300m turbine spacing)
- The added downtime becomes significantly higher with turbine spacing larger than 1300 m
- Every 10% reduction in coverage percentage results around 6% increase in downtime (for coverage percentages between 50-100%)
- The added downtime becomes significantly higher with less than 50% evacuation radius coverage

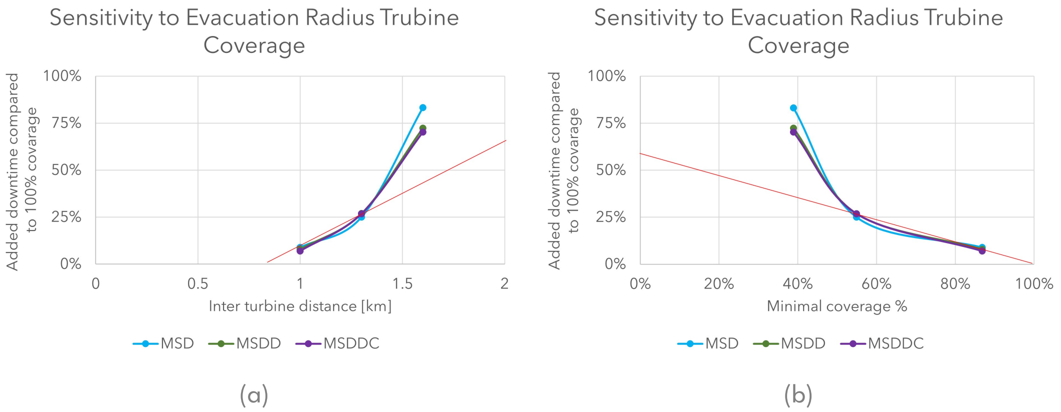


Figure 7.9: Added downtime due to evacuation criterion

7.5.2 Alternative preventive maintenance order

This case only differs from the base case in the order in which preventive maintenance is performed. The preventive maintenance order in the base case is column by column as is depicted in figure 7.10a. This order causes the right half of the wind farm to not be within the evacuation radius for multiple days. Turbines that have failures occur during the time the mothership is performing maintenance at the far left of the farm can therefore not be visited for a long period, causing downtime. Changing the preventive maintenance order so all turbines are within the evacuation radius in a smaller number of days is therefore evaluated. This order is shown in figure 7.10b. Changing the to this preventive maintenance order causes all 144 turbines to be within the evacuation radius in 4 days. This can take up to 24 days using the stratagy shown in figure 7.10a. Figure 7.11 and table 7.8 show the results of this case.

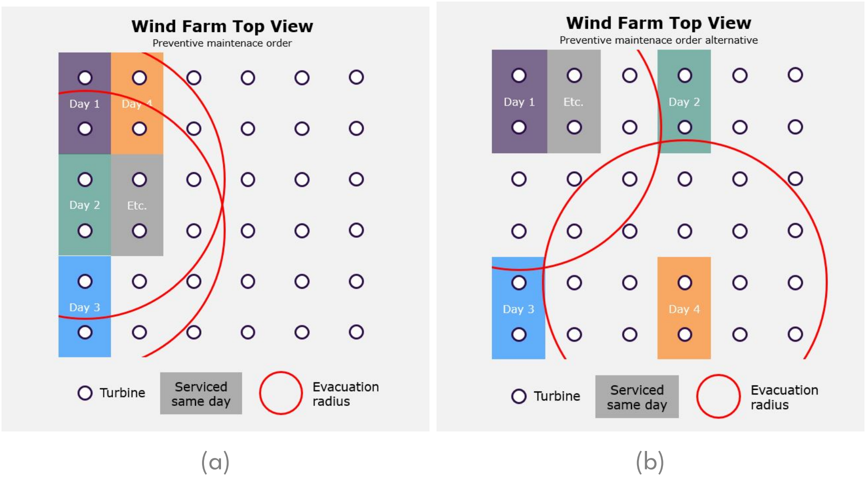


Figure 7.10: Preventive maintenance order

Figure 7.11 and table 7.8 show that changing the preventive maintenance order to this alternative does decrease the downtime of the marine solutions but only by -6-7%. The significant gap in performance between the marine solutions and the other solutions remains. The performance of these solutions remains essentially unchanged by this change in preventive maintenance order.

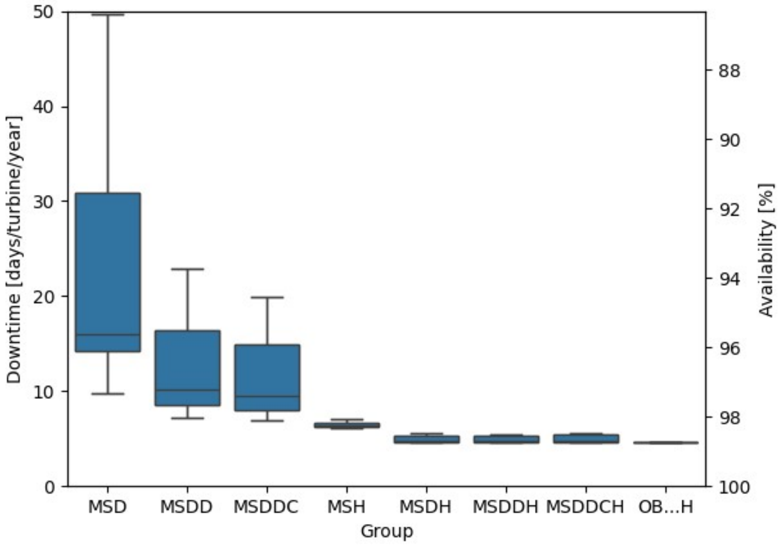


Figure 7.11: Preventive maintenance order - results

Table 7.8: Alternative maintenance order - Differences compared to base case

Δ% to base case	MSD	MSDD	MSDDC	MSH	MSDH	MSDDH	MSDDCH	OB...H
Best	-4.7%	-7.0%	-6.7%	0.2%	0.4%	0.5%	0.5%	0.0%
Worst	6.1%	-3.8%	-2.2%	0.0%	0.3%	0.2%	0.1%	-26.5%
Range	9.1%	1.6%	0.4%	-0.9%	-0.1%	-1.4%	-21.1%	-95.8%
Mean	1.3%	29.2%	-3.2%	0.1%	0.4%	0.5%	0.4%	-2.3%

7.6 Emissions

The same 8 groups are used to analyze the emissions of the fleet configurations. The results are shown in figure 7.12. The results presented in this figure originate from the base case. Only this case is shown since the relation between the different groups stays the same in all cases, see appendix C. Changing the craft selection order does however significantly reduce the emissions of the hybrid and offshore base solutions. The figure shows that the amount of emissions is mostly determined by the fleet composition since the variance within the groups is relatively small. The variance of the offshore base is much larger than the others. This is caused by the fact that this group contains fleets consisting of just one helicopter but also those with two DCs, a CTV, and a helicopter.

The difference in emissions between groups MSD and MSDD is significantly smaller than the difference between groups MSDD and MSDDC. This difference is caused by the CTV's trips to port. The CTV has to do this under its own power, while the DCs use no power during trips to and from port because they are then stowed onboard the mothership.

The hybrid solutions all perform better than the marine solutions that use the same number of support craft. This is caused by the fact that the helicopter operates for a shorter amount of time for the same visit and has lower fuel consumption than the vessels. It is therefore from an emissions standpoint more efficient to perform visits with a helicopter.

The offshore bases have the lowest emissions of all the groups. This is caused by the total abscess of any emissions from the offshore base due to the electricity it receives directly from the wind farm.

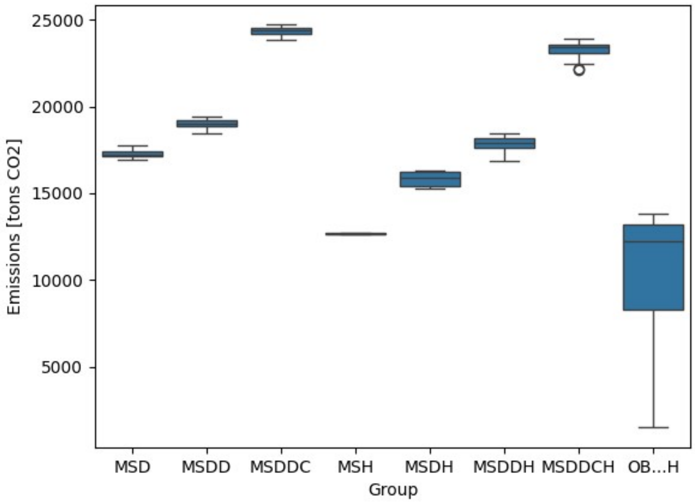


Figure 7.12: Base case - Emissions

7.6.1 Combining Downtime and Emissions

Figure 7.13 shows a scatter plot of the results of the base case. The downtime or emissions do not change very much due to changes in craft selection order or preventive maintenance order. So, only the results of the base case are shown. The figure clearly shows that the offshore bases perform best in both metrics. MSH and MSDH can also obtain similar performance but produce more emissions. The marine solutions perform worst in both metrics. The performance of currently available configurations is shown using x's. These are configurations of which the transfer limit of the support vessels is equal or lower than 2m Hs and no helicopter is present. These configurations are therefore already slightly more advanced than current solutions, but this provides a clear image of the status quo using the data available. The performance of a SOV with a DC of 1.5m Hs is highlighted to show the performance of the currently most used configuration. This clearly shows this configuration will not be able to deliver the required level of performance in this case.

