Increasing accessibility by implementing the far offshore transfer vessel: a systems engineering approach

H.C. Kamerbeek (4383508)

Supervisors: Dr. A. A. Kana & R. C. Wigmans

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by

H.C. Kamerbeek

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Company supervisors - Siemens Gamesa Renewable Energy

Responsible supervisor:	R. Wigmans
Email:	rene.wigmans@siemensgamesa.com
Daily supervisors:	F. Santiago Sanches & S. Brans
Email:	fernando.santiago@siemensgamesa.com & sophia.brans@siemensgamesa.com

Thesis exam committee

Chair:	Dr. A.A. Kana	TU Delft
Staff member:	Dr.ir. Y. Pang	TU Delft
Staff member:	Prof.ir. J.J. Hopman	TU Delft

Author information

Studynumber:	4383508

Preface

Dear reader,

The report in front of you is the final work to conclude my masters in Marine Technology. The endlessly interesting field of offshore renewable energy is a relatively new field of research. Because of that, I was allowed to tackle a problem that was still very broad in its scope. Critical thinking and creativity were necessary to find the right questions concerning this topic. Finally, a new application of existing vessels became the solution proposed to improve the maintenance system in far-offshore wind farms. Trying to improve a system with such a significant role in battling climate change, motivated me a lot.

Starting this research, I was a little overwhelmed by the autonomy required. But this has quickly changed in the reason why I'm proud of the final result. This work is my most significant academic contribution to date and I'm glad about the result. Don't be mistaken, this research has been supported by many others.

First and foremost the chair of my committee, Austin Kana. Regardless of the immense workload you carried, you provided me with all the time and attention I asked for. Your feedback was thorough but never so harsh to demotivate me. I enjoyed our meetings and appreciate how you brought your students together during the pandemic. It's clear you take joy and pride in your work and it was a pleasure being supervised by you.

Rene Wigmans, Sophia Brans, and Fernando Santiago Sanchez have supplied me with intensive support as company supervisors from Siemens Gamesa Renewable Energy. Rene, thanks for helping me see the bigger picture and prioritizing scientific standards first. Sophia, thank you for getting me started both with the subject matter as at The Hague office. I hope you enjoy the 'sequel' to your work. Finally Fernando, thanks for listening to me rambling about statistics, logistics, and the calculations I drafted. Your advice has saved me many times from weeks of fruitless researching or coding. Thanks to all three of you for the time you've invested in me.

Then there's a large group of experts from SGRE and outside that have helped me grasp the full context of all the variables and forces that drive the offshore maintenance business. Hugo cook, thanks for helping me find what the company already knew and what it needed to know. Robert Deen, Florion Hoffman, John Snaith, Malene Juul Rasmussen, Ingmar Bos, and Zack Brockman, thank you for your time, feedback and, information. Mark Paalvast, Jaap Gelling, Harleigh Seyffert, Jelte Bos, Daniel Flato, Kai Gjerde, Helge Hesto Andersen, and Pauli Immonen, thank you for letting me interview you to get an outside perspective on the matter.

Last but not least I want to thank my parents, friends, and girlfriend. Many of whom have offered to help me, provided support, and provided fun distractions when needed. This made the last nine months a great experience.

H.C. Kamerbeek
Delft, August 2022

Abstract

The accessibility in far offshore wind farms during unplanned maintenance is reported to be insufficient. This system largely consists of daughter craft, small vessels that increase the multitasking capabilities of an SOV. The goal of this research is to improve the accessibility to ultimately increase turbine availability, which is proven in this work to be necessary. The research is carried out in cooperation with Siemens Gamesa, a major wind turbine supplier. This research builds off the basis laid by Brans et al. [Brans, 2021], who applied a needs analysis on the daughter craft system. This research applies the next step in the systems engineering sequence: concept exploration. The scope of this research extends beyond that of the daughter craft to any system that can improve the unplanned maintenance of far offshore wind farms.

Because the subject matter is relatively little covered in the scientific field, this research lays great emphasis on the context of the problem. The status quo of the sector is described in terms of equipment, operations, regulations, forms of limitations, financial context, trends, and different stages performed in unplanned maintenance. By performing an analysis of alternatives a high potential for system improvement is found.

A set of performance requirements for the accessibility system is developed to structurally assess the system and possible improvements. These performance requirements are used to determine which alternative system holds the most potential for accessibility improvement. Increasing daughter craft dimensions is chosen as the most potent alternative. A feasibility study is performed on deploying CTV-sized vessels far-offshore for two weeks thereby significantly reducing transfer time and distance. These vessels are called far-offshore transfer vessels (FOTV). Different configurations are tested for storing the FOTVs far-offshore when not in operation and interfacing with the SOV. Two principal concepts are identified: Enlarged daughter craft, where the FOTV is stored on the SOV, and the exposed principals, where the FOTV remains in the water. One configuration of the enlarged daughter craft principal is deemed feasible: The lifting launch configuration. Two configurations of the exposed principal are deemed feasible: The connected to the SOV configuration and the moored to designated platform configuration. Furthermore, a model is constructed to assess the logistic and economic merit of different combinations of FOTV, wind farm, and configuration.

This research concludes that the deployment of a FOTV combined with a lifting launch configuration is most profitable for any wind farm. Nonetheless, the exposed principal concepts outperform the current system significantly. The choice of FOTV depends mainly on the accessibility performance and day rate of the vessel but also on the wind farm. The model predicts that in the current market, the highest-performing CTVs are the most profitable options for FOTV deployment. Finally, the results show that the effects of improving accessibility vessel performance relates inverse exponentially to profit performance.

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Nomenclature

Abbreviations

ASV	Air supported vessel
$CAPEX$	Capital cost of expense
CTV	Crew transfer vessel
DC	Daughter craft
$FOTV$	Far offshore transfer vessel
GHG	Greenhouse gasses
HSE	Health, safety and environment
ISO	International Organization for Standardization
KPI	Key performance indicator
$LARS$	Launch and recovery system
$LCOE$	Levelized cost of energy
$MCDM$	Multi-criteria decision method
$MORS$	monitoring operations and registration system
$MSDV$	Motion sickness dose value
$O\&M$	Operations and maintenance
$OMSI$	Overall motion sickness incidence
ORI	Operability robustness index
RAO	Response amplitude operator
SME	Subject matter expert
SOV	Service operations vessel
VDR	Vessel daily report
WEC	Wave energy converting system
WTG	Wind turbine generator

1 | Introduction

In this chapter, the problem is introduced in several steps. First, the origin of the problem is presented in section 1.1, then the urgency and importance are described in section 1.2, then the systems engineering structure is introduced in section 1.3. In section 1.4 the research strategy is explained, and finally, the initial scope and research questions are presented in sections 1.5 and 1.6 respectively.

1.1 General introduction

Global warming is one of the largest challenges for the international society. It has become more and more clear how the Greenhouse effect is a result of human emissions. The emission of greenhouse gasses like CO_2 and methane have to rapidly decrease to abate the effects on the global ecology, economy, and communities [IPPC, 2021]. Offshore wind energy is one of the most potent tools to abate the climate crisis. The harsh environment surrounding the wind farms complicates many processes. Operations and Maintenance (O&M) is particularly difficult for far-offshore wind farms. The absence of a port in the vicinity forces a decision of leaving vessels in the wind farm or frequently traveling large distances. Leaving enough large vessels in the wind farm to ensure high accessibility is an expensive option. On the other hand, using a combination of one Service operation vessel (SOV) and her Daughter craft (DC) lacks the multitasking ability to react to ad hoc maintenance in adverse weather. This Literature study aims to clarify this lack of accessibility for wind turbine generators (WTG) in far-offshore wind parks and propose the direction of improvement.

1.1.1 Renewable energy

To decrease the global GHG emissions there are roughly three strategies: Reduce energy consumption, replace fossil-fueled energy sources with renewable energy sources, or capture GHG from the air and store it somewhere else [IPPC, 2021]. This research will focus on the second form, replacing fossil-fueled energy sources with renewable energy sources, which is motivated as follows:

The global energy demand is expected to increase for at least the next three decades as can be seen in figure 1.1 . The main drivers of this increase are global population growth and economic growth [Liu, 2015]. Although the growth rate is expected to diminish it's still an addition to the already daunting energy transition. The reduction of energy consumption alone won't be enough to fight climate change.

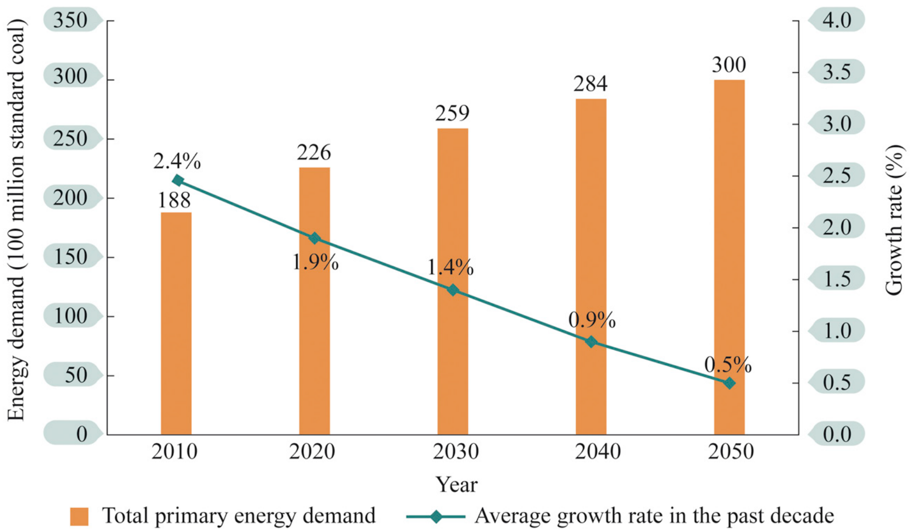

Figure 1.1: Total volume and growth rate of global primary energy demand [Liu, 2015]

Technologies that actively extract GHG from the air like carbon capture might help the transition period but eventually, the world has to be powered in a sustainable way. Renewable energy sources will play a major role in solving the climate crisis. According to Bogdanov et al. [Bogdanov et al., 2021], this process is well underway with 27% of the global electricity being supplied by renewable energy. The global demand for electricity is expected to grow significantly faster compared to the global energy demand as can be seen in figure 1.2. This can be explained by the fact that all energy sectors will transition more to electricity to phase out fossil-dependent energy sources.

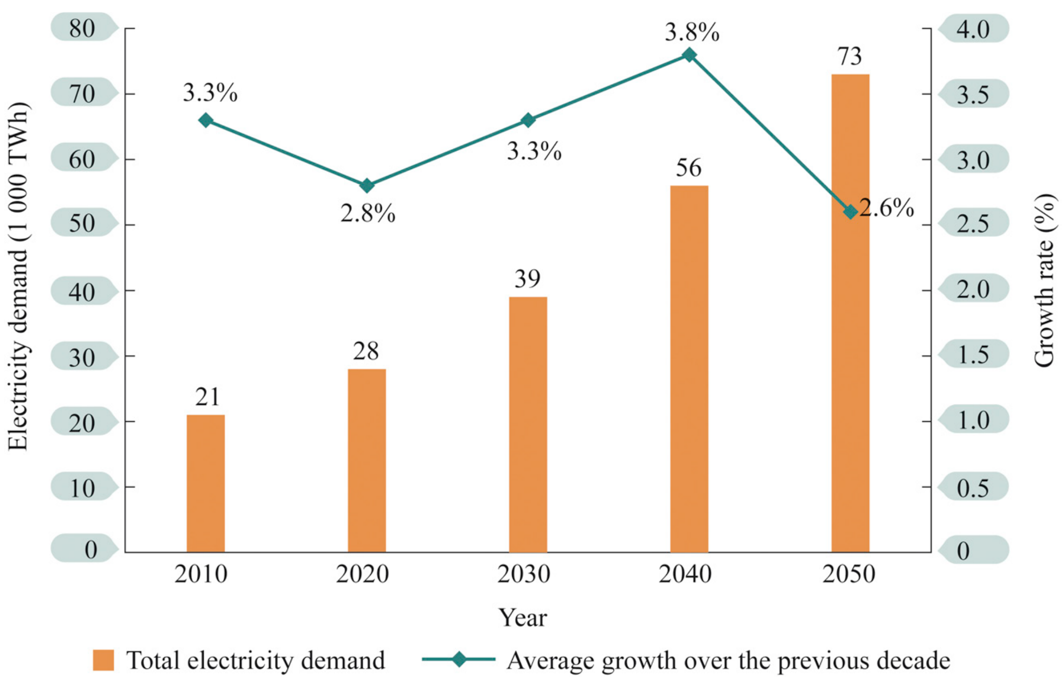

Figure 1.2: World's total electricity demand and growth rates [Liu, 2015]

1.1.2 Offshore Wind energy

There are a few different kinds of renewable energy sources to meet these rising electricity demands. When the goal is to reduce the emission of GHG, the most significant parameter to assess an energy source on is lifetime emissions over energy output. An overview of this parameter for most of the renewable energy sources and conventional fossil fuel energy sources is given in figure 1.3. Wind power is the best performing technology in this parameter. Only nuclear is comparable and performs better in some cases.

Options	Direct emissions	Infrastructure & supply chain emissions	Biogenic CO_2 emissions and albedo effect	Methane emissions	Lifecycle emissions (incl. albedo effect)
	Min/Median/Max	Typical values			Min/Median/Max
Currently Commercially Available Technologies					
Coal—PC	670/760/870	*9.6*	*0*	*47*	**740/820/910**
Gas—Combined Cycle	350/370/490	*1.6*	*0*	*91*	**410/490/650**
Biomass—cofiring	n.a. [ii]	–	–	–	**620/740/890**[iii]
Biomass—dedicated	n.a. [ii]	*210*	*27*	*0*	**130/230/420**[iv]
Geothermal	0	*45*	*0*	*0*	**6.0/38/79**
Hydropower	0	*19*	*0*	*88*	**1.0/24/2200**
Nuclear	0	*18*	*0*	*0*	**3.7/12/110**
Concentrated Solar Power	0	*29*	*0*	*0*	**8.8/27/63**
Solar PV—rooftop	0	*42*	*0*	*0*	**26/41/60**
Solar PV—utility	0	*66*	*0*	*0*	**18/48/180**
Wind onshore	0	*15*	*0*	*0*	**7.0/11/56**
Wind offshore	0	*17*	*0*	*0*	**8.0/12/35**
Pre-commercial Technologies					
CCS—Coal—Oxyfuel	14/76/110	*17*	*0*	*67*	**100/160/200**
CCS—Coal—PC	95/120/140	*28*	*0*	*68*	**190/220/250**
CCS—Coal—IGCC	100/120/150	*9.9*	*0*	*62*	**170/200/230**
CCS—Gas—Combined Cycle	30/57/98	*8.9*	*0*	*110*	**94/170/340**
Ocean	0	*17*	*0*	*0*	**5.6/17/28**

Figure 1.3: Cost and performance parameters of selected electricity supply technologies [schlomer, 2019]

The main disadvantage of offshore wind energy in comparison to onshore wind energy is the inaccessibility of offshore wind farms. This hinders the installation, monitoring, servicing, and decommissioning of the wind farm. This places financial pressure on the market which is already facing slim margins due to subsidy decreases. The price paid for power from offshore wind farms in northern Europe decreased by 11,9% per year from 2015 to 2019 [Jansen et al., 2020]. More on this in section 1.2.2.

1.1.3 Operations & Maintenance

Operations and maintenance is an umbrella term that describes a set of processes that mainly distinguishes itself from other costs by being continuous instead of singular. Operations is the broader term of the two which includes but isn't limited to processes like training, logistics, health, and safety inspection, insurance, and environmental studies. Maintenance covers both planned and unplanned maintenance of the WTG and the balance of plant [BVG associates, 2021]. The balance of plant covers all the infrastructure and hardware outside of the WTG.