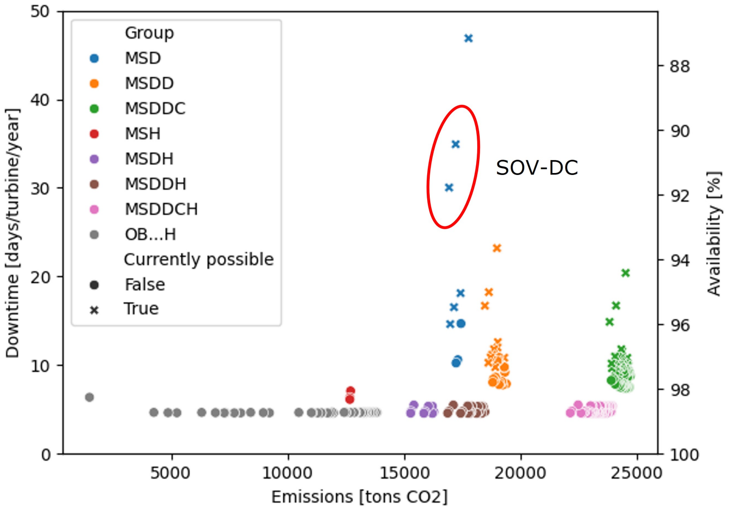


Figure 7.13: Downtime - Emissions

7.7 Chapter Conclusions

This chapter has demonstrated the method used to analyze the model's results and the sensitivity of the model to input changes using a case study. It thereby answers sub-question 6: How sensitive is the model to input changes?

The performance of the different fleet configurations should be analyzed using a relatively high number of technicians, so the performance of the fleets is not reduced due to a lack of technicians. The fleet configurations should then be divided into groups based on the craft within each fleet. This then allows for an analysis to determine the effects of changes in transfer limit and the number and types of craft that should be selected for further development. The optimum number of technicians (or other craft characteristics) for each configuration can then be determined by running a smaller set of fleets with different numbers of technicians (or other characteristics).

The sensitivity to the following variables has been analyzed.

- Have been evaluated
  - Number of technicians
  - Types of craft (Mothership, offshore base, DC, CTV, and helicopter)
  - Number of craft
  - Transfer limit
  - Craft selection order
  - Preventive maintenance order
  - Inter turbine distance
- Have not been evaluated
  - Workload (number of required visits, includes the number of turbines)
  - Distance to port (only impacts emissions)
  - Weather conditions from other sites

The performance of a fleet configuration is either restricted by the number of technicians or the workload that the fleet can handle, which depends on the number of craft and speed and workability of the craft themselves. The sensitivity of variables therefore depends on which of these variables is the restricting factor. It is however clear that the model is most sensitive to the workability of the most capable support craft. The sensitivity to the workability of the other support craft is low.

The case study results indicate that the model is relatively insensitive to changes in craft selection or preventive maintenance order only affecting the performance of the respective groups by up to 7%. The case study results do however show that the marine solutions are highly sensitive to changes in inter-turbine distance/coverage percentage of the evacuation radius, as expected based on chapter 4. Increasing the distance between turbines from 1 km to 1.6 km increases the downtime in the case study by between 23-49%.

The analysis of the case study results showed that the advantage of operating a helicopter in such a wind farm is large, due to the much larger evacuation radius and operational speed of the helicopter. The helicopter is also more efficient from an emissions point of view compared to the vessels, due to its high speed and low fuel consumption rate. The total emissions of a fleet configuration are mostly dependent on the number and type of craft employed. Other variables only have a marginal effect on emissions. The configurations with an offshore base produce the least emissions due to the absence of emissions from the mothership. CTVs produce significantly more emissions than DC, while they deliver the same operational performance.

8 Discussion

The goal of this thesis is to develop a method that can be used to explore the design space of mother-daughter concepts for offshore wind farm O&M. This chapter will discuss the accuracy and usability of the model in section 8.1. Section 8.2 will then evaluate the exploratory set and case study wind farm. Section 8.3 will then interpret the results of the case study and the sensitivity of the variables that have not been changed in the sensitivity study.

8.1 Model Evaluation

8.1.1 Accuracy

The accuracy of the downtime/availability estimate could not be established due to assumptions in the model and the resolution of the data. The analysis of the timing of all the visits does however show that the model can mimic the same workload as in real life. The model can therefore be used to analyze the relative performance of fleet configurations but no conclusions can be drawn whether a configuration can deliver a determined level of availability. This can however be done by adding in different priority levels for corrective maintenance and thereby only assuming that a turbine has stopped producing power for a small percentage of corrective visits. This effect is currently added in post-processing but can, relatively easily be implemented into the model in hindsight. The prioritizer could easily adjust the planning based on the priorities to further improve the realism of the planning algorithm. Another change that would increase the realism of the model and accuracy is implementing technician team ride-sharing routes into the model this reduces the downtime estimate for the marine solutions.

The accuracy of the fleet configurations that employ a helicopter is not known to the same degree as that for configurations that only employ vessels because the validation wind farm does not use a helicopter. Some sites use a helicopter that operates from shore. Operating the helicopter from a mothership is however a novel approach in this sector. Validating the results of these is therefore more difficult. The accuracy therefore completely relies on the conceptual model of the use of the helicopter. This has been validated using face validation. The operational cycle of the helicopter operating from a mothership is in principle also not different from that of the other support craft. The results of the configurations that use a helicopter should therefore be associated with some more uncertainty but not so much that they are completely untrustworthy.

8.1.2 Usability

The input required to run the model is relatively limited and only uses data that is abundant even at the early stages of a project. This makes it easy to use. The result analysis is however manual and requires more time and effort but this can quickly be learned. The method is currently only able to analyze the relative performance of the fleet configurations and can generate operational profiles for each craft which does restrict the usability of the method to more practical applications. This can however be changed by implementing the above-mentioned changes. This would allow the model to be used for a multitude of practical applications within offshore wind farm O&M, such as service sales support, testing new maintenance strategies/planning algorithms, or scenario testing for the effects of unforeseen events.

Using DES to analyze the performance of different fleets works well and is not too computationally expensive, especially for practical applications where there are only a handful of realistic configurations. Computing more than 1200 different fleets is however pushing what is practical. The modeling freedom and event-based nature allow for a very realistic representation of this issue and allow for many different aspects to be added in or evaluated.

8.2 Model Input

8.2.1 Exploratory Set of Fleet Configurations

The craft descriptions of the fleet configurations considered in the case study have been limited to their operational cycle, transfer limit, transit speed, and transfer time. This was done to purely analyze logistical performance and let that be the largest deciding factor in which configurations are selected for further development. The aim was also to show the effect of some performance improvements on the vessels to see what is worth investing in. The financial performance of the configurations was not estimated because the craft description was intentionally abstract. The financial performance of most of fleet configurations selected for further development can be reasonably well estimated. Estimating the financial performance of all fleet configurations would however have been much more time-consuming and would contain much more uncertainties, while the fleet selection would probably be very similar.

8.2.2 Case Study Wind Farm

The case study wind farm used in this study is large and does not represent the gross of the market. As discussed in section 5.2, there are actually very few wind farms in the development phase that are actually of this size. There are however clusters of wind farms that combined are of this size. This study therefore also provides insight into using one service solution for a cluster of wind farms. The results of this case study are however slightly optimistic when applied to a cluster of wind farms because the distance between the farms is not insignificant. The extra distance would cause the added downtime caused by the evacuation criterion to be higher and would cause emissions to increase. This would make it harder to service the cluster exclusively with vessels. Further research into using one mothership with a helicopter and one supporting craft to service clusters of wind farms might therefore be useful if this could prevent the use of one extra SOV.

8.3 Case Study Results - Interpretation

8.3.1 Expected Effects of Unchanged Variables in Sensitivity Study

Three variables have not been considered in the case study in chapter 7, the workload (visit agenda), weather conditions at different sites, and the distance to port.

The model is expected to, out of these three variables, be the most sensitive to the workload. **The workload** is determined by the number of turbines and the average number of visits that need to be performed at a turbine. The case study uses dummy values for the number of times a turbine is visited which makes the results of the case study not completely representative. The sensitivity of the model to the workload is expected to be high relative to the other variables because the workload essentially acts as a scaling factor relative to the x-axis. A lower workload will cause fewer visits that can cause downtime and there will be a smaller chance that visits will have to be performed outside of the evacuation radius at any given time. The workload is expected to be a non-linear scaling factor because the results of chapter 7 indicate that downtime increases significantly once the workload exceeds the capacity of a configuration (large performance range of group MSD).

The weather conditions are expected to be less severe at most other sites since the North Sea has high waves with relatively short wave periods when compared to the other offshore wind development areas (see section 3.3). Analysis of other sites is therefore expected to show a lower sensitivity to changes in transfer limits. The milder weather conditions will also allow the vessels to deliver the required performance with lower transfer limits.

Changing the **distance to port** variable will not influence the downtime/availability estimate because transit to and from the wind farm is assumed to always be performed at times when the technicians cannot work. The emissions estimation is however sensitive to changes in the distance to port. The model is expected to show a medium to high sensitivity to changes in this variable because the difference between using a DC of CTV was significant in chapter 7.