The cost of O&M takes up to 39% of the total wind farm cost according to BVG Associates [Dikis, 2018], almost three times that of installation and commissioning. A more comprehensive way to look at the cost of a wind farm is with the Levelized Cost Of Energy(LCOE). LCOE also takes financing costs and the discount rate into account. It is defined as the revenue required to earn a rate of return on investment equal to the discount rate over the life of the wind farm [BVG associates, 2021]. Formula 1.1 shows how the LCOE is calculated.

$$LCOE = \frac{\sum_{t=-5}^{n+1} \frac{I_t+M_t}{(1+r)^t}}{\sum_{t=-5}^{n+1} \frac{E_t}{(1+r)^t}} \tag{1.1}$$

With:

I_t	=	Investment expenditure in year t
M_t	=	Operation, maintenance and service expenditure in year t
E_t	=	Net energy generation in year t
r	=	Discount rate (or WACC)
n	=	Lifetime of project in years

The current O&M LCOE average for a European offshore wind farm is 28,2%, maintenance is 18,9% and operations is 9,3% [BVG associates, 2021]. A comparison of average O&M LCOE to the onshore wind shows little difference, 24,24 % for offshore and 23,62 % for onshore according to an American study [Administration, 2021]. Because LCOE is more influenced by expenditure early on in the process, such as CAPEX, the influence of O&M diminishes compared with non-levelized costs. According to Dewan et al [Dewan and Asgarpour, 2016], the amount of maintenance cost originating from unplanned maintenance instead of planned maintenance for far-offshore wind farms is 90%. The portion of that cost caused by weather downtime is 28%. That would mean that about 5% of the LCOE of a wind farm is due to the weather downtime during unplanned maintenance. This is a more than a significant portion which proves that a minor improvement in availability can certainly make an impact on the whole operation.

1.2 Need for improvement

Two main drivers for improving the accessibility of WTGs are distinguished in this report: Safety of the crew and Financial drivers. These reasons will be elaborated upon below. Afterward, this section is concluded with the scientific and societal relevance. As one of the most potent forms of renewable energy, offshore wind has a large role to play in the energy transition. To meet the rising electricity demand it has to overcome the inefficiencies in O&M and become a safer work environment.

1.2.1 Safety of the crew

The Global Offshore Wind Health and Safety Organisation reported 743 incidents and injuries in the affiliated wind farms in 2020 [G+ Global Offshore Wind, 2020]. 7,7% of these accidents happened during the transfer phase from a small vessel to the WTG and 3% in the transit phase. These also included the highest amount of high potential incidents. The report also points out that there is an average decrease in incidents which should be continued. A safer work environment improves the physical and mental well-being of personnel and eventually increases productivity.

1.2.2 Financial drivers

The offshore sector is growing rapidly but is struggling with its revenues. Jansen et al concluded in 2020: “The era of subsidy-free offshore wind turbines has begun. [Jansen et al., 2020]” So there seems to be light at the end of the tunnel in terms of feasibility. Increases in efficiency can make a large difference and so an increase in WTG availability would have significant financial benefits. Expectations are promising for the overall cost reductions according to Wiser et al [Wiser et al., 2016] and Costa et al [Costa et al., 2021]. A wide array of technologies and methodologies are envisioned to drive down costs [Valpy et al., 2017]. According to Valpy et al, when it comes to O&M, improvements to far-offshore accessibility will be the most effective cost reduction with 2,9%.

1.2.3 Scientific and societal relevance

The scientific relevance of this work is twofold: First, a clear overview of what is known and what knowledge is missing to improve the current system is necessary for systemic improvement. Moreover, the proposed improvement for performance assessment will accelerate the development of the accessibility system by ensuring that system improvements are valued on their performance in the current application. The outcome can guide multiple scientific disciplines to accurately work on system improvements.

Both financial and safety drivers have societal relevance. The safety improvements that originate from the knowledge gained in this work will reduce incidents. This benefits the well-being of the technicians and their surroundings. A reduction in work-related incidence may increase the willingness to join the workforce of the sector, which reduces expenditure for the company in terms of HR and salary. Moreover, the financial benefits of higher availability will reduce the cost of offshore wind energy which accelerates the development of the sector and the energy transition. Ultimately the effects in terms of climate change abatement will have the most significant societal relevance [IPPC, 2021].

1.3 System engineering

This research identifies the accessibility problem for far-offshore wind farms during unplanned maintenance as a complex problem. There are many factors and stakeholders in play. To determine the critical parts of this problem and the right approach to tackling these parts, a proven engineering design system is employed.

A structure like New product development could be used but this includes a lot of business- and marketing-oriented steps that are not within the scope of the research. While Maritime engineering is mostly a cyclical design process with more than one iteration per step, because this research isn't expected to perform a complete vessel design and is expected to maintain a high-level approach, cyclical methods are less applicable. The most recent research on the same subject by Brans et al. [Brans, 2021], has performed a part of the System engineering approach. The Needs analysis, which is the first of concept development, is carried out for the daughter craft system. This offers a structured basis for the current research.

Therefore Systems engineering approach is chosen as support for research and structure [Kossiakoff et al., 2003]. The goal of the system engineering approach is to design a fitting system in a structured manner. In this research, system engineering will be used to identify issues and resistances in designing a better method of accessing far-offshore WTGs during unplanned maintenance. The method is not used to actually design a new system. The concept exploration phase will be applied to assess the problem and explore possible solutions. This is the second phase in the first stage, concept Development, of Systems engineering as can be seen in figure 1.4. The current research will continue the systems engineering structure where Brans et al. [Brans, 2021] left off.

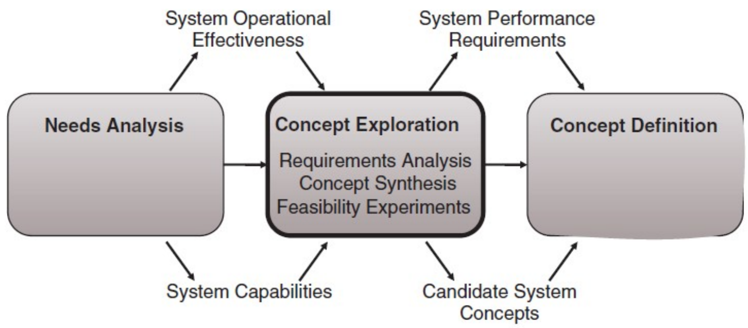

Figure 1.4: Overview of the three phases in the second stage of systems engineering: Concept Development. [Kossiakoff et al., 2003]

Within the concept exploration phase, four steps are identified. The first two will be part of this literature study, and the implementation phase of the research will finish the last two steps. This can be seen in figure 1.5 The four steps that the concept exploration phase consists off are described as follows:

1. Operational Requirements Analysis
    (a) Analysis of the stated operational requirements, the system objectives that were found in the previous phase: Needs analysis
    (b) Finding coherence among the set of objectives and adding any additional information needed to formulate the operational requirements.
2. Performance Requirements Formulation
    (a) Translate operational requirements into system functionality
    (b) Formulate the performance parameters to meet the operational requirements
3. Implementation concepts exploration
    (a) Explore all possible solutions and list their advantages in comparison to the old system
    (b) For the most promising cases, analyze the subsystem interaction
    (c) Defining the necessary set of performance characteristics for the essential functions that have to meet the operational requirements.
4. Performance Requirements Validation
    (a) Conducting an effectiveness analysis on the solutions to check if they meet the operational requirements.
    (b) Validating the conformity of the requirements. Does a system that meets the requirements fulfill the system objective? If not, the operational requirements are altered.

A visual representation of these steps can be found in figure 1.5. This figure illustrates the coherence between the system engineering structure, the set of research questions, and the structure of this research.

1.4 Research strategy

For the accumulation and documentation of knowledge, a strategy was put in place. The strategy consisted of two phases. In the first phase, a set of keywords is composed based on the goal of the research and the research questions. These are then used in Google Scholar and Scopus to find the most important papers. The importance is evaluated by the number of citations, connection to research goal, and year of publishing. In this first phase, the help of experts is requested to deliver additional papers and reports. When the bulk of the information is retrieved in the first phase the coherence between the within and between the scientific sub-fields is assessed and gaps in the knowledge are identified and filled by lesser-known articles if possible. Scopus and Connectedpapers are used as support for this process. Throughout both phases, two documentation systems are employed. First, every paper is stored in the reference manager Mendeley. Secondly, a google docs file on the company Onedrive is used to log and categorize every paper so it can be easily retrieved later in the process.

1.5 Initial scoping

At the start of the literature study, an initial scoping is performed to guide the direction of research.

1. Only unplanned maintenance is considered. Planned maintenance can be done to WTGs in close proximity to each other, allowing for a large low-speed vessel like an SOV to execute the task with little hindrance from the weather.

2. The report covers wind farms, no other offshore structures.

3. The wind farms are 'far-offshore' which means at least 65 km from the nearest coast or port.

1.6 Research question

The main research question is formulated as follows:

How can the accessibility during unplanned maintenance of far-offshore wind farms be improved?

Sub-questions:

1. What are the limitations in accessibility in far-offshore wind farms and to what extent do they hinder accessibility?

2. How can the effectiveness of the DC(or other transport) be improved and what KPIs can describe this improvement?

3. Which improvement is expected to increase accessibility the most?

4. What new challenges does this improvement introduce and what are their effects?

5. How can these challenges be met?

6. How can the performance of these novel solutions be predicted?

7. How is the system expected to differ from the status quo?

The structure of this report is dominated by the system engineering approach. The combined structure of the chapters, system engineering steps, and the sub-questions are shown in figure 1.5. Sub-question one is discussed in the first three chapters, 1, 2, and 3. The second sub-question is covered by chapters 4 and 5. The third, fourth, and fifth sub-questions are covered by chapter 5. Sub-question six is answered in chapter 6 and finally, sub-question seven is answered in chapter 7.

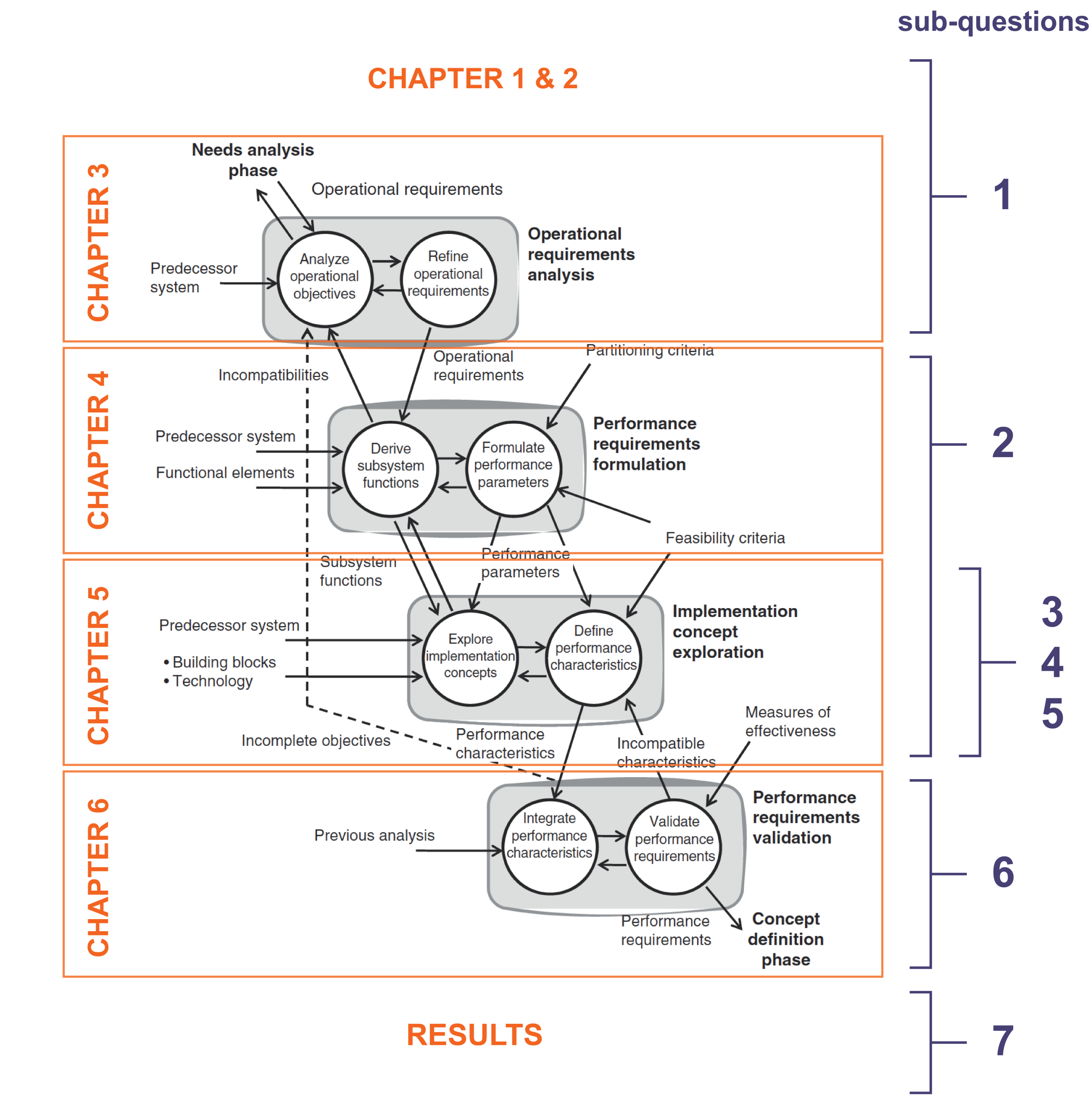

Figure 1.5: Overview of the four steps in the concept exploration phase [Kossiakoff et al., 2003] and how these are linked to the research structure and research questions.

2 | Problem background

To understand the issues surrounding the accessibility of far-offshore wind farms, the current maintenance practices will be examined in section 2.1, a few trends are mentioned in sub-section 2.1.3, overall limitations will be identified in section 2.2 and as a conclusion, the current prediction process is laid out in section 2.3.

2.1 Current system

The current method in place to deal with unplanned maintenance for far-offshore wind farms may differ between service suppliers but the core of the practice is the same. Because the distance from shore is relatively large, deploying a crew transfer vessel from a port is very costly and is very time-consuming. All technicians are paid during transit and the large distance at high-speed results in high fuel costs. The solution is to deploy a vessel closer to the wind farm.

2.1.1 Vessels and equipment

There are two important types of vessels for this system: the service operation vessel (SOV) and the daughter craft (DC). An SOV is a relatively large ship (57m - 93m) equipped to perform preventive maintenance. SOVs are able to withstand heavy sea states and have high operability because of their size, design, and motion compensation equipment. On an SOV one or multiple DCs (11m - 13m) can be stored. DCs are deployed for different tasks like equipment runs, rescue missions, and more. More importantly, DCs are used for corrective maintenance. An SOV has a low transit speed and is mostly bound to a location to assist or if necessary rescue technicians during their preventive maintenance. Therefore a DC is used if access to a WTG is needed that is located in another part of the wind farm than the SOV is situated. The DC has significantly lower sea-keeping performance than an SOV, more on that in section 2.2.
The message that a WTG has an unexpected failure needing attention is received by a planner onshore. The planner and an asset manager onboard the SOV then assess any opportunities for DC deployment, called weather windows. If vessel and personnel availability and weather allow it, corrective maintenance can be executed.

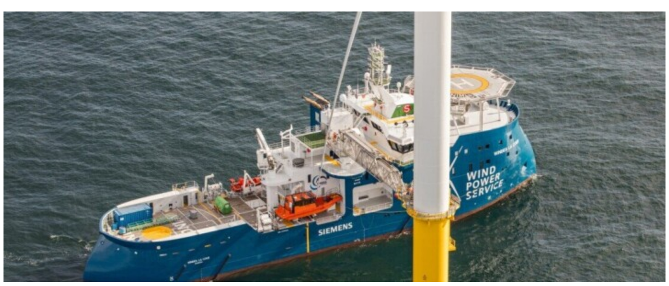

Figure 2.1: SOV servicing a WTG [Ulstein, 2021]

Figure 2.2: DC in transit [Prozero, 2021]

2.1.2 Three stages of corrective maintenance

The operations of a DC delivering technicians and equipment to and from a WTG can be divided into three phases: The launch and recovery, the transit, and the transfer. Figure 2.3 displays the three stages. The challenges specific to each phase will be elaborated upon in section 2.2.

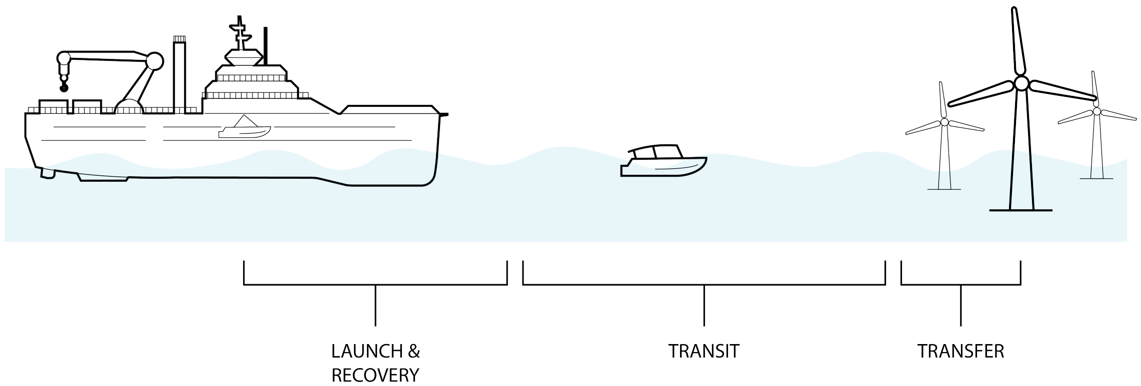

Figure 2.3: Three stages in far-offshore accessibility

Launch and recovery

The interaction between SOV and DC is central in this stage. The DC is lifted on or from the SOV by a crane or davit, which dictates the weight limit of the DC. The place on the SOV dictates the dimensions of the DC. The most crucial moment in this stage is when the DC hits the water during launch or is lifted off the water surface during recovery.

Transit

During transit, the DC travels from or to the WTG at high speed. The crew is exposed to the vessel's movement for the duration of the transit. When reaching the WTG the vessel starts the final phase: transfer.

Transfer

To move technicians and equipment from a DC to the WTG the DC pushes its bow against the ladder of the WTG.

2.1.3 trends

The average WTG capacity is growing each year and the size of wind farm capacity is too [Ramirez et al., 2020]. Besides these trends, there are a few other developments that are of interest when looking at accessibility solutions.

Wind farms are installed further from shore

The average distance between offshore wind farms and the closest shore is rapidly increasing [Ramirez et al., 2019]. In 2018 the average was 35km while in 2019 the average was already 59km. The advantages of an offshore wind farm far from shore are the higher chances of high and constant wind and no chance of obstructing the view from a beach. The disadvantages are in the transport of energy to shore, the installation in deeper waters, and the accessibility of the wind farm. The latter of course is of interest to this research. The need for accessibility improvements rises when a larger part of the wind energy is situated far-offshore.

Amount of transfers per WTG is decreasing

According to a report of SPARTA, who surveys data of 60% of UK offshore wind farms, the amount of transfers per WTG is steadily decreasing [Riis, 2019], see figure 2.4. This shows that the maintenance operations in the offshore market are maturing. This doesn't directly affect the accessibility issue as the number of transfers doesn't directly influence the process or quality of the transfers. Nonetheless, as this research aims to improve accessibility, the required transfer frequency does determine the impact of those improvements.

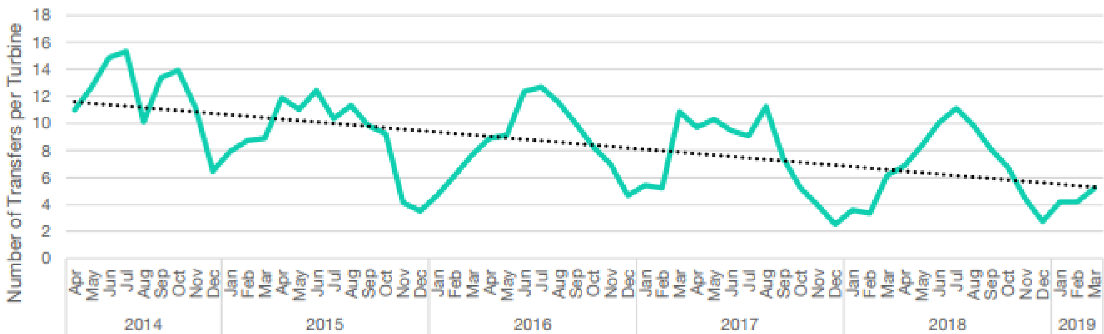

Figure 2.4: The number of transfers per WTG in a selection of UK offshore wind farms. [Riis, 2019]

Service contracts to other parties

Most offshore wind farms are maintained and serviced by the supplier of the WTGs. This is a logical dynamic looking at the level of sophistication in offshore technology. The supplier of a highly complex product is intuitively the first to turn to when the product malfunctions. In some instances, however, the wind farm owner has taken the maintenance in-house or outsourced the work to third parties. According to Dikis et al, the amount of third parties delivering service or collaborating on service contracts is expected to grow in order to drive down costs [Dikis, 2018]. The report of SPARTA states that wind farms where the original equipment manufacturer performs all the O&M are scoring worse in terms of production-based availability and lost energy production, shown in figures 2.6 and 2.5. Although these are statistics and not necessarily causalities, these figures might influence wind farm owners to alter maintenance providers [Riis, 2019]. In the figures, the orange bar represents the results for external service suppliers and the green bar represents the results of service delivered by WTG suppliers.

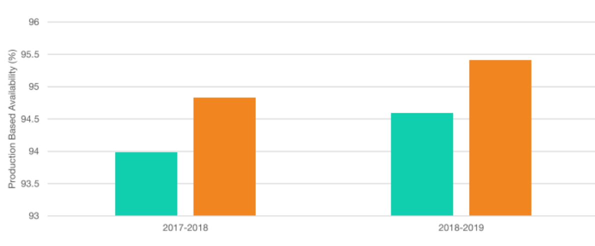

Figure 2.5: Production based availability by year and maintenance provider [Riis, 2019]

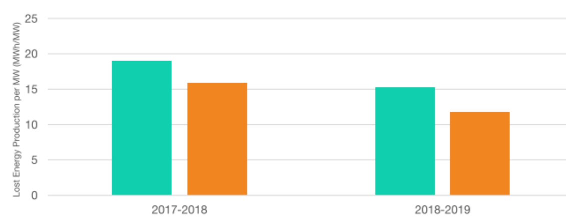

Figure 2.6: Lost energy production per MW by year and maintenance provider [Riis, 2019]

2.2 Limitations

The current accessibility for unplanned maintenance by DCs is reported to be limited. The WTGs in a far-offshore wind farm can generally be accessed by a daughter craft between 0 and 10 days per month. With low accessibility in the winter and higher accessibility in the summer [1]. The limitations are discussed per phase: launch and recovery, transit, and transfer.

A large part of the accessibility issues seems to arise from wave-induced motions on DCs. A good understanding of waves and their effect on surface vessels is required to analyze the accessibility. Wave dynamics is a complex field consisting of several uncertainties and assumptions. Nevertheless, there are models that can approximate the pressure of waves on surfaces such as the hull of a vessel. The sum of the forces on the hull, combined with the gravitational force on the vessel determines its movements. The movements of a vessel due to waves cause an array of issues, such as motion sickness and safety issues, which will be part of this research.

2.2.1 Launch and recovery, crane capacity

When a DC is lifted from the SOV onto the waves, the captain is already on board the DC according to an operations service logistics employee of Siemens Gamesa. It's easy to board the vessel when it's stationary on deck and a lot harder when it's floating beside the SOV. Most SOVs use cranes or davits on the side of the ship. When the vessel is attached to the crane but also touches the water surface the force balance becomes more dynamic. Between the phase that the whole vessel is supported by the crane and the phase that the whole vessel is supported by buoyancy, heavy accelerations and forces on the crane can occur. Because the DC is launched in the vicinity of the SOV, collision risk is also a factor to take into account. Sophisticated lifting appliances can restrict yaw movement without attaching tag lines to the bow and stern of the DC, figure 2.8. If enough space is available, a more sophisticated dual lift point system can be employed, figure 2.9. The most common downside of the dual lift point system is the change of not simultaneous disconnection of both points [Mctaggart et al., 2016]. The more duel point systems are more common in naval applications where launches are required while the mother ship has a speed above 6 knots. This increases the difficulty because of the dynamic interaction between both vessels [McTaggart, 2014]. This is however not a common requirement for offshore applications.

Figure 2.7: Single point crane system with tag line from bow [Mctaggart et al., 2016]

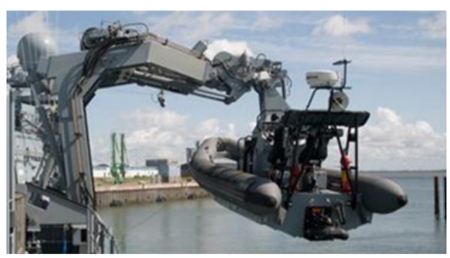

Figure 2.8: Sophisticated single point davit, restricting yaw [Mctaggart et al., 2016]

Figure 2.9: Dual lift point davit [Mctaggart et al., 2016]

[1]Robert Deen, Maintenance supervisor - Siemens Gamesa

The weather conditions dictate the motions of the SOV. When a DC is launched from the side of the SOV, the heave and the roll motion are important for the vertical motions the DC will undergo during launch or recovery. The United States Coast Guard RMS ship motion limits for side launch and recovery are [Mctaggart et al., 2016]:

Roll angle	4.0 deg
Pitch angle	1.25 deg
Vertical acceleration	0.1 g
Lateral acceleration	0.1 g

These are examples of limits that will vary for different vessels and operations. But this stage does impose weather requirements on the operations and so will be assessed further to improve accessibility.

2.2.2 Transit, seasickness

The transit stage doesn't cover any interaction with the SOV or WTG, only the voyage between the two locations. There is an urgency to service a WTG with an unexpected failure, that's why vessel speeds are usually high, between 25 and 45 knots [Brans, 2021]. This high speed increases the chance of uncomfortable conditions for the crew. This can lead to seasickness or more general: motion sickness. This is undesirable because it negatively affects the well-being of the crew and may cause delays in schedule. Over the last years, there have been discoveries in the medical field surrounding the effect of frequent exposures to high accelerations. The topic first came up due to reports of former bobsled athletes with comparative symptoms. It appears that multiple accelerations close to the concussion threshold but not severe enough for a disposable concussion will have significant long-term effects [McCradden and Cusimano, 2018]. Because there is no data available on accelerations for daughter craft in transit there is no way to determine if current technicians are at risk of what is now called 'sled head'. The effects and causes of motion sickness have been thoroughly studied by dr. Jelte Bos. In his work in 2004, he studied the effects of motion sickness on the quality of work [Bos, 2004]. by using a subjective rating system for motion sickness on NATO ships in 1997 where crew members could rate 'misery' on a scale of 0 to 10 a correlation was found between tasks failed and motion sickness as shown in figure 2.10. This shows that the effect of the transit phase on technicians can have a significant impact on their ability to perform the maintenance tasks that are required from them. Moreover, this increases the chance of errors being made while executing the transfer phase, thereby increasing the risk of incidents.

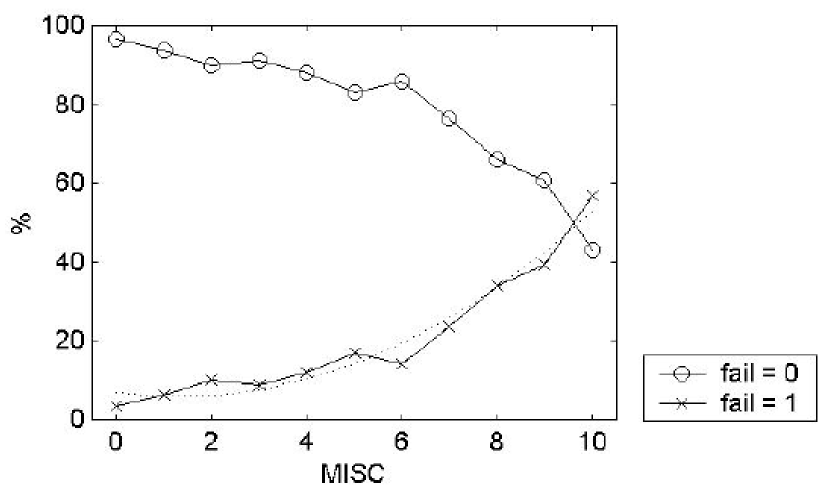

Figure 2.10: Correlation between tasks failed and a subjective motion sickness scale [Bos, 2004]

2.2.3 Transfer, relative speed, and acceleration

The transfer phase covers the access and egress between the WTG and the DC. By pushing the fender on the bow of the DC in bollard condition the vessel motions are reduced. This way a technician can approach the bow and step on the boat landing ladder. In figures 2.11 and 2.12, the layout of the situation is shown.

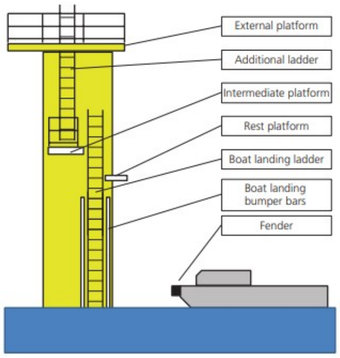

Figure 2.11: Overview of access structure [Energy institute and G+ Global offshore wind, 2018]

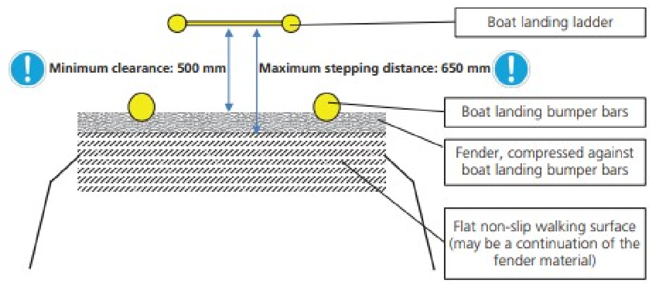

Figure 2.12: Safety clearance between DC and ladder, topview [Energy institute and G+ Global offshore wind, 2018]

The goal is to transport equipment and technicians between the DC and WTG in a safe manner. Because the WTG is not moved by waves, or very little in the case of a floating structure, the relative speed and accelerations between the WTG and DC increase the difficulty to execute the operation. There are two categories of push-on transfer: Slip and non-slip, the latter uses the friction of the bow on the ladder to compensate for any forces originating from heave or pitch motions of the vessel. This does increase the severity of the slip if this compensation is not large enough. Therefore the first strategy does allow slippage in order to make the occurrence more predictable and less severe. Most DCs employ this last strategy as they are too small and lack the necessary propulsion for the non-slip strategy. According to the regulations mentioned in section 2.2.4 the chance of falling overboard is reduced by the use of fall arrest systems. In the case of falling overboard, the chance of drowning is reduced by mandatory personal flotation devices, personal locator beacons, and immersion suits.

2.2.4 Regulations

Siemens Gamesa adheres to the G+ good practice guidelines of Working at height in the offshore wind industry [Energy institute and G+ Global offshore wind, 2018] and the laws and regulations of the local nationality if those impose stricter norms than that of G+. At a European level a set of directives are also adhered to:

- Directive 2014/90/EU: Ensuring uniform application of the SOLAS (Safety of Life at Sea) Convention on marine equipment.
- Directive 2009/16/EC (including amendments from directive 2017/2110): on common rules and standards for ship inspection and survey organizations and for the relevant activities of maritime administrations.
- Directive 2009/45/EC (including amendments from directive 2017/2108): on safety rules and standards for passenger ships.
- Directive 2012/35/EU: Training and competency standards for seafarers.