8.3.2 Offshore Base Results

The results of the fleet configurations using an offshore base with a helicopter are different than expected. The expectation was that these configurations would perform slightly worse than the configurations with a mothership because the mothership would provide extra capacity to perform transfers. The offshore base configurations with a helicopter however all perform at the level of the best mothership configurations with a helicopter. This could be explained by the fact that the average travel distance for the offshore base configuration might be lower due to its central location. The results of the policy case are however peculiar since the performance of the offshore base configurations becomes considerably worse, while the performance of the mothership configurations with helicopters improves. It is therefore hard to argue that the decrease in performance is caused by visits that have to be pushed to the next day due to the preoccupation of the helicopter. A deeper analysis of these results is therefore required to make sure these results are correct and if so what causes these results.

8.3.3 Effect of Evacuation Requirement

The limitations of the evacuation requirement were expected to be significant based on the findings of chapters 2 and 4. This was linked to the performance of the currently operational vessels and the urgency of most corrective visits. The real-life visit data used for the validation of the fleet evaluation model however showed that turbines are stopped in much fewer cases than initially expected. The limitation of the evacuation criterion in wind farms of this size is however still significant, causing between 2-4 days of downtime/turbine/year for fleets only containing vessels for the case study wind farm. This accounts for between 27-55% of the maximum allowable downtime if 98% availability is required in the service contract. The magnitude of this effect is however expected to not only be a function of the geometric layout of the wind farm but also of the total number of corrective visits that have to be performed.

8.3.4 Vessel Performance Improvement Avenues

The performance of the vessels can be improved in two ways. Either improving the number of hours that the vessels are allowed to work so, workablility. Or increasing the number of transfers a vessel can perform within those hours. Improving the workability of the mothership will most likely not result in less downtime since the transfer limit of SOVs typically lies between 2.5-2.8m Hs and technicians typically will not transfer in sea states worse than 3m Hs. The results of the model do show that increasing the transfer limit of the support craft will result in a significant downtime reduction. Increasing the workability of CTV-type craft will most likely be expensive because the vessels will have to become either larger and/or more complex.

Increasing the operational speed of the vessels can either be done by decreasing the sailing time and/or transfer time. The sailing time and overall transfer time can be reduced by putting multiple teams on one DC/CTV and sailing to multiple turbines before returning to the mothership. This is not done in the model but is already done in the field. Increasing the sailing speed of the mothership is not possible, because its speed is limited to 6 knots within the wind farm to reduce the risk of a large vessel colliding with a turbine at relatively high speeds. Increasing the sailing speed of the support craft is theoretically possible but difficult because traveling at high speeds through rough seas causes seasickness using conventional hull forms. This issue is more difficult to solve than simply making the vessels go faster.

Decreasing the transfer time might be more valuable than increasing the sailing speed, because increasing the sailing speed only really adds value on longer sailing distances, while the transfer time is roughly the same for every transfer. Additionally, investing in measures to lower the transfer time for CTV-type craft does not only benefit offshore wind farms but also nearshore wind farms no matter what size. The time savings per transfer can also be multiplied by two because the support vessels have to perform two transfers per drop-off or pick-up operation. Reducing the transfer times for the support vessels might be possible with B2W-type systems if they can transfer all the technicians and equipment in one go.

8.3.5 Promising Fleet Configurations Based on the Case Study

Based on the results of the case study and the discussion above some fleet configurations show promising results. These configurations are discussed below in order of highest likelihood of being implemented in reality. It is however important to again mention that the visit agendas used in the case study are not 100% representative of reality. So, analysis using representative visit agendas should be done to confirm that these configurations truly show promising results.

- **SOV with support vessels and rescue helicopter**
  Up to 1% of availability can be lost due to the small evacuation radius of the support vessels, this is significant since a typical service contract requires the farm availability to be at least 98%. Increasing the speed of these craft to increase the evacuation radius is however difficult. It is possible to charter a helicopter that is always on standby to perform an evacuation. This would probably be too expensive for only one wind farm but might be a profitable option if this helicopter is chartered by multiple wind farms for this purpose. This type of setup is already required by German law[1].

- **Offshore base**
  The performance of fleet configurations with a helicopter operating from an offshore base appears similar to those operating from a mothership, although these results do require some extra analysis, as previously mentioned. This configuration will produce significantly less emissions than other alternatives. An offshore base can also be designed so it does not have the take-off and landing restrictions that a mothership will most likely have. Integrating the accommodation and helicopter hangar into the substation might also be more cost-effective than building a self-propelled mothership. The number of technicians required to deliver the required performance might also be lower compared to a purely marine-based solution (based on analysis of Figure 7.3a), further saving costs. A floating offshore base might also be able to function as an offshore harbor. This reduces emissions further by allowing the use of DC instead of CTVs. This configuration does however require significant development.

- **SOV with helicopter**
  The performance of a helicopter operating from an SOV/mothership is good but might be significantly reduced by take-off and landing restrictions. A helicopter operating from an SOV however requires significantly fewer design changes than storing, launching, and recovering one or multiple CTV-sized vessels or designing an integrated helicopter

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[1] From conversations with SGRE employees between May and August 2023

port, accommodation substation. The SOV will also be able to perform the visits that a helicopter might not be able to. This could therefore prevent the use of an additional support craft compared to the previous configuration and will most likely require fewer technicians to deliver the same performance as a purely marine-based solution (based on analysis of Figure 7.3a). This configuration could also more easily service a cluster of wind farms.

9 Conclusion

This chapter discusses the answers to the research questions stated in section 1.6 in section 9.1. The limitations of this study and recommendations for future work are made in sections 9.2 and 9.3 respectively.

9.1 Answers to Research Questions

Sub-question 1:

"What maintenance needs to be performed at offshore wind farms and how will this develop in the future?"

Turbine OEMs generally only perform maintenance on the turbines and possibly some items on the TP. The maintenance scope most notably does not include the foundation of the turbines. The foundation type of a wind farm therefore only has indirect influence on the maintenance activities, such as increased failure rates due to the more severe motions of floating turbines. Maintenance is currently performed under a preventive-corrective maintenance strategy, with the following maintenance categories: annual service, lift inspection, unplanned maintenance, major component exchange, and evacuation.

This strategy requires a large number of turbine visits, which are expensive and dangerous for the technicians. The aim of the industry is therefore to reduce the number of turbine visits. This will be done by implementing a calendar-based-opportunistic maintenance strategy. Condition monitoring systems and predictive models will be used on around 10% of the service scope to reduce the hours spent on inspections during the annual service. This freed-up time will be used to perform activities that will prevent the need for some corrective visits later in the year. These changes will mostly affect the activities on the turbine but will not have a significant impact on the logistics of the technicians, apart from the possibly lower number of corrective visits.

Sub-question 2:

"How will offshore wind farms develop in the future?"

Offshore wind farms will continue to grow in capacity, with an expected maximum size of around 3.15 GW and an average of around 1 GW. Turbine capacity and size will continue to increase as well, increasing the distance between turbines. There are however conversations about limiting the maximum size of a turbine and there is already a maximum size for turbines in the Netherlands. The gross area of wind farms will also keep increasing. Wind farms will overall not move further offshore, with the general maximum distance to shore in the coming years, being between 90-100 km from shore. The average distance to shore will likely not increase past 40 km. Floating wind farms will in the future be similar to bottom-founded wind farms. The only significant differences are greater distances between turbines and increased water depth. The former will increase the effect of the evacuation criterion. The latter only influences the major component exchange maintenance category significantly, because jack-up vessels cannot be used at most floating wind farms. The capacity of floating wind farms will also lack slightly behind bottom-founded wind farms. This is however to be expected from a technology that started to be developed twenty years later.

Sub-question 3:

"Which craft are involved in offshore wind farm maintenance and what mother-daughter concepts are discussed in literature?"

CTVs are used to transfer technicians and parts for maintenance to nearshore wind farms, whilst SOVs are used as an offshore maintenance hub that can transfer technicians and parts for maintenance to large far offshore wind farms. SOVs usually also have a fast DC that can transfer technicians and parts but the DC has very poor seakeeping behavior, meaning it can often not be deployed. SATVs are also used for far offshore wind farms but are deployed at smaller farms that do not require the capacity of an SOV. Helicopters are used in near and far offshore wind farm maintenance but their use and contract types vary significantly. This is because they are typically seen as a last resort and contracted per site causing them to possibly not be optimally integrated in offshore wind farm maintenance.

Mother-daughter concepts for offshore wind farm maintenance have been researched in several studies. All of these articles use CTV-sized vessels as DC, deployed from either a floating or bottom-founded offshore base. Some of these articles do show the potential of these concepts, however, all of the articles focus on a single concept and do not seek an optimal solution. The bottom-founded concepts generally show worse performance that the floating offshore bases. The performance of the bottom-founded concepts also show great sensitivity to the foundation price of the base.

Sub-question 4:

"What modeling method can best be used to estimate the performance of the concepts?"

The modeling method should be able to model the following items:

- The various types of maintenance visits
- Transport of the technicians
- The technicians and craft as a finite resource
- The effects that the weather conditions have on the scheduling of visits
- The evacuation requirement

The use of deterministic, stochastic, and simulation models has been evaluated. The simulation approach has however been selected because this approach can most accurately model the evacuation requirement. This is important because the effects of the evacuation requirement have not been modeled before in literature. It is therefore more important to model this phenomenon accurately instead of making an abstract reduction of it. This would be required for the deterministic and stochastic approach. The downside to the simulation approach is the extra computational time compared to the other methods. This however did not prove to be an issue for this application.