Siemens Gamesa is also a member organization of the global wind organization which sets the standard for training of offshore personnel. In addition to these regulations, Siemens Gamesa adds company policy. There will be no maintenance work carried out with wind speeds above 18 m/s.

2.3 Accessibility prediction

There are methods to predict the accessibility of a specific vessel in a specific area currently in use in the offshore sector [2]. These predictions are based on a set of requirements including but not limited to: hindcast data of the area, a selected time window, and two parameters that are supplied by the DC manufacturer: maximum significant wave height and maximum wind speed. In the case of an SOV or CTV, the maximum significant wave height is replaced by a 'restriction rose', shown in figure 2.13, depicting a maximum wave height specific to a certain angle interval relative to the SOV or CTV. This allows the shipbuilder to more accurately describe the limits of the SOV or CTV by adding wave direction as a parameter.

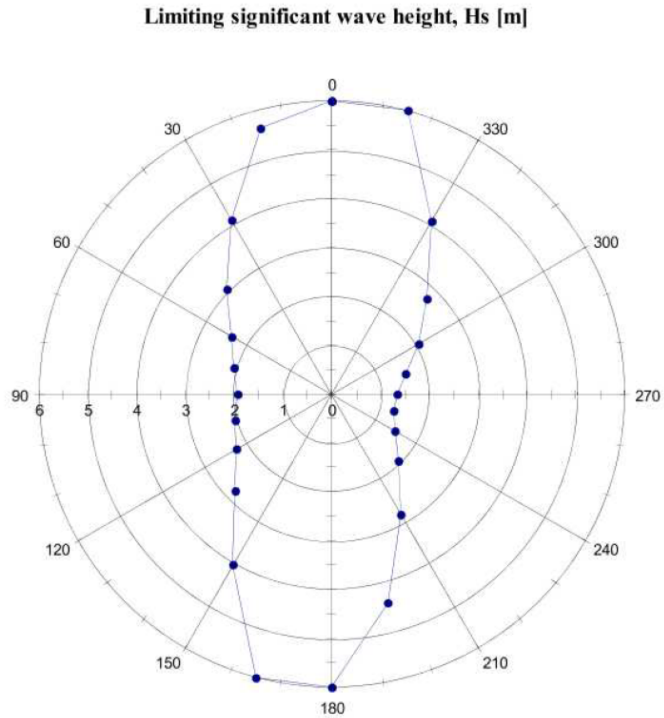

Figure 2.13: An example of a restriction rose of an SOV employed by Siemens Gamesa. For every 15 degrees interval, a different significant wave height [m] is allowed to adhere to all safety criteria.

An in-house tool formulates graphs displaying the accessibility predictions based on twenty years of data. The accessibility is used in the 'Opsmas', a master file for the logistics and operation. This allows the sales department to accurately configure a fleet with the right vessels for a wind farm to propose to a client.

This chapter has established the status quo of the current system. Here the research changes from a descriptive to a normative role in the next chapter. The system engineering method will be employed to dissect the maintenance practices in requirements and find out what an improved far-offshore maintenance system should look like.

[2]John Snaith - program manager, Logistics sales support, Siemens Gamesa

3 | Operational requirements analysis

The first step of the concept exploration phase is Operational requirements analysis. In this step, the operational requirements that are formulated by Brans et al. [Brans, 2021] in the needs analysis phase, are analyzed and used as a basis to form performance requirements. This is done in section 3.1. To quote Kossiakoff et al.(2003), "Operational requirements focus on the "why", defining the objectives and purpose of the system. Performance requirements focus on the "what," defining what the system should do (and how well). [Kossiakoff et al., 2003]". The uncertainties and unknowns are assessed and listed in section 3.2 Then section 3.3 provides additional context. In the next chapter, Section 4.1, the performance requirements are developed.

3.1 Operational requirements

When developing operational requirements, the most common sources are the users and operators of the predecessor system. In the case of this research, the main sources are the interviews with Siemens Gamesa's employees and the work of S. Brans [Brans, 2021]. The system that was evaluated in this work was the DC for unplanned maintenance in far-offshore wind farms with an emphasis on the transfer phase. The full set of operational requirements is shown in figure 3.1. The fundamental objectives (green) are regarded as fulfilled by the current DC design. This assumption is left open to discussion in the current research and the set is analyzed for completeness and coherence.

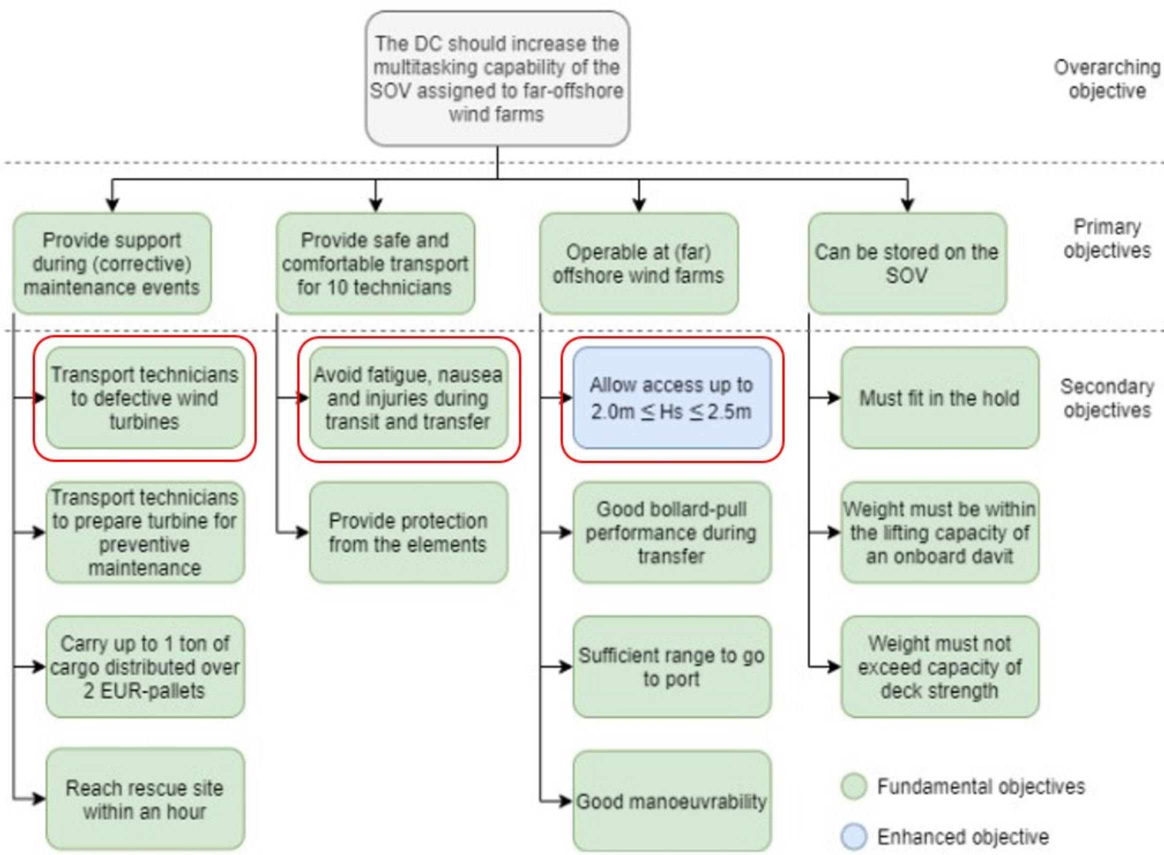

Figure 3.1: Operational requirements of daughter craft [Brans, 2021]

The requirements listed in figure 3.1 relate to a DC system. However, this research isn't limited to the DC system but aims to examine the overall system requirements, this set requires expansion. While on the other hand, not all requirements are linked to the accessibility that the vessel provides. Therefore not all requirements in figure 3.1 are necessary for this research. First, the accessibility-related requirements from the work of Brans are selected and adjusted, afterward the set is made complete to include all accessibility-related requirements. The secondary objectives of interest are circled in red and listed below, some receive adjustments to fit in the current scope:

Transport technicians to defective wind turbines

One of the most important objectives is this basic one. The system must be able to transfer people from the SOV to the WTG. This requires propulsion and in the case of a DC, buoyancy. The element of speed should be introduced here, sufficient speed should be achieved together with all the other objectives regardless of the circumstances.

Avoid fatigue, nausea, and injuries during transit and transfer

The literature together with statements from Siemens Gamesa's employees suggests that this is a critical objective. The stresses that are put on the crew can significantly hinder the accessibility. To be complete, the movements of launch and recovery also add to this hindrance so they need to be included in this objective.

Allow access up to $2.0m \leq H_s \leq 2.5m$

The objective is too specific for an operational requirement. The specificity of parameters and ranges comes later in the process, this way different ways to express the performance are still possible. So 'Allow sufficient safe access to turbines during adverse weather conditions' is adequate for this stage.

The other objectives are important and should not be neglected. But anecdotally, these objectives are not the focus of this research and are therefore not further developed. Some also receive minor adjustments or require some comments:

Transport technician to prepare turbine for preventive maintenance

This objective is very similar to the first objective discussed, but instead of corrective, this concerns preventive maintenance. This is not part of the scope but is expected to benefit from improvements with the corrective accessibility. The planning for preventive maintenance would surely benefit from improved accessibility too.

Carry up to 1 ton of cargo distributed over 2 EUR-pallets

This objective is too specific for this stage. It's not directly linked to the accessibility at this point so will not be further developed.

Good bollard performance during transfer

The only function of this objective is to safely allow transfers at higher sea states. Therefore this objective is overlapping with other objectives sufficiently to make it redundant.

3.2 Limitations

The predecessor system is used to gain an overview of the subsystems. In figure 3.2 a schematic visualization is made of the different input functions, transformative functions, and output functions. The two central grey modules represent the transformative functions that simulate and predict the motions of the vessel and crew. The motions of the vessel are increasingly difficult to predict with higher speed, which makes the prediction less accurate at high speed. The blue output represents accessibility as a percentage over time. The arrows between the groups display the form in which information is transferred. The green and orange inputs represent the various inputs needed to estimate accessibility. The color difference between the inputs shows which input demands extensive research. The two orange inputs lack the specificity to confidently state in which form their information will be transferred.

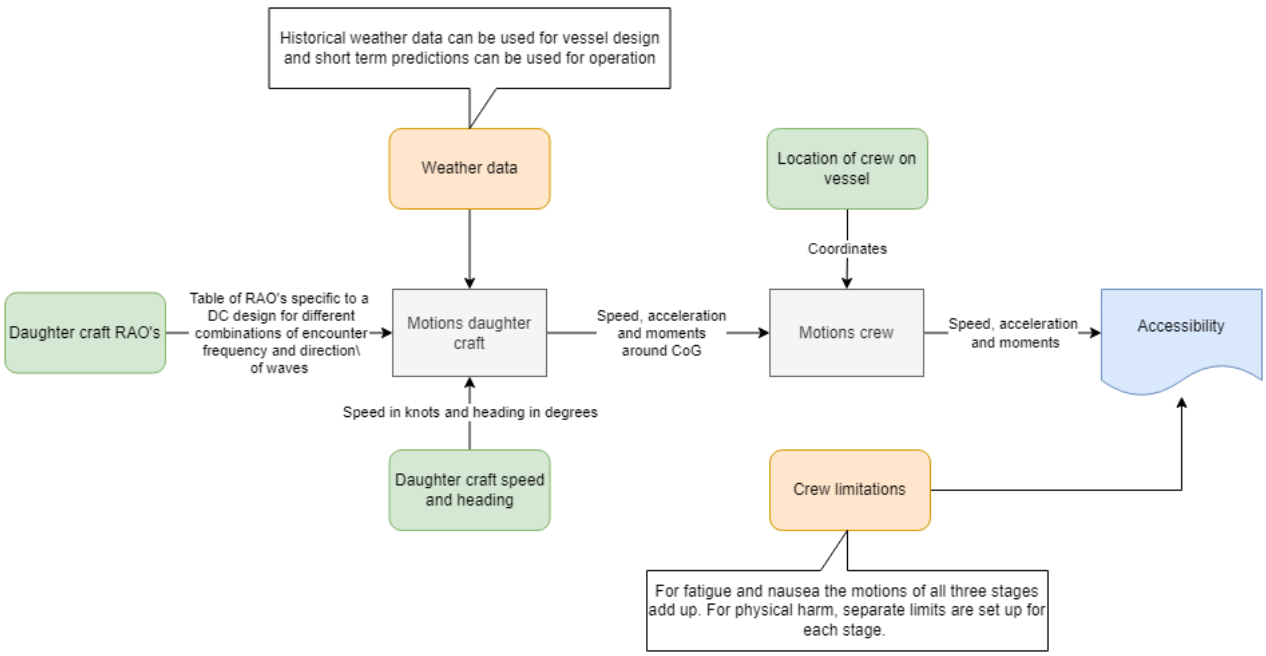

Figure 3.2: Visualization of factors in far-offshore accessibility

With this visualization, every input function, transformative function, and output function is clearly categorized. Each individual function is assessed and a set of questions is formulated in a way that the answers would solve the lack of specificity in the performance requirements. These questions can help form a road map for further research. In the

3.2.1 Human limitations

This input function is split up in multiple parts, it covers four performance requirements: 2.e, 3.a, 3,b, and 3.c. There are three categories of limits identified: Fatigue, nausea, and physical harm. The subject naturally also covers all three phases of accessibility: Launch and recovery, transit and transfer. The questions that remain unanswered are listed below:

1. What is the most accurate and fitting form of describing fatigue loads on a person?
    (a) How can these loads be added between the three stages?
    (b) Which set of parameters describe the loads?

(c) Does the maximum load differ between occupations?

2. On what basis can the maximum load be determined for fatigue?
3. What is the most accurate and fitting form of describing nausea loads on a person?
   (a) How can these loads be added between the three stages?
   (b) Which set of parameters describe the loads?
   (c) Does the maximum load differ between occupations?
4. On what basis can the maximum load be determined for nausea?
5. What is/are the best parameter(s) to describe the cause of physical harm?
   (a) Specific for launch and recovery
   (b) Specific for transit
   (c) Specific for transfer
6. On what basis can the maximum load be determined for physical harm?

3.2.2 Weather conditions

The way weather data is described defines how the seakeeping performance of a vessel is described. This statement can be reversed by saying the way a vessel's performance in adverse weather conditions is described, defines how the weather data has to be delivered. Either way the weather a vessel should be able to safely operate in has to be described in a way that covers all factors that influence the vessel's operations but isn't unnecessarily complex. Only using the significant wave height is not complete, but trying to predict every wrinkle on the water surface would be too complex. The literature proposes several alternatives, these are discussed in section 4.4. If one or more suffice, the most fitting will be chosen otherwise a novel version has to be proposed. The question regarding weather condition formulation are listed below:

1. Which information concerning the weather conditions has to be assessed when predicting vessel movement?
   (a) Does this differ between the three stages?
2. What is the most effective way of formulating that information for offshore accessibility applications?

3.2.3 Daughter craft RAO's

The response of the vessel to certain weather conditions has to be known to predict the motions of the vessel. Current RAOs are given for combinations between the relative angle of waves to a vessel and the encounter period of the waves. The questions remaining for describing the response of DCs to weather conditions are listed below:

1. Are there RAOs compatible with the chosen formulation of weather conditions?
   (a) If not, can these be formulated?
2. Do the RAOs differ for the three different stages?

3.2.4 Daughter craft speed and heading

The formulation of speed and heading is clear but the control needed to safely operate in adverse weather conditions is not yet quantified.

1. How can the amount of control needed to safely operate in adverse weather conditions be quantified?
   (a) Specific for launch and recovery
   (b) Specific for transit
   (c) Specific for transfer

3.2.5 Location of the crew

The location of the crew on the vessel combined with the vessel motions determines the motions the crew are exposed to. The dynamic of this function is clear and doesn't require more assessment. The influence of the location might be of interest.