Multi-agent modeling and discrete-event simulation can both be used to analyze the performance of the concepts. Multi-agent modeling is a useful method, especially to see the combined effects of planning policies and different craft (characteristics) but this requires significantly more time to set up and provides a level of detail that is not required for this purpose. A discrete-event simulation (DES) is therefore chosen because it is significantly easier to set up and provides the right amount of capabilities to take into account the elements that are important for this problem.

Sub-question 5:

“How accurately can the method predict the performance of the concepts?”

A three-month period of visits and weather at the Rental Seamade wind farms has been compared with the output of the model using the same visits, weather conditions, and service fleet. The service fleet consists of an SOV assisted by a CTV but does not operate a helicopter. A direct comparison of the downtime was not possible because of the assumption of the model that turbines stop for all corrective visits. Comparing the dates at which each visit is executed and assessing how many visits are performed each day was therefore the only alternative. This however does make it difficult to establish the exact accuracy of the model. The simulation showed a close resemblance to the data from the Rental Seamade wind farms and crucially did not build up an ever-increasing backlog of visits compared to those wind farms. The downtime estimation of the model is therefore deemed to be close to the real-life performance for fleet configurations that only use vessels. The accuracy of the fleet configurations that use helicopters could not be established by the comparison and can therefore only be ensured based on the conceptual model verification.

Sub-question 6:

“How sensitive is the model to input changes?”

The performance of a fleet configuration is either restricted by the number of technicians or the workload that the fleet can handle, which depends on the number of craft and the speed and workability of the craft themselves. The sensitivity of variables therefore depends on which of these variables is the restricting factor.

The case study results discussed in chapter 7 indicate that the model is relatively insensitive to changes in craft selection for corrective maintenance visits or preventive maintenance order. Only affecting the performance of the respective groups by up to 7%. The case study results do however show that the marine solutions are highly sensitive to changes in inter-turbine distance/coverage percentage of the evacuation radius, as expected based on chapter 4. Increasing the distance between turbines from 1 km to 1.6 km increases the downtime in the case study by between 23-49%.

The total emissions of a fleet configuration are mostly dependent on the number and type of craft employed. Other variables only have a marginal effect on emissions. The helicopter is more efficient from an emissions point of view compared to the vessels, due to its high speed and low fuel consumption rate. The configurations with an offshore base produce the least emissions due to the absence of emissions from the mothership. CTVs produce significantly more emissions than DC, while they deliver the same operational performance.

Sub-question 7:

“Which new fleet configurations show promising performance based on the results of a case study considering a potential future wind farm?”

The results of the case study indicate that using a helicopter has a significant advantage over using a pure marine-based service fleet, in both farm availability and fleet emissions. Three types of fleet configurations show promise to provide higher availability and possibly cost reductions. These are discussed on the next page.

- **SOV with support craft and a rescue helicopter**

  Up to 1% of availability can be lost due to the small evacuation radius of the support vessels, this is significant since a typical service contract requires the farm availability to be at least 98%. Increasing the speed of these craft to increase the evacuation radius is however difficult. It is possible to charter a rescue helicopter that is always on standby to perform an evacuation, which removes the planning restrictions due to the evacuation requirement for the vessels. This would probably be too expensive for only one wind farm but might be a profitable option if this helicopter is chartered by multiple wind farms for this purpose. This type of setup is already required by German law[1].

- **SOV with helicopter**

  The performance of a helicopter operating from an SOV/mothership is higher than that of purely marine solutions but might not be as advantageous as shown in the case study due to take-off and landing restrictions. The magnitude of the effects of these limitations is however unknown. This configuration does however show promise because it would require significantly fewer design changes than storing, launching, and recovering one or multiple CTV-sized vessels. Additionally, the case study results indicate that this configuration would probably require fewer technicians to deliver the same performance as purely marine solutions, thereby saving costs. This configuration could also more easily service a cluster of wind farms.

- **Offshore base**

  The performance of fleet configurations with a helicopter operating from an offshore base appears similar to those operating from a mothership. An offshore base can also be designed so it does not have the take-off and landing restrictions that a mothership will most likely have. Additionally integrating the accommodation and helicopter hangar into the substation might be cheaper than building a self-propelled mothership. This configuration will probably also require fewer technicians to deliver the same performance as purely marine solutions, further saving costs. This configuration might however require an extra support vessel or extra helicopter for redundancy purposes.

Main Research Question

> "What method can best be used to explore the design-space
> of mother-daughter concepts for offshore wind farm O&M?"

The most influential factors that limit the performance of a service fleet at large far offshore wind farms are the weather conditions and the evacuation requirement. The evacuation requirement has previously however not been considered in literature, because inter-turbine distances and the physical size of wind farms have typically been too small for this to truly be a restricting factor. It is however starting to become a restricting factor more and more.

The method proposed in this thesis uses a DES to model the transport of technicians throughout the wind farm. This model uses the wind farm layout, weather data, and number of visits to estimate the downtime/availability and CO_2 emissions of a large set of mother-daughter concepts. The financial and technical feasibility should be evaluated in a later stage when the most promising concepts based on logistical performance have been selected. This allows for new innovation directions to be discovered, increases the accuracy of the financial performance estimates, and eliminates unnecessary technical development of concepts of low value. The model aims to provide an accurate representation of how much workload each fleet can deliver. This is done by simulating all the preventive and corrective visits, excluding major

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[1] From conversations with SGRE employees between May and August 2023

component exchanges because these require a heavy lifting crane and therefore fall outside of the mother-daughter concept scope. The visits are planned using an algorithm that looks for the first opportunity to plan the visit while taking into account the weather, number of available technicians, craft availability, and the evacuation requirement. The simulations are run multiple times (10 times for the case study) with different weather conditions and visit distributions across (visit agendas) the year to obtain reliable performance estimates.

The design space of mother-daughter concepts should be explored by running the model using the exploratory set of fleet configurations and inputting various wind farm layouts with varying realistic visit agendas and weather conditions. The optimum number of technicians used for the analysis should first be selected. The number of technicians should be high enough that the configurations are not significantly restricted by the number of technicians. The output of each of these cases should then be analyzed by dividing all the fleet configurations into groups based on the craft each fleet contains. This grouping allows the performance of each type of fleet to be compared to one another, while the performance difference within the groups shows the effects of different transfer limits. The analysis should then focus on identifying cross-over points between different configurations and on selecting specific fleets based on performance and expected configuration cost. The step size of individual craft characteristics and the number of employed technicians can then be reduced to more accurately determine the optimum values to achieve a required level of contractual availability for example.

The proposed method therefore uses a DES to estimate fleet performance. An exploratory set of fleet configurations should be run across different wind farms. These results should be graphically analyzed to determine what the most promising fleets are.

9.2 Limitations

This section identifies and discusses the limitations that impact the methods ability to inform decision making for the development and application of new mother-daughter concepts. The main limitation is that this method only focuses on the logistical performance of the fleet configurations. The financial and technical feasibility of the configurations is only qualitatively assessed. While this suffices for the initial selection process, further quantitative analysis is required to determine the optimal fleet configuration.

The second limitation is that the downtime calculation in the model causes the results to have significantly more downtime than would occur in reality. This is somewhat adjusted for during post-processing by multiplying the downtime not caused by the work on the turbine itself by 15% (the percentage of corrective visits that actually cause a turbine to stop). This causes the results to be a good indicator of relative performance between the fleet configurations but makes it more challenging to say with absolute confidence that some configurations provide the required performance.

Finally, the performance estimates of the model for configurations that use a helicopter could not be validated. The accuracy of these estimates is therefore only supported by the accuracy of the conceptual model and has not been established by comparison to real-life data. The results of these configurations should therefore be treated with a higher level of caution.

9.3 Recommendations for Future Work

Model Improvements

The fleet evaluation model can be improved to increase the accuracy of the results. More detail can always be added but the following two improvements will meaningfully improve the accuracy of the model and make the model more useful to the service sales department.

- Adding priority designations to corrective visits and changing the downtime calculation accordingly

  The model currently assumes that all corrective visits cause downtime starting from the visit inception time. This is only the case for around 10% of the visits from the validation wind farm. Additionally, a turbine that has multiple visits that are to be planned at the same time will generate multiple hours of downtime, which is impossible in reality. The visit agenda should therefore include corrective priority levels that impact both the order in which they are released to the planner by the prioritizer and the times used to calculate the downtime caused by the visit. The downtime for most visits would then only be the duration of the visit itself. This would also largely remove the accumulation of multiple downtime hours per simulation hour, because the chances of this occurring would be much smaller. This effect can however be completely removed by some post-processing of the visit dataframe.

- Implementing ride-sharing

  The model currently plans each visit separately. This means that every group of technicians is transported separately to each turbine. CTVs however can carry multiple teams. A CTV could therefore load up multiple teams and transfer them to multiple turbines before returning to the mothership. This saves both transit and transfer time. Implementing this cycle into the planner and DES environment would make the representation of the craft more realistic and will most likely result in slightly less downtime for the vessels.