3.3 Triumvirate of conceptual design

To fully define a system concept the six well-known interrogatives can be used: Why, what, how, who, where, and when. This research aims to define the first two by formulating the performance requirements and further developing the operational requirements. The other two products are the concept of operations (CONOPS) and operational context, together they form the 'Triumvirate of conceptual design' as shown in figure 3.3. In the work of Brans et al. [Brans, 2021] an extensive stakeholders analysis was performed for offshore O&M with an emphasis on accessibility. This analysis is used as a basis for the Concept of operations and the operational context description.

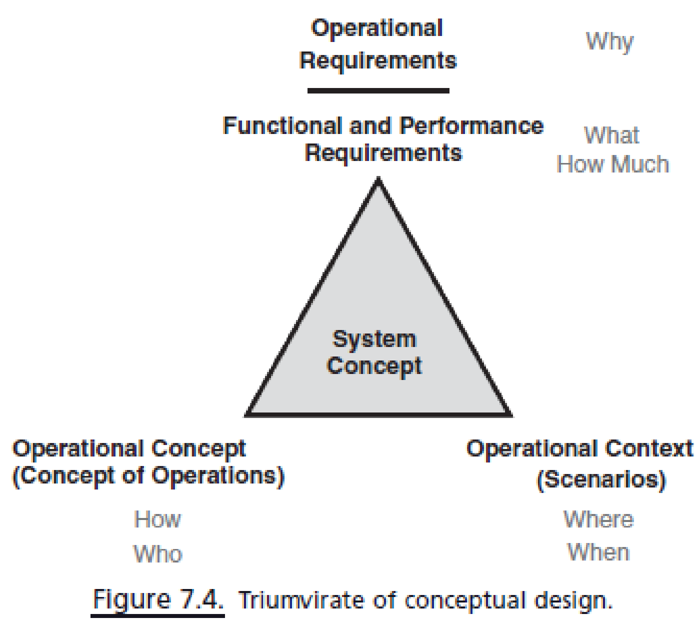

Figure 3.3: Triumvirate of conceptual design [Kossiakoff et al., 2003]

3.3.1 Concept of operations

The operational and performance requirements avoid describing a system that meets the requirements while CONOPS does describe the system and how it works. It is a broad term that can refer to a single system or a set of systems that work together. General components of are:

1. Mission description, with success criteria
2. Relationships with other systems or entities
3. Information sources and destinations
4. Other relationships or constraints

Mission description, with success criteria

The mission of the accessibility system consists of safe and timely transport of personnel and equipment from and to offshore WTGs to execute (unplanned) maintenance. The key principle of transfer by stepping over between vessels and offshore structures is described in the G+ good practice guidelines as follows [Energy institute and G+ Global offshore wind, 2018]:

The aim should be to ensure that people do not fall into the sea or become trapped between the vessel and any part of the offshore structure during transfers, through a combination of having a suitable design of boat landing, vessel selection, operating procedures, training, and competence. Residual risks from falling should be mitigated by using suitable protective equipment.

Success criteria are the safety and well-being of the crew first, then the transport of personnel and equipment, and lastly the time criteria. This is the same for the operational context description.

Relationships with other systems or entities

The accessibility for unplanned maintenance is mostly linked to the accessibility system for planned maintenance. This relationship has dictated the architecture of the unplanned maintenance system. The main goal of the SOV is linked to the planned maintenance system and is designed with this priority hierarchy. This is not limited to the SOV, the DC is also used for the preparation of planned maintenance. The priority hierarchy of planned maintenance preparation and unplanned maintenance is context-dependent. The urgency of the specific cases dictates for which maintenance the DC is used for first [1].

Information sources and destinations

Information sources consist of the weather reports, vessel specifications the vessel owners, and the MORS system that notifies the team onboard the SOV of any errors at the WTGs. Information destinations consist of VDR reports that log vessel activity and HSE reports if a crew member feels something wasn't executed according to safety standards. The VDR is focused on SOV use but DC usage is mentioned.

Other relationships or constraints

One important relation to mention is that of Siemens Gamesa and the vessel owner. The SOVs, CTVs, and DCs are 'rented' from and operated by the vessel owner. It is therefore not only up to Siemens Gamesa if a vessel can be deployed or operated, this is always in cooperation with a third party.

[1] Robert Deen, Maintenance supervisor - Siemens Gamesa

3.3.2 Operational context description

The operational context description describes the environment the systems operate in. As seen in figure 3.3 this final part focuses on the 'where' and 'when'. General components are:

1. Mission description, with success criteria
2. Friendly parties, with the kind of benefits they offer
3. Threat actions, these can be human or other
4. Environment, the physical environment of the system
5. Sequence of events, the order a system operates in

Friendly parties, with the kind of benefits they offer

TU Delft has no other goal than to aid Siemens Gamesa by increasing knowledge in the offshore industry. The overarching goal of the university is to accelerate the energy transition.

Threat actions, these can be human or other

The most prominent threat to accessibility is adverse weather. It is not certain how the changing climate will affect the weather conditions in wind parks but there is a significant chance that it will change for the worse, reducing accessibility if the system stays the same.

Environment, the physical environment of the system

The physical environment of the far-offshore accessibility system for unplanned maintenance is different for every wind farm but there are many similarities between them. Most importantly, the nearest port is at least 65 km away.

Sequence of events, the order a system operates in

The first step in the operational sequence is the notification from the MORS system. A maintenance planner on board the SOV will assess the notification and if necessary plan a maintenance run. The planner checks if there is a team available for troubleshooting and if there is a weather window that complies with the vessel limits. If so a request is sent to the bridge where the caption assesses the request. If the captain of the SOV agrees, the preparations are made to deploy. This will take between 45 and 60 minutes [2]. The DC captain and the technicians on board also have the chance to address unsafe situations and anyone can abort the operation if they feel it's necessary. When the DC is deployed by crane or davit, it performs the transit and transfer stages as described in section 2.2. The SOV caption fills in the VDR at the end of the day describing the DC operation and weather conditions at that moment.

With a clear understanding of the uncertainties and limitations of the current system and the right perspective on the place of performance requirements in the process, the Performance requirements formulation phase can be initiated.

[2] Ingmar Bos, Senior technician - Siemens Gamesa

4 | Performance requirements formulation

The second step of this phase is called performance requirements formulation. The final goal of this step is to formulate a set of system performance characteristics that is both necessary and sufficient.

First, the set of performance requirements is developed in section 4.1, and a way of combining these KPIs into a single score is proposed in sections 4.2 and 4.3. Then section 4.4 discusses the reality of predicting these KPIs for a potential vessel design. Finally, in section 4.5 the effects of this reality on the current research are explained.

4.1 Performance requirements

Performance requirements describe the 'what' and the 'how much'. To an engineer, this sounds like describing the right parameters. There are a few steps to be taken before the right parameters and their ranges can be determined. When developing performance requirements, the information from previous stages, the needs analysis, is combined with existing literature to form adequate requirements. There are four stages in developing requirements as can be seen in figure 4.1. All four steps will be performed to develop the performance requirements. After the steps are executed to satisfaction, two additional tools will be used to improve perspective on the requirements and assess them, the triumvirate of conceptual design and analysis of alternatives. The process is shown instead of only showing the final set of performance requirements to give the reader an understanding of the context and the reasoning for the end result. There are usually multiple interpretations and angles possible in requirement formulation. Therefore the reasoning behind the set of requirements is almost as important as the set itself.

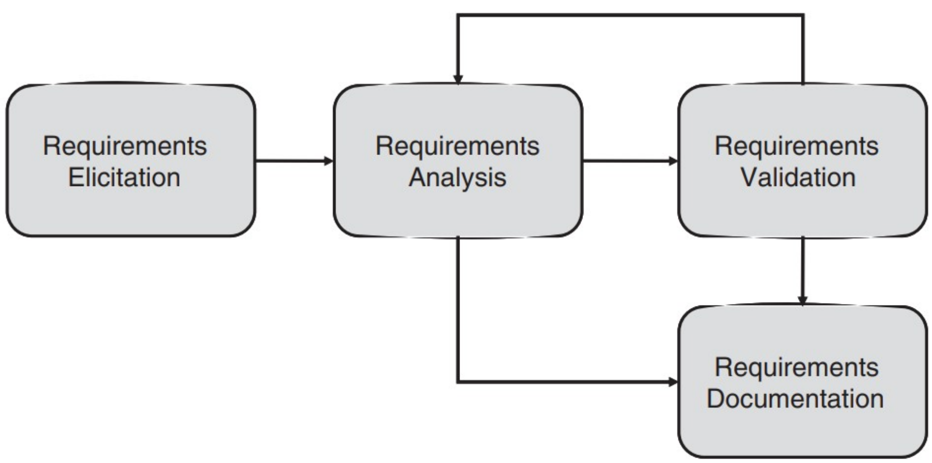

Figure 4.1: Four stages of requirement development [Kossiakoff et al., 2003]

4.1.1 Elicitation

The three operational objectives of interest to accessibility are taken as a basis for the elicitation of the performance requirements. The first elicitation of performance requirements is listed below the corresponding operational requirement. There will be three iterations throughout this report, so this is not the final set.

1. Transport technicians to defective WTGs at sufficient speed.
   (a) Buoyancy, or at least protection from the water
   (b) Propulsion, to reach each destination in a short enough time
   (c) Sufficient space to accommodate the technicians
   (d) Steering in transit and in zero speed conditions.
2. Allow sufficient, safe access to WTGs during adverse weather conditions
   (a) Robust launch and recovery system that can operate in adverse weather conditions
   (b) The vessel mustn't capsize because of adverse weather conditions
   (c) The vessel should remain sufficiently in control of speed and direction during adverse weather conditions
   (d) Technicians should be able to safely access and egress WTGs from the vessel during adverse weather conditions
3. Avoid fatigue, nausea, and injuries during launch, recovery, transit, and transfer.
   (a) The motions experienced by the crew shall not exceed a limit regarding fatigue
   (b) The motions experienced by the crew shall not exceed a limit regarding nausea
   (c) The motions experienced by the crew shall not lead to physical damage to the crew

With this set of requirements, the development cycle is initiated.

4.1.2 Analysis

In the analysis stage, a set of tests or questions is used to assess the requirements individually and as a whole. The questions are shown below [Kossiakoff et al., 2003] and their effect on the initial set is listed below the corresponding question.

Questions to test each requirement individually:

1. Is the requirement traceable to a user need or operational requirement?
   (a) Because of the structure that links performance requirements to the corresponding operational requirement, this test is passed by all performance requirements.
2. Is the requirement redundant with any other requirement?
   (a) There is overlap between 1.d and 2.c, although it might seem incomplete to not mention steering under the first operational requirement. 1.d can be omitted from the set if 2.c includes transit and zero speed.
   (b) There is overlap between 1.a and 2.b, these could be combined in theory. But they remain separate because their distinction matches the distinction between their corresponding operational requirements. The first is general and the second refers to heavy weather conditions. But an element of stability should be added to 1.

(c) Regarding the overlap of 3.a and 3.b with 3.c: The limit for physical harm may never be reached when the limits for fatigue and nausea aren't exceeded. But the literature points toward longer exposure to motions as the cause of fatigue and nausea. While a single event can cause physical harm.

(d) Finally an overlap between 2.b and 3.a, 3.b, and 3.c could be described. These will remain unchanged, the overlap does not render any of the requirements redundant.

3. Is the requirement consistent with other requirements?

   (a) None of the requirements contradict another or force an infeasible solution at this point. The stability requirement might interfere with the decreased motion requirements as a high metacentric height can cause higher accelerations.

4. Is the requirement unambiguous and not subject to interpretation?

   (a) 1.a, 1.b, 1.c, (1.d) are clear but lack a parameter and range. For 1.a that would be buoyancy in [kg] added to vessels weight until freeboard is reached and a minimum metacentric height [m] for stability. For 1.b a minimal design speed in [knots]. For 1.c a minimum number [-] of seats available for technicians.

   (b) For all requirements under 2. 'adverse weather conditions' need to be quantified. This is a complex requirement to quantify. A combination between significant wave height, wave direction, wave period, wind speed, and wind direction or a combination between wave spectrum, wind speed, and wind direction is an adequate way of quantifying the weather conditions according to current literature [Drago et al., 2017]. Then a range has to be determined. This will most probably be site-specific, depending on the form of the parameter combination.

   (c) 2.a should be more specific, it should operate without failure or damage to the lifting system, SOV, or DC. Ideally, a percentage[%] depicting the change of failure is estimated.

   (d) 2.c needs parameters and ranges. A percentage [%] of the speed that may differ because of wind and waves. A number of degrees [°] the direction may be altered by wind and waves.

   (e) For 2.d the chance for the vessel to break contact with the secondary steel must be quantified [%/min]. Secondly, a maximum for the chance [%/min] of a certain length[m] slippage must be defined.

   (f) For 3.a and 3.b the most suitable parameter and limit for accelerations over time must be chosen from the literature.

   (g) For 3.c the maximum single acceleration must be chosen for each position the crew is in, e.g. sitting in a damping chair or standing on the foredeck.

5. Is the requirement technologically feasible?

   (a) This depends on the final ranges and parameters chosen. But the work of Brans has proven the feasibility of improvement.

6. Is the requirement affordable?

   (a) While this is a very crucial question, it is left out of scope for now.

7. Is the requirement verifiable?

   (a) Yes, each requirement can be verified. To verify a single requirement, it has to be possible to prove that the requirement has been fulfilled. As the requirements are expressed in clear parameters and will receive concrete limits, it will be possible to verify the requirements.

The following questions refer to the whole set of performance requirements:

1. Does the set of requirements cover all of the user needs and operational requirements?
    (a) The performance requirements cover all accessibility-related operational requirements.
2. Is the set of requirements feasible in terms of cost, schedule, and technology?
    (a) Cost and development schedules are out of scope. Technologically feasibility will depend on the limits that are chosen. This may point out that the ideal situation under current conditions is infeasible and that some requirements must change, e.g. the capacity of the SOV crane or expected accessibility.
3. Can the set of requirements be verified as a whole?
    (a) Verification can be done by performing a case study with a system that complies with all performance requirements and determining if the accessibility would increase without decreasing any other operational requirement. Part of the verification will happen in the validation phase where users and subject matter experts (SMEs) assess the set of requirements.

The analysis has shown that the set of performance requirements is not finished yet. More specificity must be added. First, this section aims to clarify the structure of the requirements. Assuming the parameters and ranges for the parameters are found, the set of requirements is further developed. The improved set of requirements is shown below.

1. Transport technicians to defective WTGs at sufficient speed.
    (a) Buoyancy, or at least protection from the water. Weight of vessel and required cargo and passengers until freeboard is reached [kg]
    (b) Propulsion, to reach each destination in a short enough time. Minimum design speed [knots]
    (c) Sufficient space to accommodate the technicians, number of seats for technicians [-]
    (d) Stability, a minimum metacentric height [m]
2. Allow sufficient, safe access to WTGs during adverse weather conditions
    (a) **Adverse weather conditions will be depicted by a set of parameters. Including wind speed [m/s], wind direction [°], and either a combination of significant wave height [m], wave direction [°], and wave period [s] or a wave spectrum [m^2/Hz]**
    (b) Robust launch and recovery system that can operate without failure or damaging the lifting system, SOV, or DC in adverse weather conditions. A chance of failure expressed in a percentage over a number of launches and recoveries [%]
    (c) The vessel mustn't capsize because of adverse weather conditions
    (d) The vessel should remain sufficiently in control of speed and direction in transit and at zero speed during adverse weather conditions. Control of speed is expressed in a percentage of the speed that may differ because of wind and waves [%], control of direction is expressed in a number of degrees the direction is altered by wind and waves [°].
    (e) Technicians should be able to safely access and egress WTGs from the vessel during adverse weather conditions. A percentage over time depicting the chance of the DC breaking contact with the ladder [%/min] and a set of percentages over time depicting the change of a certain distance slippage [m], percentages will drop while slippage distances increase [%/min].

3. Avoid fatigue, nausea, and injuries during launch, recovery, transit, and transfer.
   (a) The motions experienced by the crew mustn't exceed a limit regarding fatigue. Many options are present in literature, most in the form of a number of a certain acceleration over time [Hz]
   (b) The motions experienced by the crew mustn't exceed a limit regarding nausea. Many options are present in literature, most in the form of a number of a certain acceleration over time [Hz]
   (c) The motions experienced by the crew mustn't lead to physical damage to the crew. Maximum acceleration depending on the location of the crew [m/s^2]

The majority of the uncertainty is found in three subject groups. The first is human limits, there needs to be a set of limits found to keep nausea, fatigue, and physical harm at a minimum, also during transfer. The second is the description of weather conditions and how the limit is set for which conditions accessibility is required. The final subject group is a set of vessel performances like speed, control, and stability. The last subject is expected to be the least complex and might have the widest ranges in comparison to the first two subject groups.

4.1.3 Validation

The set of performance requirements is 'informally validated' by four SMEs from Siemens Gamesa and the TU Delft [Kossiakoff et al., 2003]. It's more of an assessment than a validation but nevertheless an important step in the development of the performance requirements.

- Austin Kana: Assistant professor, ship design, production, and operations - TU Delft
  - Continuation on wave steepness
  - Including equipment
  - Wording changes and structure clarification
  - Deemed set complete and coherent.
- Rene Wigmans: Global head of offshore service logistics - Siemens Gamesa
  - Stressed the importance of bringing the limitations of the crew in the process as early as possible.
  - Deemed the set complete and coherent.
- Fernando Sanchéz Santiago: Principal naval architect - Siemens Gamesa
  - Suggested format changes to make a clear distinction between requirement and the unit of the parameter.
  - Showed the need to include current in the weather conditions
  - Doubted the critically of 2.d as the control might only be critical in transfer, which is covered by 2.e.
  - Finally the formulation of 3.a and 3.b is fit for improvement. The unit is not clearly enough depicted.
- Florian Hoffman: Deputy site manager, Gemini - Siemens Gamesa
  - Deemed the set complete and coherent.

The Adjustments are all taken into account and included in the final set. Resulting in the final set shown below. 2.d is left in the set because the need for control in transit and launch and recovery might still be critical. The structure is chosen as such that the requirement starts with the requirement described in words and is followed by the expression of this requirement in *Italic*.

1. Transport technicians to defective WTGs at sufficient speed.
   (a) Buoyancy, or at least protection from the water. *Weight of vessel and required cargo and passengers until freeboard is reached [kg]*
   (b) Propulsion, to reach each destination in a short enough time. *Minimum design speed [knots]*
   (c) Sufficient space to accommodate the technicians and equipment. *number of seats for technicians [-], volume [m^3] and weight [kg]*
   (d) Stability. *Minimum metacentric height [m]*
2. Allow sufficient, safe access to WTGs during adverse weather conditions
   (a) **Adverse weather conditions will be depicted by a set of parameters. Including current speed[m/s], current direction [°], wind speed [m/s], wind direction [°], and either a combination of significant wave height [m], wave direction [°], and wave period [s], wave steepness[-], or a wave spectrum [m^2/Hz]**
   (b) Robust launch and recovery system that can operate without failure or damaging the lifting system, SOV, or DC in adverse weather conditions. *A chance of failure expressed in a percentage over a number of launches and recoveries [%]*
   (c) The vessel shall not capsize because of adverse weather conditions
   (d) The vessel should remain sufficiently in control of speed and direction in transit and at zero speed during adverse weather conditions. *Control of speed is expressed in a percentage of the speed that may differ because of wind and waves [%], control of direction is expressed in a number of degrees the direction is altered by wind and waves [°].*
   (e) Technicians should be able to safely access and egress WTGs from the vessel during adverse weather conditions. *A percentage over time depicting the chance of the DC breaking contact with the ladder [%/min] and a set of percentages over time depicting the change of a certain distance slippage [m], percentages will drop while slippage distances increase [%/min].*
3. Avoid fatigue, nausea, and injuries during launch, recovery, transit, and transfer.
   (a) The motions experienced by the crew shouldn't exceed a limit regarding fatigue. Many options are present in literature, most in the form of *frequency of different individual acceleration amplitude ranges over set time span [Hz]*
   (b) The motions experienced by the crew mustn't exceed a limit regarding nausea. Many options are present in literature, most in the form of *frequency of different individual acceleration amplitude ranges over set time span [Hz]*
   (c) The motions experienced by the crew mustn't lead to physical damage to the crew. *Maximum acceleration depending on the location of the crew [m/s^2]*

4.1.4 Documentation

Documentation of large and complex systems usually requires a dedicated system to keep track of all performance requirements. Because this research only focuses on the accessibility of the system, a simple table will suffice. An example of such a table is given in table 4.1

Requirement	Parameter	Lower bound	Upper bound	Note
Buoyancy	kg	6000	-	
Propulsion	knots	22	-	
Space	#	5	-	
	m^3	6	-	
	kg	1500	-	
Stability	m	0,4	-	
Robust L&R	%	-	0,01	
Capsize	-	-	-	
Control	%	-	20	
	°	-	15	
Transfer	%/min	-	0,1	
	%/min	-	3	>20 cm
		-	0,5	>50 cm
		-	0,1	>80 cm
Fatigue	Hz	-	0,002	>0,3 G
			0,0002	>0,8 G
			0,00002	>1,0 G
Nausea	Hz	-	0,001	>0,3 G
			0,0001	>0,8 G
			0,00001	>1,0 G
Damage	m/s^3	-	15	

Table 4.1: Example table of requirements and expressions, the upper and lower bounds are baseless

4.2 Combining KPIs

When all KPIs are known for a few vessels and a comparison is made. It's expected that not one vessel trumps the others on all KPIs but that trade-offs have to be made. The question remains on how this is done. A complex decision involving multiple criteria per alternative can be solved using a Multiple criteria decision method (MCDM). In the research of Ren et al. [Ren and Lützen, 2017] five methods are discussed in order to find an alternative energy source for shipping. The same five methods are compared for application in this research because of the similarities in the goal, structure, and complexity between this work and that of Ren et al. The five methods are TOPSIS, PROMETHEE, VIKOR, DEA, and ELECTREE. All methods can be extended by using fuzzy theory or grey theory.

4.2.1 TOPSIS

The Technique for Order of Preference by Similarity to Ideal Solution is the first method discussed. The method is described as a simple, suitable, and practical method [Pavić and Novoselac, 2013]. The method was first used by Hwang and Yoon in 1981 [Lai et al., 1994]. The basis of the method lies in finding the optimal alternative by taking the shortest distance to the Positive Ideal Solution (PIS) and the longest distance to the Negative Ideal Solution (NIS). In general, this means that a lower score in one parameter can be compensated by a higher score in another parameter. Important is that each parameter has either a monotonically increasing or decreasing preference. This is an assumption that has to be met for the method to result in useful results.

4.2.2 PROMETHEE

The second method, Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE), is described by [Behzadian et al., 2010] as the method that is gaining the most popularity within academic research. The method is based on sociology and mathematics. The goal of the method is to provide a comprehensive and rational framework for structuring a decision-making problem. It is an outranking method that was first presented by Brans et al. in 1982. The method uses pairwise comparison, each alternative is compared with the other alternatives individually. Using a preference function the relative difference between two alternatives on each parameter is translated into the multi-criteria preference index. This includes the weights per parameter and gives a score between 0 and 1 denoting the preference of one alternative over another. Now the positive and negative outranking flows can be constructed per alternative and these determine the rank of the alternative [Abdullah et al., 2019]. The method is relatively difficult to use.

4.2.3 VIKOR

The third method, (in Serbian) VIseKriterijumska Optimizacija I Kompromisno Resenje, was developed to solve decision-making problems with conflicting and non-commensurable criteria. The method is, like TOPSIS, a compromise method. Both methods take the distance to the optimal and worst solution into account [Opricovic and Tzeng, 2007]. VIKOR uses a slightly more difficult but in certain situations a more accurate method to determine this 'closeness'. Additionally, VIKOR has an iterative loop that evaluates the weights given by the 'Decision maker'. It allows the decision-maker to execute the method without an active role for the decision-maker.

4.2.4 DEA

The initial idea of Data Envelopment Analysis was introduced by Farrel in 1957, but the first DEA model, as originally presented in Charnes, Cooper, and Rhodes (CCR), was introduced in 1962 [Cooper et al., 2011]. The present form was first used in 1978. The goal of the method is to use linear programming to estimate an empirical production technology frontier, a tool to measure productive efficiency. The main advantage of the model is its broad applicability due to the low amount of assumptions. It utilizes Decision-Making Units in a large range of ways. The method is extensive and the results often require further assessment before conclusions can be drawn.

4.2.5 ELECTRE

The final method was thought of by Bernard Roy in France in 1965. The full name in France is ÉLimination et Choix Traduisant la REalité. Like PROMETHEE, it's an outranking method that can discard alternatives that are below a certain threshold. The method was made when a French consultancy firm ran into problems with a weighed sum technique. The goal of the method is to choose, rank and sort when dealing with real-world decision problems [Alkhairi et al., 2019].

4.2.6 Method selection

After five of the most suitable methods are assessed, the most suitable can be chosen from the selection. The requirements for this application are:

- Ease of use
  - Because the proposed system must replace a very simple system, the increase in the difficulty of use shouldn't be too steep.
- Clear ranking of all alternatives as a result
  - The method must show a ranking from the best alternative for this application to the worst.
- Clear how the rank is constructed
  - It must be easy to trace back why an alternative received a rank.

Because of the second requirement, both DEA and ELECTREE are discarded. These methods don't result in a clear ranking of all alternatives. The three methods left are a good fit for this application. The difficulty of the calculation procedure of the TOPSIS and VIKOR is comparable according to the paper of Vakilipour et al [Vakilipour et al., 2021]. The difficulty of PROMETHEE is higher because it doesn't offer higher accuracy in return the method is discarded. To compare the effectiveness of the last two methods, the paper of Opricovic [Opricovic and Tzeng, 2004] is consulted. In Opricovis's paper, the difference in aggregation is highlighted. Where TOPSIS relies equally on the distance to the ideal as to the distance to the negative ideal. But this is rarely a goal to be far away from the negative ideal. The VIKOR method uses the weight ν to adjust for this misplaced preference. In conclusion, the VIKOR method is the most preferred for this application.

4.3 VIKOR method

In this subsection, the chosen method is thoroughly explored, to understand how the rank is constructed.

This compromise method will assess the technologies upon their parameters and, combined with the respective weights, resulting in a rank of the technologies. Multiple options are available for executing this method. Matlab, Excel, or Python are the most common. Matlab and Excel are both frequently used by Siemens Gamesas employees. To ensure that the method can also be used in the field, the most accessible of the two is chosen, Excel. A simple example of the VIKOR method used to assess technology improvements for the government shipping service of Fiji can be found in appendix B.

4.3.1 Method for weights selection

After a method is chosen, a way of deciding the weights has to be determined. Three types of approaches are known:

- Objective methods, where weights are determined based on the data of the alternatives. Two examples are the entropy method and the criteria importance through inter-criteria correlation (CRITIC) method.
- Subjective methods, where weights are determined based on the preferences of the decision-maker. Two examples are the analytic hierarchy process (AHP) and the Delphi method.
- The third option is to combine a subjective and an objective method.

In this research, a subjective method will be proposed because both the parameters of the alternatives are uncertain and the critically of each parameter hasn't been quantified before.

4.4 How to reduce performance uncertainty?

The problem surrounding low accessibility in far-offshore wind farms has been examined and split into categories and questions. The main two challenges appear to be the comfort and safety of the crew. The comfort is expressed in fatigue and nausea that complicates the work of the technicians. The motions during transit and transfer seem to be the main drivers behind this lack of comfort. The safety of the crew is mainly at risk during the transfer phase and is also complicated by the vessel motions. The vessel motions at zero speed can be predicted with relatively high accuracy which allows the evaluation of different solution designs. The vessel motions during transit decrease in accuracy when the speed increases. An example of this is shown in the work of Prini et al. shown in figure 4.2 This makes it more difficult to assess possible solutions.

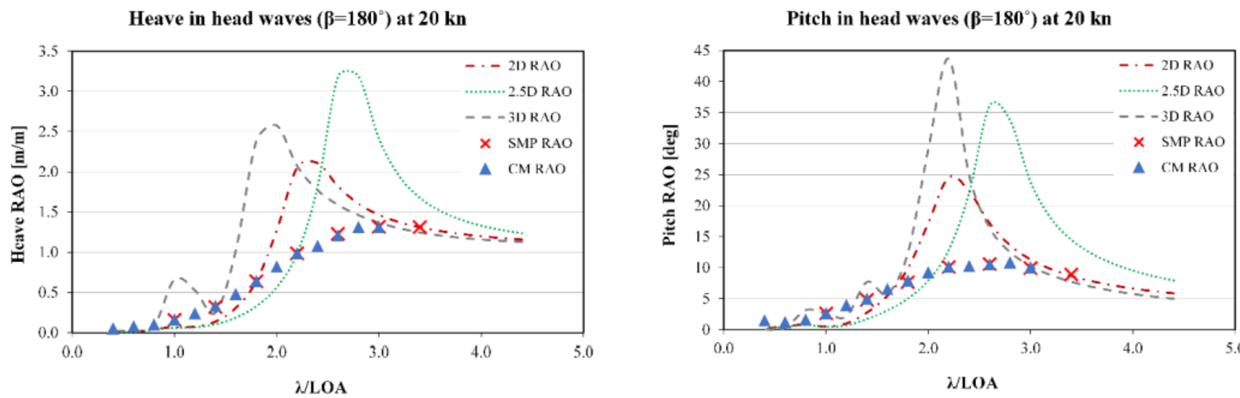

Figure 4.2: Heave and pitch RAOs for a 17m vessel in head waves. Comparison between model tests (SMP & CM) and numerical simulations (2D, 2.5D & 3D)

4.4.1 Motion sickness

The root cause of motion sickness is explained as a lack of conformity between eye signals and signals from the vestibular system, part of the labyrinth in the inner ear. It's therefore more common to experience seasickness below deck, where the stimuli from the eye give an obstructed view of the motions. The exact relation between ship motions and motion sickness is yet to be determined. McCauley and O'Hanlon have made quantitative estimations on the impact of ship motions have on the percentage of people to get seasick. They concluded that heave motions have the most impact while pitch and roll have very little effect [Cepowski, 2012]. This conclusion is later questioned by Wertheim et al, especially for smaller vessels [Wertheim et al., 1999]. So roll and pitch do have an influence and should also be taken into account. There are multiple methods to quantify motion sickness based on vessel motions or accelerations. Motion Sickness incidence (MSI) and motion sickness dose value (MSDV) are the most common, the latter being recommended by the International Organization for Standardization (ISO) [Cepowski, 2012], [BSI, 1997]. The ISO 2631 does not cover long-term effects on the brain like 'sled head'. Two methods stand out as a possible KPIs for motion sickness. The Operability robustness index (ORI) and the overall motion sickness incidence (OMSI). Both methods propose an inclusive method that describes a vessel's performance in terms of sea keeping. The methods share the same flaw, they are based on the assumption of linearity. This is inaccurate for a small vessel in high-speed transit. If the vessel is not planning, a software system like Wasim of DNV could offer a solution. There are novel methods that use vessel motion data and weather data during the operation of the vessel to build a model for motion prediction. An example of such a method is proposed by Han et al. [Han et al., 2021]. The flaw of this approach is that it offers no knowledge before deployment. So looking back at figure 3.2, while weather data and crew limitations are the unknowns, the uncertainty stems from the transformative function motions of daughter craft.

4.4.2 Transfer safety

In the case of transfer safety, the same problem arises if the performance requirements are quantified. But because the vessel is stationary the interaction between the waves and the vessel is more linear and simulations exist that can predict the slippage of the bow, see figure 4.3. Such a method is proposed by MO4. The notes of an interview with co-founder Mark Paalvast can be found in appendix A.