Helicopter Validation

Validating the use of a helicopter that operates from a mothership is difficult since real-life data is not available. Future work could however compare the model to another site that does use a helicopter to transfer technicians for maintenance purposes. This comparison would not be completely representative because sites that operate a helicopter from shore have the technicians that fly on the helicopter typically stationed on shore. A second base for technicians is not yet present in the model, so the helicopter would have access to the total number of technicians which would restrict the usage of the helicopter much less compared to real life. All trips of the helicopter should also include the additional flying time from shore to the wind farm. This would however already a significant improvement. The most fair comparison would require a second base to be added to the model but this would require significant modifications to the model.

Fleet Configuration Selection Process

The case study in chapter 7 has demonstrated the workings of the method. The input used in this case study is, however, not entirely representative therefore no concrete conclusions can be drawn about which fleet configurations should be selected for further development. The model with the standard exploratory set of fleet configurations should therefore be run with representative visit agendas and for multiple wind farm layouts. These results should be analyzed using the method shown in chapter 7 and compared to one another to establish cross-over points. For example under what conditions purely marine solutions become significantly inferior to configurations that also use a helicopter. Some more runs with a higher set resolution can then be run to more accurately determine craft characteristics, once the broad picture has been established.

Promising Case Study Configurations

Three different fleet configurations showed promise in the case study. The future work for these configurations is discussed below. It should be considered that the output of the previous section should confirm the promise of these configurations, otherwise this recommended work should not be performed.

1. **SOV with support vessels and rescue helicopter**

   Future work should focus on determining the exact magnitude of the advantage of this configuration. The further development of this configuration will be relatively limited since similar chartering structures are present in Germany because German law requires a helicopter to be on standby for evacuation. It will therefore purely entail adapting the business case to different projects.

2. **SOV with helicopter**

   Further development of this concept requires finding out what the take-off and landing restrictions are for operating a helicopter from an SOV. The consequences of these restrictions should then be evaluated. The business case should then be worked out.

3. **Offshore base**

   Some accommodation platforms have been built but the financial performance is highly dependent on the water depth. An integrated floating substation-maintenance base could therefore be developed. A study into the technical and financial feasibility of this concept should however take place.

Other

The exact magnitude of the influence of some of the helicopter restrictions is not apparent currently. Future work should therefore focus on quantifying the downtime caused by the restriction of the nacelle orientation, blade position, and transport capacity of the helicopter. This means that in some cases the helicopter has to make two trips to a turbine to transfer both technicians and equipment.

The performance behavior of the fleet configurations using an offshore base is unexpected. These should therefore be investigated more intensely to verify that these results are correct and if so to find the cause of these characteristics.

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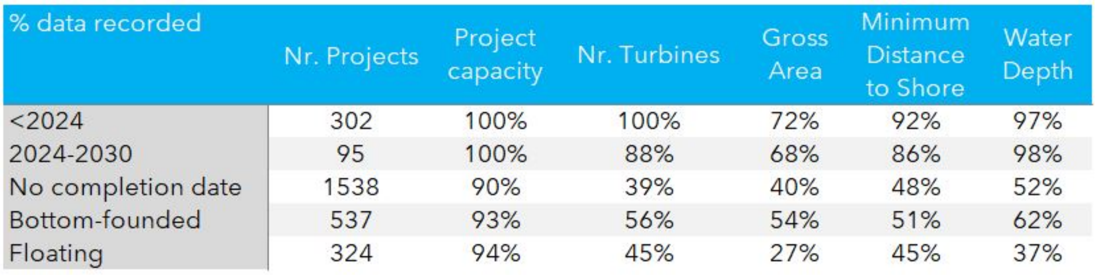
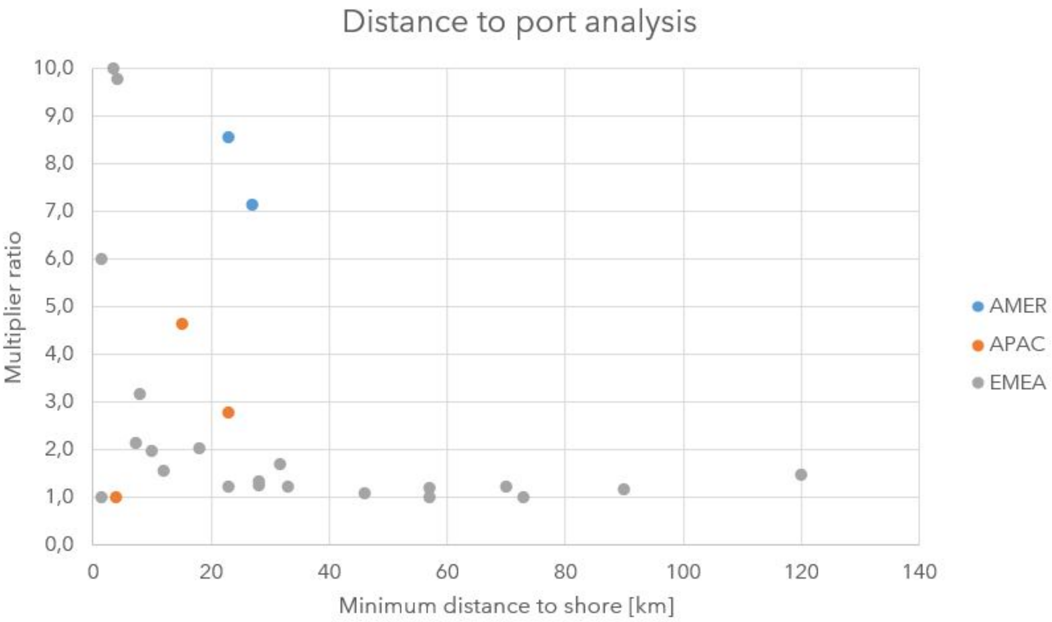
A Worldwide Wind Farm Analysis

A.1 Reported Data

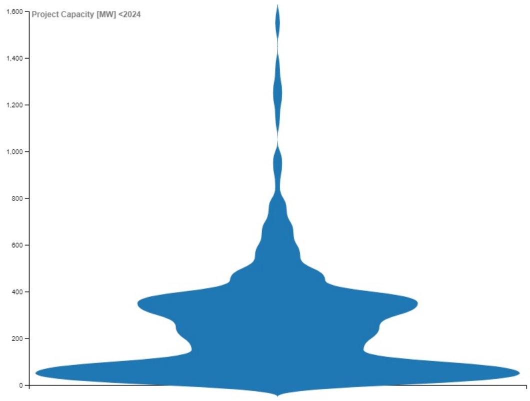


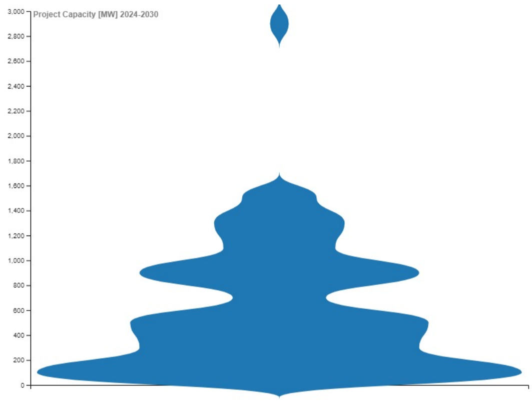
% data recorded	Nr. Projects	Project capacity	Nr. Turbines	Gross Area	Minimum Distance to Shore	Water Depth
<2024	302	100%	100%	72%	92%	97%
2024-2030	95	100%	88%	68%	86%	98%
No completion date	1538	90%	39%	40%	48%	52%
Bottom-founded	537	93%	56%	54%	51%	62%
Floating	324	94%	45%	27%	45%	37%