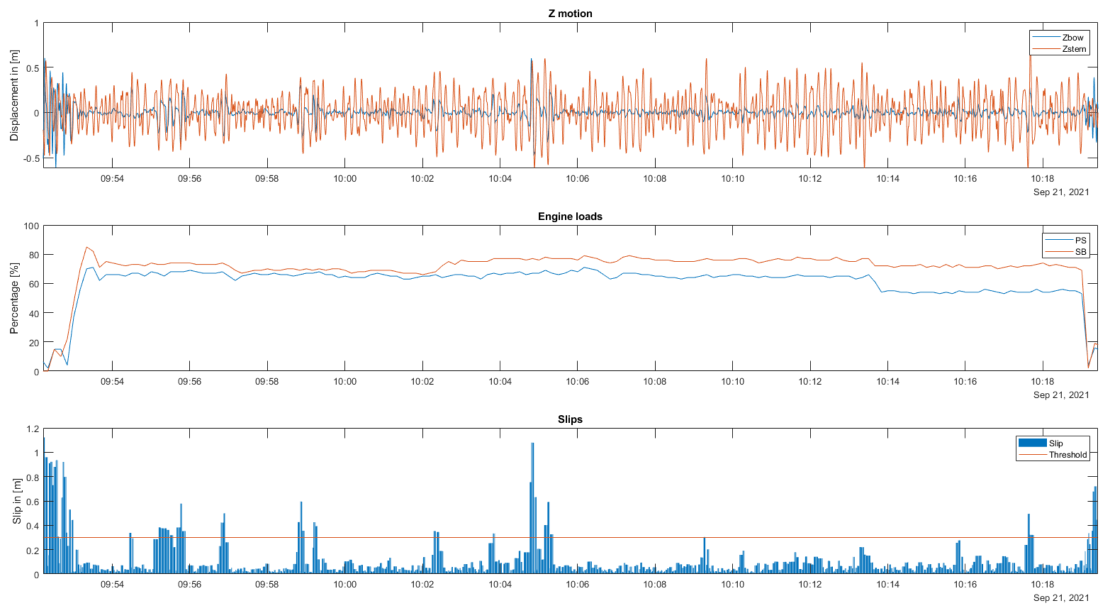

Figure 4.3: Example of a validation study of MO4, showing the vertical motion, engine load, and slippage. The orange line in the bottom graph depicts the threshold of 0,3m. MO4 predicted an 8% of breaching the threshold, in this case, it was 10%. Graph by courtesy of MO4

4.4.3 Weather description

The form of weather description is very visible when in the current system as the requirements, significant wave height, and wind speed, are directly linked to the weather forecast. In this research, the form of weather prediction is expected to follow the form of the KPIs. Multiple forms could offer enough accuracy but the determining factor will be the form of information needed to predict the vessel motions during transit and transfer.

A part of the uncertainty can be solved but seasickness will remain difficult to predict before operation. The set of performance requirements function as the current KPIs but those related to seasickness might be changed for an inclusive method.

4.5 Adaptation to uncertain performance prediction

As stated in the intro of this chapter, the goal of this step is to formulate a set that is both necessary and sufficient. This can be assessed by verifying the following two statements [Kossiakoff et al., 2003]:

1. A system that meets the system operational requirements and is technically feasible and affordable will comply with the performance characteristics.

2. A system that possesses these characteristics will meet the system operational requirements and can be designed to be technically feasible and affordable.

These statements describe the interaction between a set of well-formed operational requirements and a set of well-formed performance characteristics.

The set that is formed in this chapter does meet these criteria for the extent of its specificity. but this specificity is not sufficient in all three subjects: Human limits, description of weather conditions, and vessel performance. The system engineering method has laid bare a set of unknowns that needs further assessment before the subsystems can be assigned their performance requirements. The overarching question of what system can perform the best in terms of accessibility is difficult to be answered without more specificity in the requirements. Therefore the direction of this research to answer the research question has changed.

The KPIs or requirements won't be developed any further because extensive research is necessary to calculate the necessary parameters. Without the actual parameters the method can't be validated and the main research question will remain unanswered. Instead the systems engineering approach will be continued by using the current way of describing vessel performance. This lowers the accuracy of the outcome but does offer a larger amount of vessel performance data. In the next chapter, the different concepts will be discussed and the most promising will be selected.

5 | Implementation of concept exploration

The third step of this phase is called the implementation of concept exploration. Which revolves around the performance analysis and effectiveness analysis. A set of system alternatives is given in section 5.1. The initial scope of alternatives to analyze is reduced to a single alternative in section 5.2, the new challenges are presented in 5.3, operational configurations are introduced and compared in section 5.4, and the performance and effectiveness analysis are performed in sections 5.6.1 and 5.6.2 respectively to check if the new system meets all the previous set requirements and what performance characteristics define these system improvements. Finally, the vessels and wind farms chosen for the calculation are introduced in sections 5.7 and 5.8 respectively.

5.1 Analysis of alternatives

A set of system alternatives or improvements are presented below. The analysis is inductive in nature, so methods like brainstorming and out-of-the-box thinking are required [Kossiakoff et al., 2003].
The subsystem distinctions are made by the performance requirements. Each alternative will relate its improvements and possible shortcomings to these performance requirements. Although these parameters won't be quantified in this research, these are the precise points of improvement. In table 5.1 an overview is shown for all ten alternative systems.

1. Heading and speed control

   The angle of the waves on the heading of a moving vessel greatly influences the motions of the vessel. The angle could be improved by not taking the fastest route but a combination of preferred angles, this would of course increase transit duration. This alternative is mostly reliant on 2.d, which might negatively affect 1.b, and improves 3.a, 3.b, and 3.c. An interesting approach to this alternative is the haptic throttle control proposed by Kok et al. [Kok et al., 2018].

Figure 5.1: Daughter craft changing heading [4offshore, 2022a]

2. Wave reduction

   The waves could be reduced locally by deploying floating breakwater with or without wave energy converting (WEC) systems [Zhao et al., 2019]. This alternative improves performance on requirements 2.b, 2.c, 2.d, 2.e, 3.a, 3.b, and 3.c.

Figure 5.2: Floating breakwater [Zhao et al., 2019]

3. Dynamics between hull and waves

   The interaction between hull and waves could be improved by air-supported vessel (ASV) technology as for the ASV mono soft motion mentioned in the paper of Tudem et al. [Tudem and Livgård, 2011]. Or by hull alterations, proved feasible in the work of Brans et al. [Brans, 2021]. This alternative improves performance on 3.a, 3.b, and 3.c.

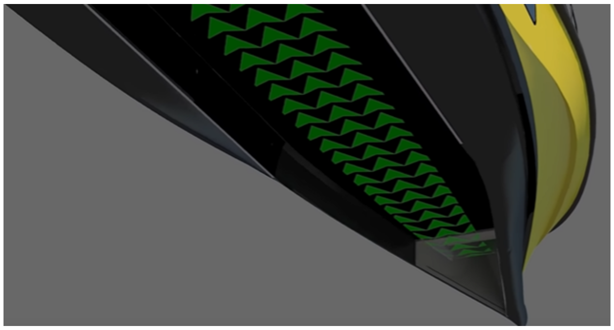

Figure 5.3: ASV technology shown in render from Tuco Marine [Prozero, 2022]

4. Increasing DC dimensions

   Alteration to the SOV allowing larger dimensions is expected to increase accessibility. This is proven by the difference in performance between DCs and CTVs. Examples of alterations are found in the work of McCartan et al. [McCartan et al., 2015]. This alternative has the potential to improve all performance requirements, except the effect on 2.b might be negative or neutral.

Figure 5.4: SOV alterations allowing increased dimensions for daughter crafts [McCartan et al., 2015]

5. Dynamics between hull and vessel structure

   The interaction between the hull and the upper structure could be improved by technology like that of Nauti craft with the suspension hulls. This alternative improves performance on 2.c, 3.a, 3.b, and 3.c.

Figure 5.5: A suspension hull during a high speed turn [Craft, 2022]

6. Decrease motion sickness susceptibility

   The reaction to the motions can be improved with medication, technology, and training. Heavy meals should be avoided, the crew should be hydrated, have plenty of fresh air and be able to see the horizon. Some medication does make the user drowsy, these should be avoided. There are also collars on the market that decrease the effect of brain injury by increasing blood pressure in the head. This alternative improves performance on 3.b.

Figure 5.6: The Qcollar, a neck collar to increase and maintain a high blood pressure in the head to decrease the negative effect of high accelerations on the brain [Qcollar, 2022]

7. Avoiding weather conditions by diving

   Traveling and transferring under the wave spectrum could improve many requirements but probably might not reach speed or cargo capacity requirements. This alternative negatively affects 1.a, 1.b, and 1.c. It improves performance on 2.c, 3.a, 3.b, and 3.c.

Figure 5.7: A small submarine on the market for leisure purpose [Deepflight, 2022]

8. Novel hull type

   A new hull type is proposed by Rafnar Marine that promises improvements in seakeeping performance during transit. Most of all, the slamming motion is drastically reduced. This alternative improves performance on 3.a, 3.b, and 3.c.

Figure 5.8: ök hull by Rafnar marine [Marine, 2022]

9. Decreasing roll motion

   Installing a gyroscope on a daughter craft can reduce roll motion during all three stages of operation. This alternative improves performance on 2.c, 3.a, 3.b, and 3.c.

Figure 5.9: Gyroscope by Quick [Quick, 2022]

10. Decreasing roll, pitch, and yaw

    By installing a novel device by Rotorswing, the device uses a Magnus rotor to counteract vessel rotations from zero speed up to 25 knots. This alternative is expected to improve performance on requirements 1.d, 2.c, 2.e, 3.a, 3.b, and 3.c.

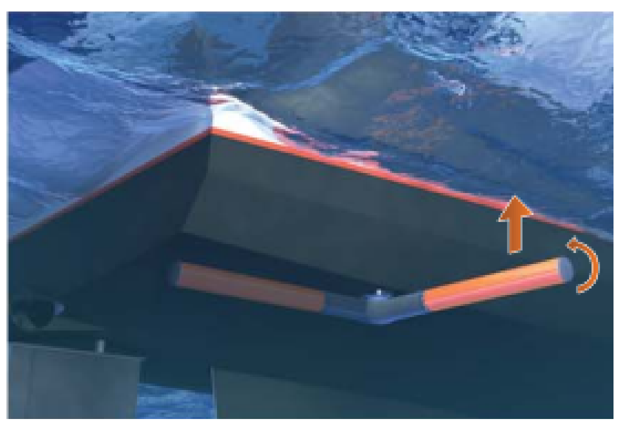

Figure 5.10: Render of Rotorswing attached to a vessel [HiswateWater, 2022]

Aternatives\Requirements	1.a	1.b	1.c	1.d	2.b	2.c	2.d	2.e	3.a	3.b	3.c
Heading and speed control		-							+	+	+
Wave reduction					+	+	+	+	+	+	+
Dynamics between hull and waves									+	+	+
Dynamics between hull and vessel structure						+			+	+	+
Increasing DC dimensions	+	+	+	+		+	+	+	+	+	+
Decrease motion sickness suceptibility										+	
Avoiding weather conditions by diving	-	-	-			+			+	+	+
Novel hull type									+	+	+
Decreasing roll motion				+		+			+	+	+
Decreasing roll, pitch, and yaw				+		+		+	+	+	+

Table 5.1: Overview of alternative systems and the requirements where the alternative is expected to improve (+) or decrease performance (-) compared to the predecessor system

5.2 Preferred system selection

In section 5.1 10 categories of system improvements were introduced. This research has discovered that the comparison between those alternatives is complex at this point in time. Most alternatives have not been tested for this application and so no parametric values are available. To test the feasibility of all categories, extensive research has to be conducted that exceeds the scope of this research. Therefore a single category will be selected and tested on its technical and financial feasibility. The selection of the alternative system is based on expected technical improvement and the extent of knowledge available to assess the alternative.

All system improvements are expected to improve accessibility. For example, large-scale improvements like a floating breakwater is compared to a smaller system improvement like a gyroscope. Large-scale alterations are expected to yield more results than a gyroscope, as the gyroscope mostly affects the roll motion during transfer. The transfer stage is deemed most critical for accessibility but heave, pitch, and sway are also important motions when it comes to transfer safety. So the gyroscope does target the most crucial phase but aims to improve only part of this phase. Floating breakwater has never before been applied far offshore, only close to a shoreline or harbor. This increases the difficulty to give significant predictions of the performance of the system both technically and financially. Because the differences in expected performance are complex to compare, solutions that have more certain performance are preferred. Furthermore, the transit and L&R stage shouldn't be neglected and solutions that don't offer improvement in all three stages are discarded for further research.

The system alternative that offers improvement on the most performance requirements is the 'increasing DC dimensions' category, visible in table 5.1. This is in part because it covers a wide array of alternatives. The daughter craft size restrictions are changed so that a larger vessel can be used to perform unplanned maintenance. This would allow a daughter craft comparable in size to a CTV. The performance characteristics of CTVs in terms of seakeeping and accessibility are both higher and better to predict than that of a daughter craft. Which makes this category very attractive.

The accessibility performance between DCs and CTVs differs based on design and region of deployment. But in general, the CTVs allow safe transfer in harsher weather conditions than DCs do. For example, the DCs within operation of Siemens Gamesa have Hs limits between 0.9m and 1.2m. While the transfer limits of CTVs range from 1.5m to 1.8m.

Besides changing the SOV, there are other solutions imaginable to keep a larger vessel in the vicinity of the wind farm for an extended time. The financial effects introduced by this system are reasonably well to predict when existing vessels are used. To avoid confusion with other vessels this research will name this larger DC: Far offshore transport vessel or FOTV. The distinction will develop further through the research but for now, it depicts a vessel that remains in a wind farm for a few weeks like an SOV with a design and size comparable to that of a CTV.

To realize the goal of keeping a significantly larger vessel than a daughter craft offshore can be reached by different designs. The two principal concepts defined in this work are the enlarged daughter craft concept and the exposed concept. The enlarged daughter craft concept consists of all designs where the FOTV is stored on the SOV when it's not in operation. The exposed concepts cover all designs where the FOTV is stored outside the SOV on for example a mooring buoy or at a WTG.

5.3 Challenges of a far offshore transport vessel

Most challenges arise in the interface with the SOV. Where the DC has a dedicated davit, the launch and recovery of the FOTV requires larger lifting equipment. Also, the crew and equipment have to be transferred from and to the FOTV. In the paper of Mccarten et al. [McCartan et al., 2015] a stern lifting launch system is proposed for larger vessels. But this is for a significantly different SOV than currently in operation. The goal is to operate in worse weather conditions than currently done with the DC, so the challenges in terms of launch and recovery are increased. The transfer of crew and equipment between the FOTV and the SOV must be able to meet or outperform the transfer between FOTV and WTG, otherwise, the intended effect of the FOTV is significantly decreased.

The second challenge is the effects of the offshore elements on the FOTV over time. This is most relevant for the exposed concepts, as the vessel will be left unmanned in harsh weather conditions. The wear and tear of the mooring and vessel itself have an effect on the length of the operation lifetime and therefore on the cost of the vessel.

Because the FOTV has to remain outside of port longer than a CTV, the vessel will need to be resupplied. First off all the fuel tanks on board are most probably not suited for operations of two weeks. Fresh water may need replenishing and sewage or black water needs to be removed.

5.4 Operational configuration of a far offshore transport vessel

Both principal concepts cover multiple design configurations. These design configurations are listed below together with their high level advantages and disadvantages. Finally, the most promising design configurations are chosen for further assessment.