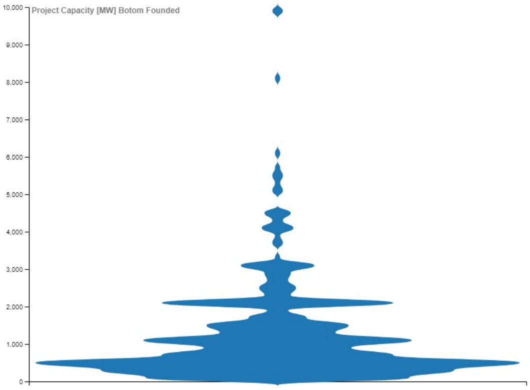
A.2 Distance to Port Analysis

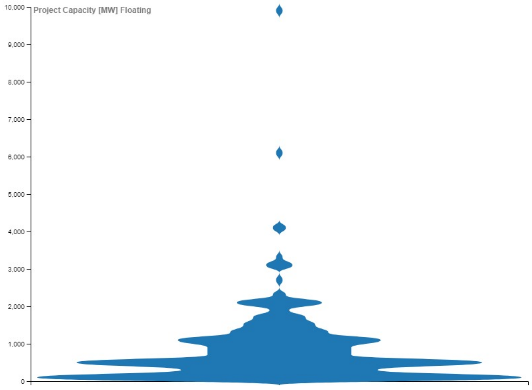


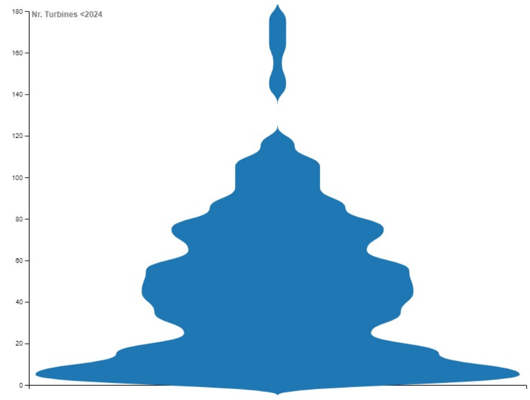
A.3 Violin Plots

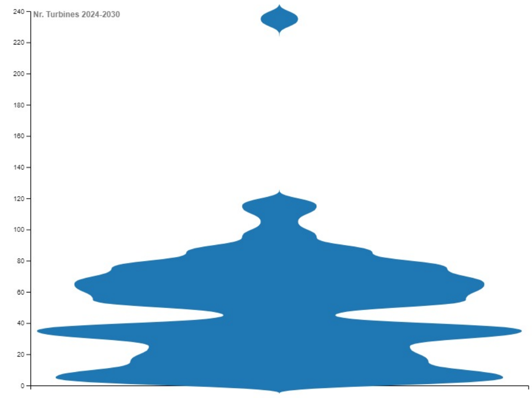


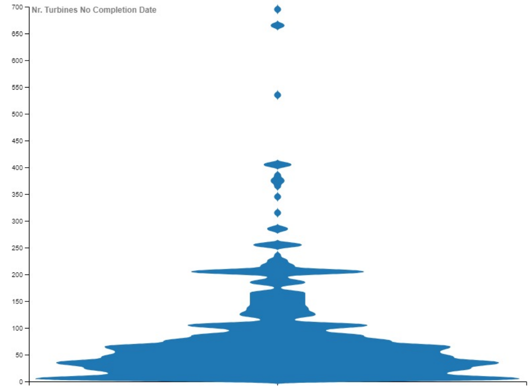


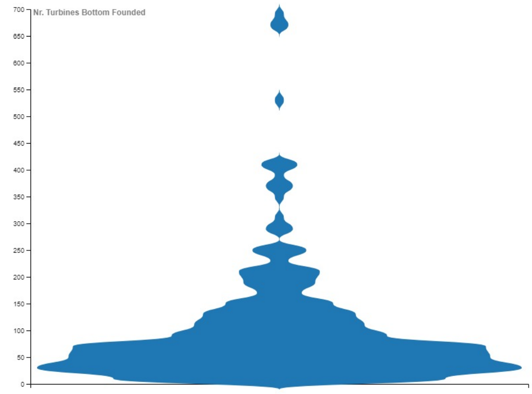


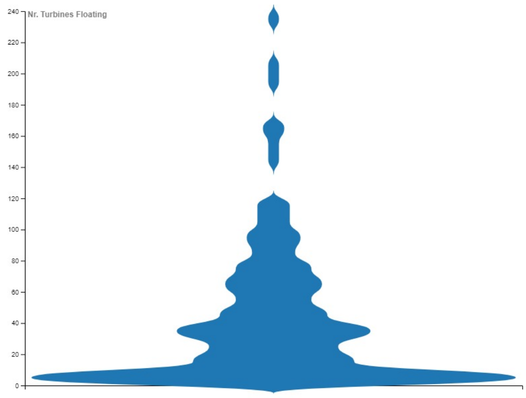


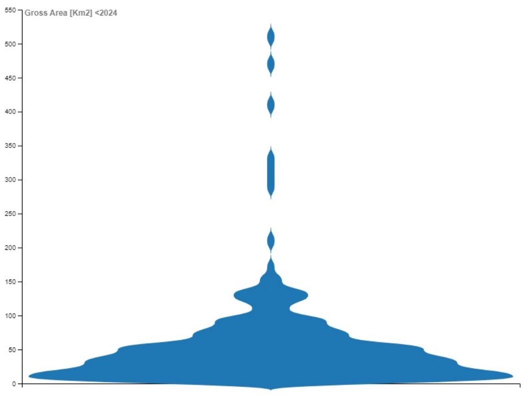


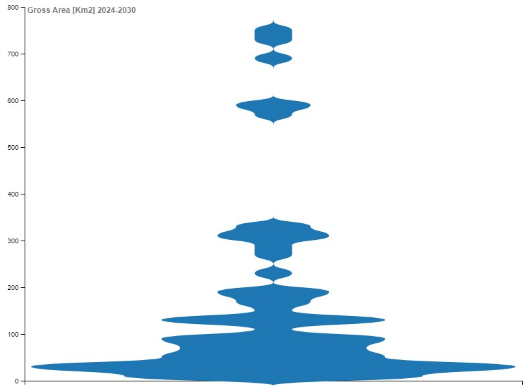


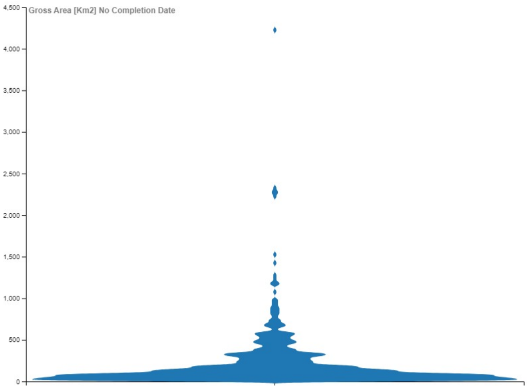


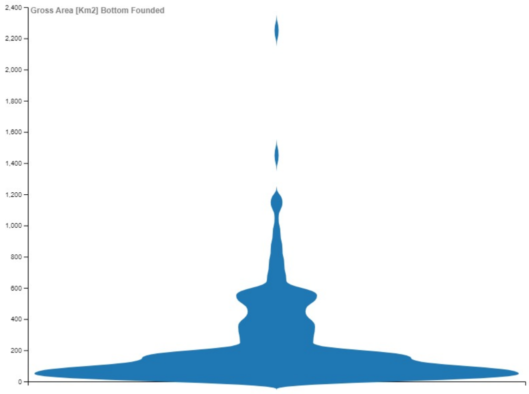


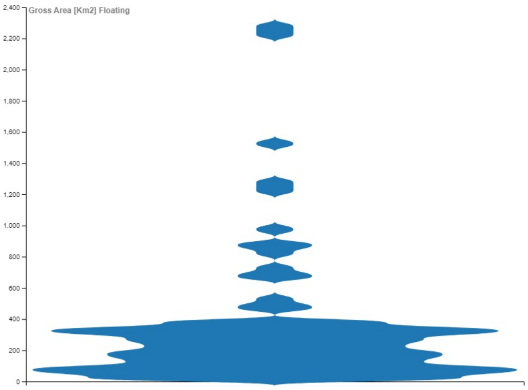

Nr. Turbines Floating
240
220
200
180
160
140
120
100
80
60
40
20
0

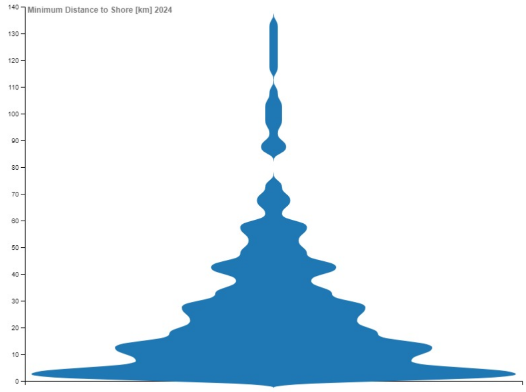

Gross Area [Km2] <2024
550
500
450
400
350
300
250
200
150
100
50
0

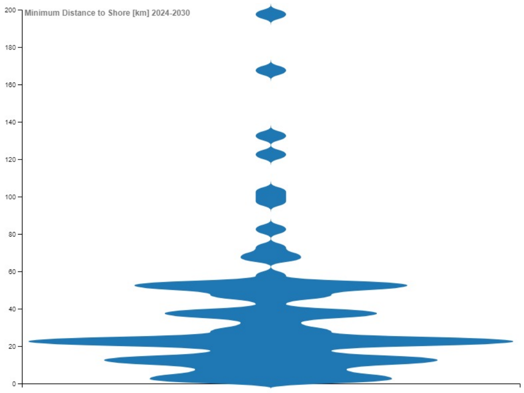

Gross Area [Km2] 2024-2030
800
700
600
500
400
300
200
100
0

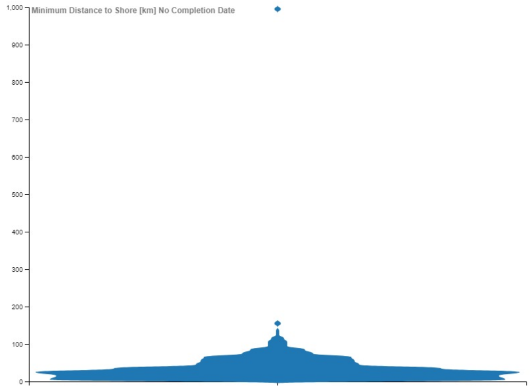

Gross Area [Km2] No Completion Date
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0

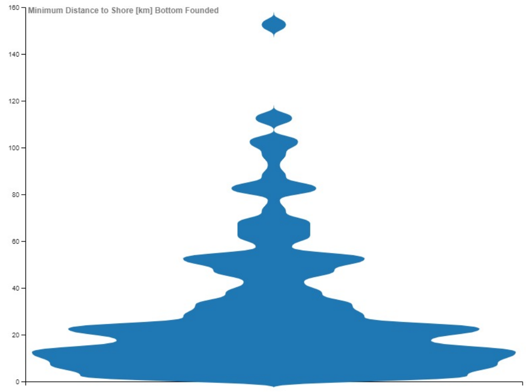

Gross Area [Km2] Bottom Founded
2,400
2,200
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0

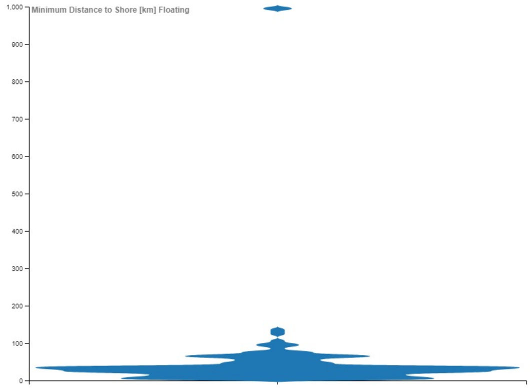

Gross Area [Km2] Floating
2,400
2,200
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0

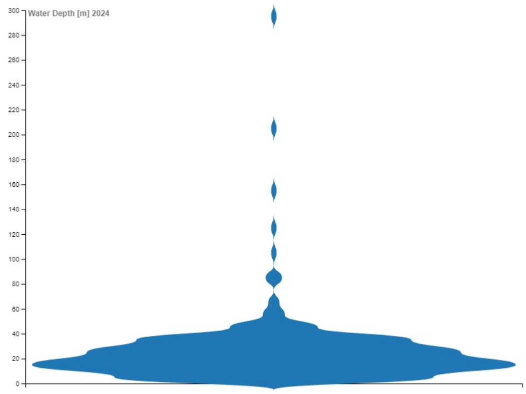

Minimum Distance to Shore [km] 2024
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0

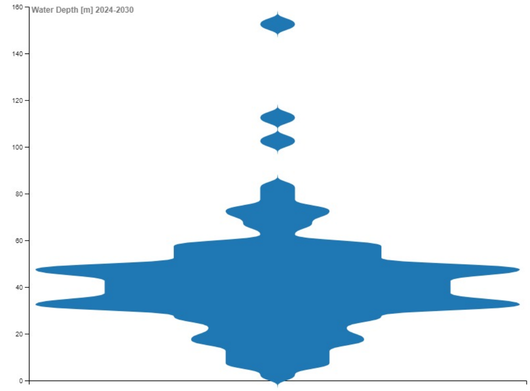

Minimum Distance to Shore [km] 2024-2030
200
180
160
140
120
100
80
60
40
20
0

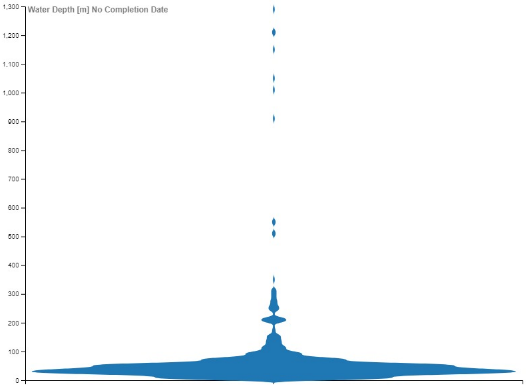

Minimum Distance to Shore [km] No Completion Date
1,000
900
800
700
600
500
400
300
200
100
0

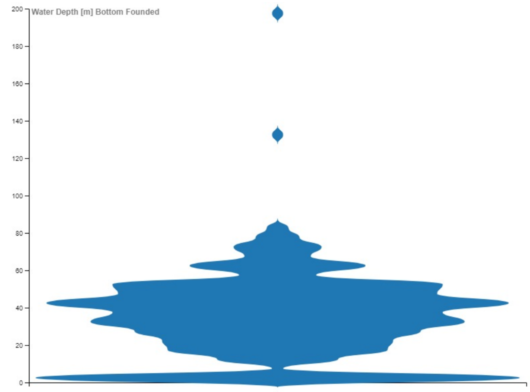

Minimum Distance to Shore [km] Bottom Founded
160
140
120
100
80
60
40
20
0

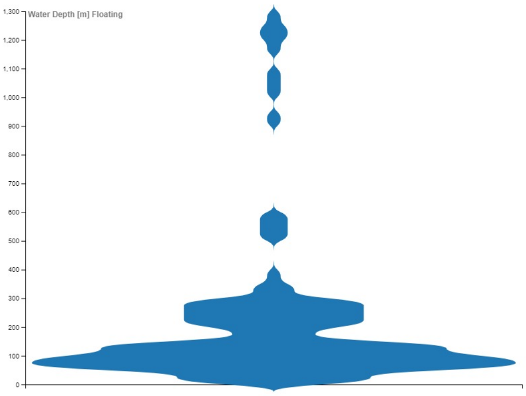

Minimum Distance to Shore [km] Floating
1,000
900
800
700
600
500
400
300
200
100
0


Water Depth [m] 2024
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0

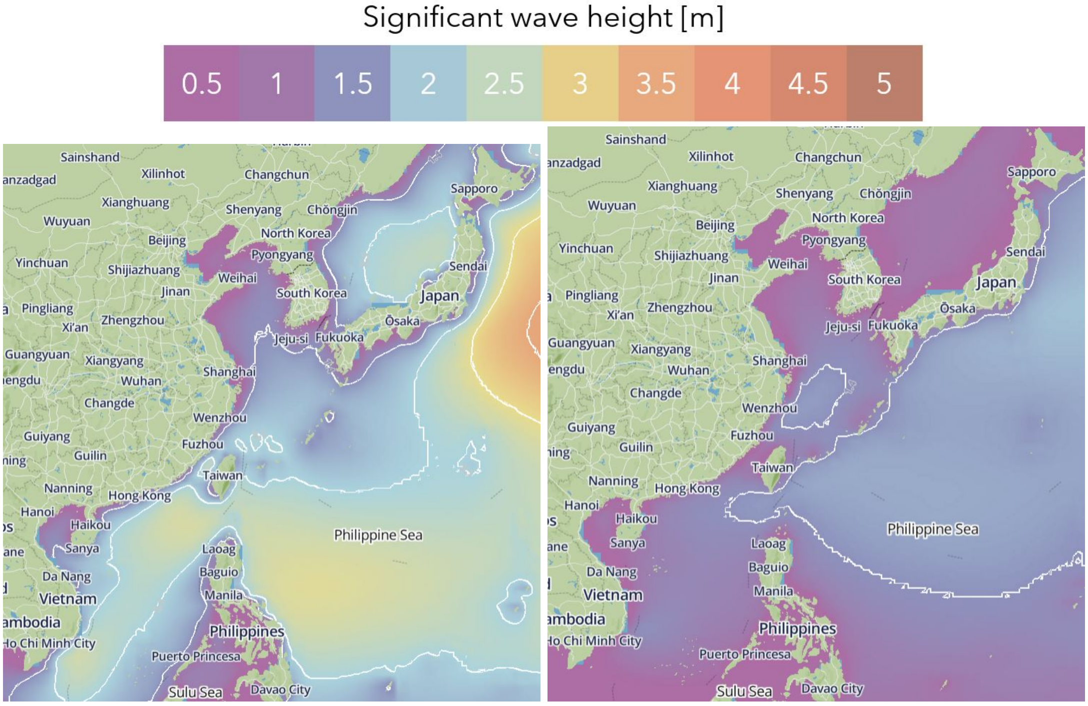

Water Depth [m] 2024-2030
160
140
120
100
80
60
40
20
0


Water Depth [m] No Completion Date
1,300
1,200
1,100
1,000
900
800
700
600
500
400
300
200
100
0

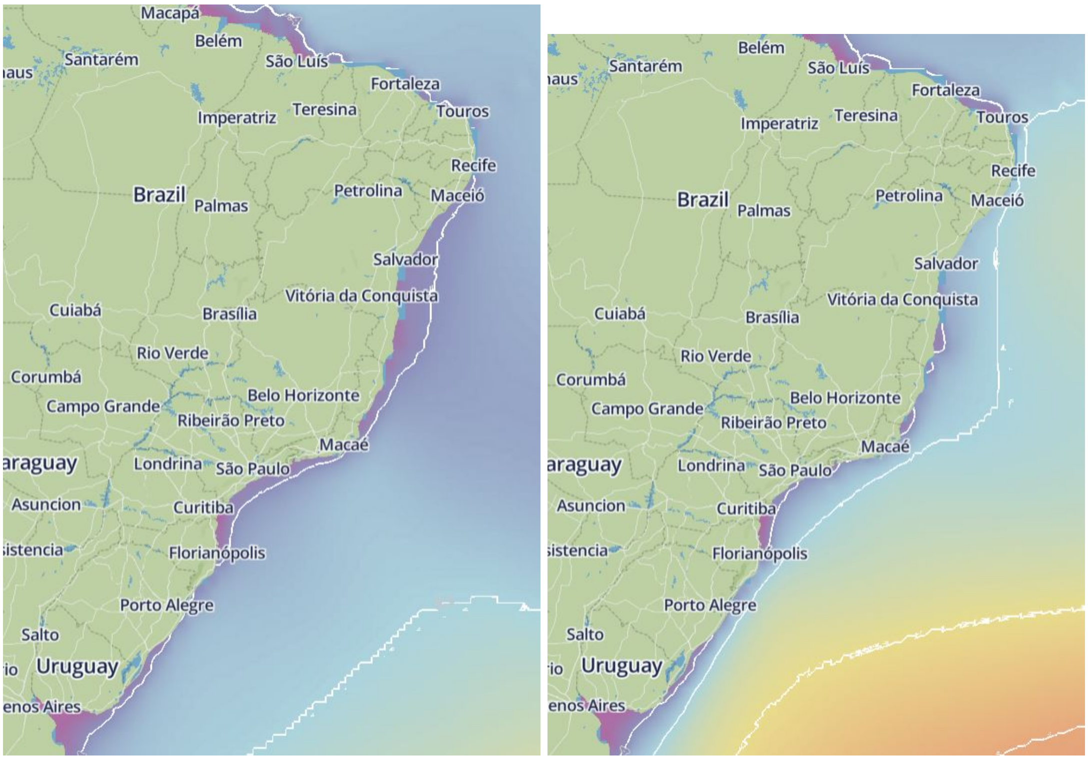

Water Depth [m] Bottom Founded
200
180
160
140
120
100
80
60
40
20
0


Water Depth [m] Floating
1,300
1,200
1,100
1,000
900
800
700
600
500
400
300
200
100
0

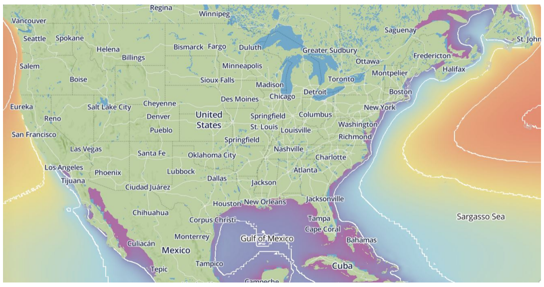
A.4 Mean Significant Wave Height Worldwide



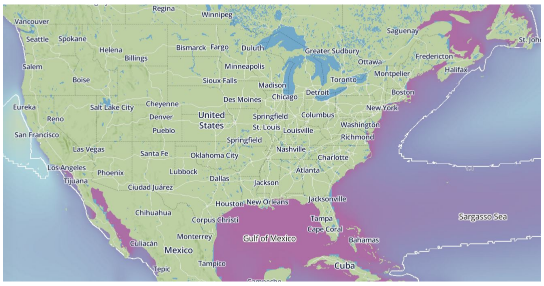
(a) Asia in January (b) Azia in July



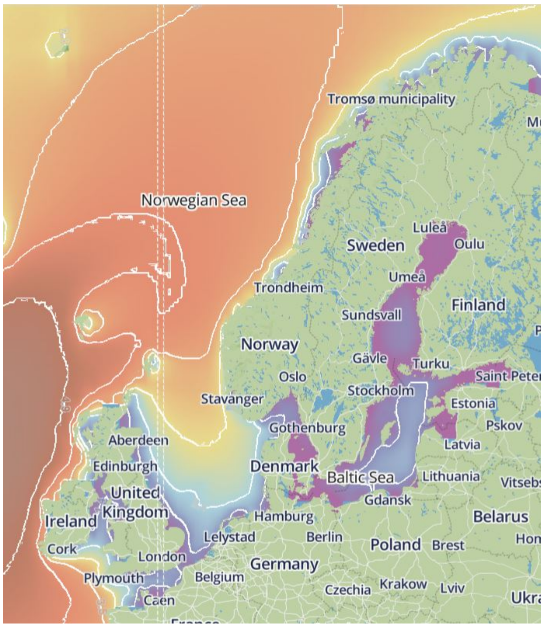
(c) Brazil in January (d) Brazil in July



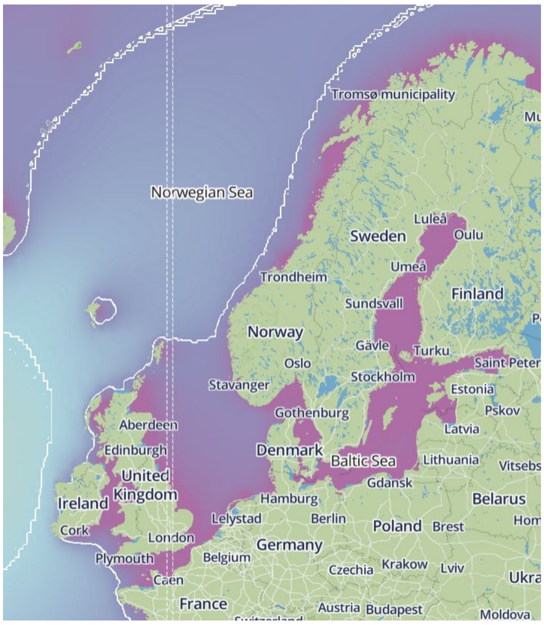
(a) North America in January



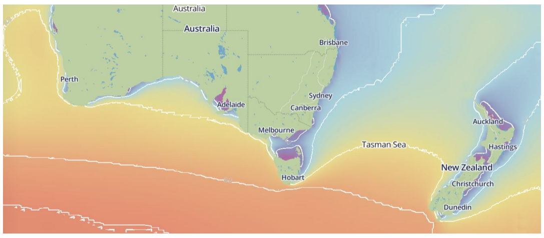
(b) North America in July



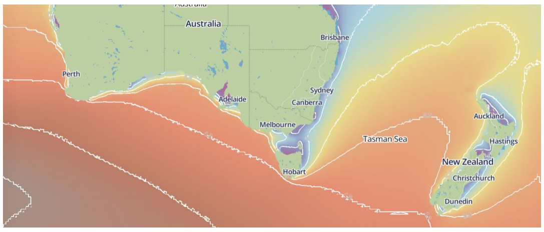
(c) Northern Europe in January



(d) Northern Europe in July



(e) Oceania in January



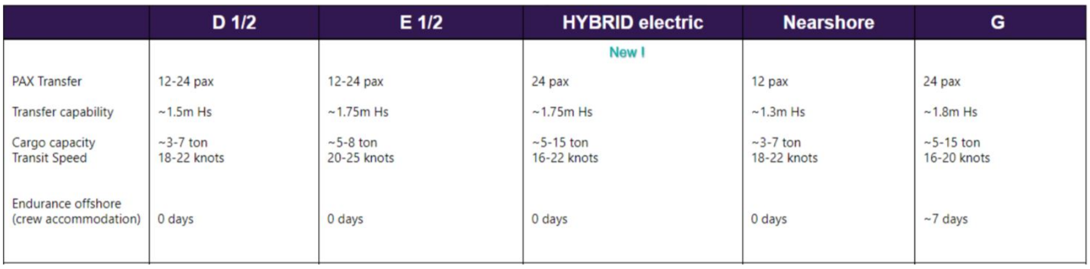
(f) Oceania in July

(g) Mediterranean in January

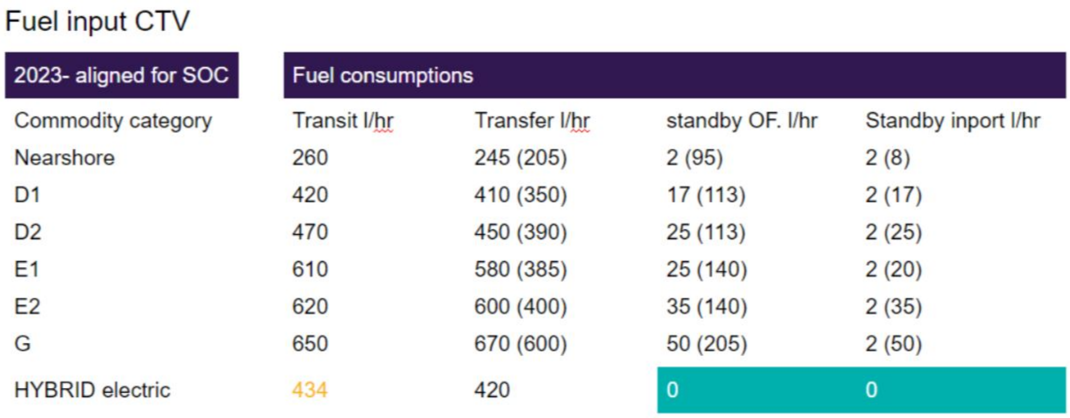
(h) Mediterranean in July

B Fuel Consumption Data

CTV classes



	D 1/2	E 1/2	HYBRID electric	Nearshore	G
			New !		
PAX Transfer	12-24 pax	12-24 pax	24 pax	12 pax	24 pax
Transfer capability	~1.5m Hs	~1.75m Hs	~1.75m Hs	~1.3m Hs	~1.8m Hs
Cargo capacity	~3-7 ton	~5-8 ton	~5-15 ton	~3-7 ton	~5-15 ton
Transit Speed	18-22 knots	20-25 knots	16-22 knots	18-22 knots	16-20 knots
Endurance offshore (crew accommodation)	0 days	0 days	0 days	0 days	~7 days



Fuel input CTV

2023- aligned for SOC	Fuel consumptions			
Commodity category	Transit l/hr	Transfer l/hr	standby OF. l/hr	Standby inport l/hr
Nearshore	260	245 (205)	2 (95)	2 (8)
D1	420	410 (350)	17 (113)	2 (17)
D2	470	450 (390)	25 (113)	2 (25)
E1	610	580 (385)	25 (140)	2 (20)
E2	620	600 (400)	35 (140)	2 (35)
G	650	670 (600)	50 (205)	2 (50)
HYBRID electric	434	420	0	0

C Emission Results