5.4.1 Enlarged daughter craft concepts

In this principal concept, the logistics and organization remain the same as in current practice. The FOTV stays aboard the SOV until it's needed for operation. The intended improvement is that the FOTV is able to perform safe transfers in harsher weather conditions and therefore more often than a DC. The challenges that arise with this principal concept are almost all in the execution of the launch and recovery.

launch and recovery Currently, almost all DC are launched and recovered from the side of the vessel, as described in section 2.2.1. This is done by lifting the DC from the deck in the water with a davit or crane. There is a standby vessel, the Esvagt Aurora, in the Barentsee that launches a Safe Transfer Boat from a stern ramp [Ship spotting, 2022]. According to the interview with Daniel Flato in appendix A, most of the severe incidents with daughter craft happen during launch and recovery because the connection between the daughter craft and the lifting equipment fails. This hazard is almost independent of weather conditions and is therefor no significant factor for accessibility but should nonetheless be included in the design. A stern ramp design would greatly reduce this hazard as the DC is never suspended above the water or the SOV. An example of a stern ramp is shown in figure 5.11. A combination between suspension and ramp is called an intermediate system, shown in figure 5.12. An example of an intermediate system is lowering a cradle in the water which is lifted back on deck once the DC has docked in the cradle. Whether the system uses suspension, a ramp, or an intermediate system, all systems are designated as launch and recovery systems (LARS) [Smith, 2010].

Figure 5.11: PQBS-T stern ramp system from Palfinger [Palfinger, 2022]

Figure 5.12: Intermediate system example: Kongsberg Boat Transfer System [Kongsberg, 2022]

Multiple design configurations are possible. This research identifies three key decision points:

- Is the LARS located at the side or stern of the SOV?
- Does the LARS utilize a ramp, suspension, or intermediate system?
- In case of suspension: is the FOTV parallel to the SOV or perpendicular during the L&R?

Stern or side launch The first design decision is most dependent on the SOV design. The LARS will occupy a significant amount of space. The Lifting launch is less complex from a design point of view because there is more flexibility in terms of the exact location and if launched from the stern, the propulsion line has to be adapted [Sheinberg et al., 2003]. Furthermore, the SOV can position in a way the L&R is executed in the lee of the SOV. This reduction in waves is most ideal in Lifting launch compared to stern ramp launch.

On the other hand, the vertical vessel motions of the location of the LARS differ for the stern and side. But this is heavily dependent on the SOV design and prevailing wave conditions in the operational area.

Type of launching system The decision between the LARSs themselves is a complex one. Because of the larger dimensions and weight of the FOTV, the current systems on the market aren't sufficient. According to several davit, crane, and stern ramp launch system suppliers, the weight capabilities of a stern ramp launch system are the highest. But still, this is limited to around 40 tons [Palfinger, 2022]. For davit or cradle, this would be around 60 and 20 tons respectively [Vestdavit, 2020] [Kongsberg, 2022]. The width of the vessel is expected to be a limiting factor for stern ramp launch systems.

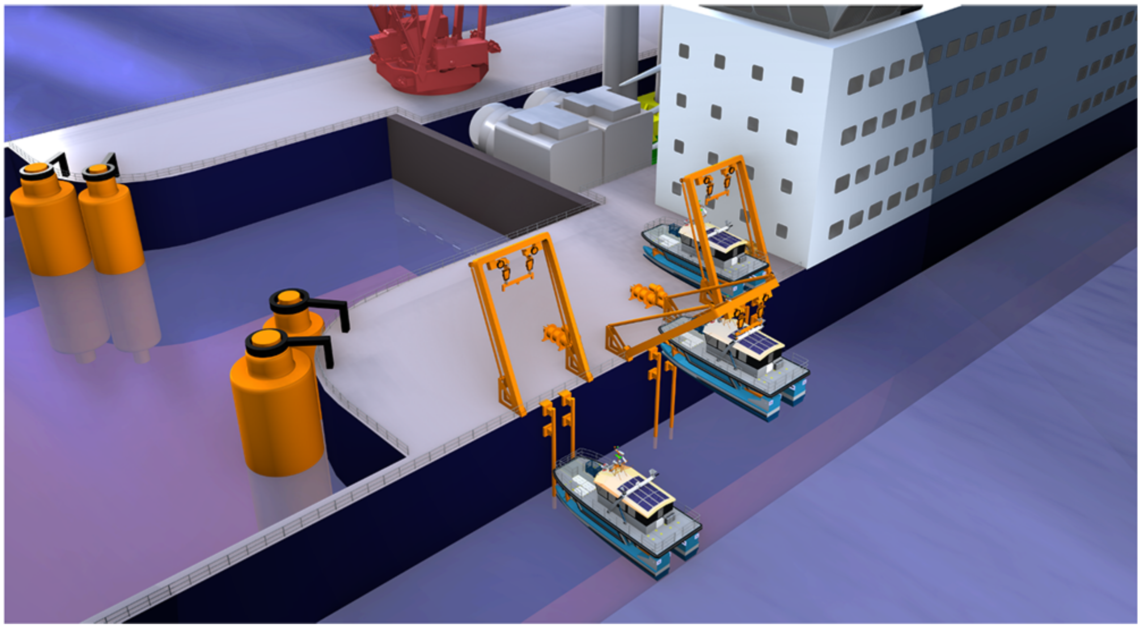

Figure 5.13: Example of perpendicular L&R by Nauti-craft [Nauti-craft, 2022]

Parallel or perpendicular arrangement When the FOTV can push its bow against the hull of the SOV during L&R as shown in figure 5.13, the control over the operation is increased in comparison to parallel L&R. This does have implications on the deck space needed to store this system. The highest performance is expected for perpendicular operations but this might not be needed when parallel operations limits are still above the limits of transfer. This decision will depend on the SOV deck layout and other operations limits, most likely the transfer limits.

5.4.2 Exposed concepts

The principal concept that covers all design configurations in which the FOTV is stored outside of the SOV are called the exposed concepts. A clear advantage of these concepts compared to the enlarged daughter craft concepts is that there are no restrictions on weight and dimensions. These concepts allow larger and heavier FOTVs. The design configurations in this principal concept are distinguished from each other by the location of the mooring. Four general locations are assessed:

- Attached to the SOV
- Moored to a WTG
- Moored to one of a set of designated mooring platforms
- Moored to an offshore hub in the center of wind farm

To compare these design configurations the general design has to be determined. Then the designs are assessed based on the expected duration of reaching the FOTV from the SOV, the expected safety of reaching the FOTV, the expected feasibility of leaving the FOTV moored at the given location, and the technical feasibility of the system.

Attached to the SOV To moor the FOTV to the SOV a mooring system has to be designed that prevents collision between both vessels but allows the crew to transfer between the vessels. When the SOV is in transit the FOTV can't impede the operation of the SOV. A possible system consisting of two rigid beams would hold the FOTV in position and can function as a gangway from and to the vessel. The forces exerted on these beams by the waves are expected to be very high. In particular, the moments on the attachments of the beams when the two vessels are moving out of phase. These attachments should then be hinged and damped in two rotational degrees of freedom. The impulse forces on these attachments will be high too, so the beams will have some sort of dampened telescoping functions.

The SOV can also be outfitted with a regular boat landing and the FOTV with a gripper [Mobimar, 2012]. The gripper is displayed in figure 5.14.

Figure 5.14: Gripper system Mobimar [Mobimar, 2012]

Because the technology is already developed, a more accurate prediction can be done on the feasibility. Of course, the gripper was meant for short duration and aided by the thrust of the DC, this can have a negative effect on the durability of the design. In terms of energy output the gripper doesn't require power in either gripping or sliding mode, just the hydraulic power pack to be on standby, according to Pauli Immonen of Mobimar, see appendix A.

The time required to transfer between the SOV and FOTV is very low. The safety is fairly high because it can be designed in a way that the crew never has to step onto a surface, over water, with different relative motions to the surface it was on before. The feasibility of leaving the FOTV on this mooring is increased because the vessel can be monitored from the SOV. On the other hand, the operations of the SOV are most likely hindered by this configuration. This could be minimized by placing this system on the opposite side of where the walk to work operations are carried out. The technical feasibility is low, the mooring system needs to endure a lot of oscillating forces over time. It's uncertain if there is a design with proper material choice that allows this mooring system to operate for an extended period of time. The configuration with a gripper system faces issues when the SOV is in transit whether it's attached to the side or stern of the SOV.

Moored to a WTG The FOTV could be moored to a WTG close to the SOV. Either to the boat landing or to a designated mooring structure of the WTG. A mooring system has to be designed to hold the FOTV against the boat landing. This mooring will allow vertical translations, rolling, and pitching of the FOTV but no breaking of contact. This will have consequences for the tower design as not only pushing forces but also pulling forces are exerted on the boat landing structure. The advantage of using the existing boat landing is that no extra structure has to be added to the WTGs. A possible downside of using the existing boat landing is that it is usually located in the same orientation that the walk-to-work equipment of the SOV connects to. This would mean that the FOTV would be between the WTG and SOV during transfer. Most walk-to-work gangways are between 20m and 30m with some reaching 32m. This length must cover part of the SOV, a safety margin between SOV and FOTV. So depending on the length of the FOTV and the safety margin this design will require additional structures for the WTGs. After a troubleshoot run the FOTV would moor at the next WTG the SOV intends to visit. There the crew and technicians of the FOTV transfer back to the SOV when the planned maintenance technicians step over. This is also where the SOV will need to return to when the next FOTV operation is carried out.

The time needed to access the FOTV is dependent on how often the FOTV is used and how far the SOV travels between two FOTV operations. If the interval becomes too large at some point, the SOV will have to pick up the FOTV to move it closer to the future operational area of the SOV. The safety is the same as that of a normal transfer as the walk-to-work equipment always has higher limits. Logistically the configurations are expected to be feasible, the SOV has time to make the relatively short trips to a WTG. The technical feasibility of the mooring system itself is again questionable. The loads over time might be too much for the mooring system. On the other hand, the mooring system of a single WTG only has to operate for a couple of days a year as the FOTV rotates through the wind park.

Moored to one of a set of designated mooring platforms Similar to single buoy mooring for oil tankers, larger buoys are placed that function as transfer hubs. One side of the buoy will attach to the FOTV and the other side will allow a connection with the SOV. A device will be installed on the buoy that can maintain the orientation of the SOV landing when the SOV makes its approach. During transfer between the SOV and the buoy, the connection is maintained by pushing the buoy out of its rest position with the SOV and using the underwater design of the buoy and SOV hull. The mooring system between the FOTV and buoy allows pitching and rolling but no yaw The buoys will be located at several central locations in the wind farm to minimize travel time from SOV but also minimize the number of buoys.

The time spent to reach the FOTV from the SOV will depend on the number of buoys located in the wind farm. But it will be longer than the previous two designs. The safety of this design is comparable to that of the transfer to the WTG. It's expected to be better because the relative motions between the buoy and the other two vessels are smaller than that of the relative motions between the FOTV and a WTG boat landing. These expectations come from the design of the buoy and not from assumptions of synchronous motions of two floating objects, these will move out of phase when not connected. Because there are no restrictions to the position or orientation of the FOTV while moored, the mooring system doesn't need to restrict any movement except keeping the FOTV connected to the buoy. The technical feasibility is higher than in the previous two designs. The expected wear and tear on the mooring system, buoy, and FOTV are lower than for the previous two designs.

Moored to an offshore hub in the center of wind farm The central hub is the most ambitious of all three as it intends to create a hub where the crew and technicians can stay for weeks. This will require building a housing facility and a way to dock or moor the FOTV. This design would also allow the elimination of the SOV and perform both planned and unplanned maintenance with a number of FOTVs.

5.4.3 First selection of design configurations

A set of design configurations is selected from the two principal concepts. Two configurations for the enlarged daughter craft concepts and four configurations for the exposed concepts.

1. Enlarged daughter craft concept: Lifting launch
2. Enlarged daughter craft concept: stern ramp launch
3. Exposed concept: Connected to SOV boat landing
4. Exposed concept: Moored to a WTG
5. Exposed concept: Moored to a designated platform
6. Exposed concept: Moored to an offshore hub

Before a more thorough assessment is done on the configurations, a selection is done to eliminate the configurations that aren't expected to reach the minimum of safety, performance, and feasibility.

The four exposed concepts are not legal, the IMO International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) chapter viii 17.1 states: 'at no time shall the bridge be left unattended'. Some of the configurations are imaginable to be executed with personnel on board. This is already partially done on wind park Gemini by the CTV Njord Zephyr. This vessel stays in the wind farm, moored to a buoy, for multiple days with crew onboard if the weather allows it. The research of Jelte Bos, section 5.6.2, speaks in favor of configurations that limit the number of different vessels a technician has to stay on. Every new motion frequency that is introduced, lowers the resistance against other frequencies. Each configuration is discussed below and removed from or kept in the selection.

Enlarged daughter craft concept: Lifting launch The Lifting launch configuration poses high potential in terms of technical feasibility. According to large suppliers like Vestdavit, vessels of 60 tons can safely be deployed and they expect to deploy 80 tons in the near future. Safety can be increased by maneuvering the SOV so that the L&R is executed in the lee of the SOV. On the other hand, the static and dynamic stability of the SOV has to be considered when a heavy FOTV and davit are placed at the side. During L&R the vessel is suspended far from the transverse center of gravity.

Enlarged daughter craft concept: stern ramp launch The option to deploy the FOTV differs from Lifting launch in a few ways. stern ramp launch can be executed at a higher speed than a Lifting launch and doesn't introduce transverse stability challenges. L&R operations during transit could occasionally save time and make the SOV more flexible but aren't expected to yield high improvements. The transverse stability challenges can be overcome but not without cost, so in theory, the stability aspect would make the stern ramp launch configurations more attractive financially. But because the stern ramp launch system requires rearrangement of the engine room and propulsion line, this financial improvement doesn't hold in the bigger picture. Moreover, the capacity of the stern ramp launch now and in the near future is significantly lower than that of the Lifting launch configuration. Therefore this configuration is removed from the selection.

Exposed concept: Connected to SOV boat landing The advantages of this configuration are that it doesn't require space on the SOV but still is so close to the SOV. This way the deployment is expected to be relatively fast and the FOTV can be monitored from the SOV. Under current international law, the FOTV may not be left unattended. This implies that a crew should remain onboard while Connected to the SOV boat landing. The disadvantage of the system is that it hinders the operation of the SOV in transit. The advantages of being close to the SOV diminish comparatively when other exposed configurations also are manned during mooring. By using some of the more novel connection techniques, a gripper system, this configuration is expected to operate well. The FOTV could disconnect during SOV transit and is expected to be in operation most of the time that the SOV is in transit.

Exposed concept: Moored to a WTG The second exposed configuration uses existing infrastructure and benefits from the walk-to-work equipment installed on the SOV. The configuration is deemed feasible on its own at this stage. But in comparison with the other concepts, it seems to fall short. In comparison to the previous configuration, the FOTV will be a bit further from the SOV and the deployment is expected to be longer. On the other hand, it might interfere with the current operations by being connected to the SOV while the next configuration can be placed in a convenient area. Consequently, this option isn't expected to outperform all other configurations and is therefore discarded.

Exposed concept: Moored to designated platform The advantage of this configuration is that the mooring system is relatively simple and known. The location of the mooring can be decided to minimize transit distance and time. The disadvantage is that new infrastructure has to be built for this configuration instead of using existing mooring points like WTGs. The configuration is expected to perform above the basic expectation and therefore remains in the selections.

Exposed concept: Moored to offshore hub The last exposed configuration is the most ambitious one. The safety improvements are expected to be high but so are the cost connected to this configuration. If this configuration is executed, it's expected to combine multiple functions to this hub. The electrical transformation, housing, and mooring of these FOTVs might be combined on a single platform. Although this research deems this option viable, it is discarded because the content of the platform is out of scope. Alternatively, a pilot vessel like the Wandelaar could be deployed and used as a floating offshore hub. This doesn't offer the same weather limits as a bottom-founded offshore hub but might improve operability.

Candidate selection

1. Enlarged daughter craft concept: Lifting launch
2. Enlarged daughter craft concept: stern ramp launch
   - Discarded because of inferior weight capabilities compared to lifting launch.
3. Exposed concept: Connected to SOV boat landing
4. Exposed concept: Moored to a WTG
   - Discarded because of inferior logistics to moored to SOV and moored to a designated platform.
5. Exposed concept: Moored to a designated platform
6. Exposed concept: Moored to an offshore hub
   - Discarded because the content is out of scope.

5.5 Candidate concepts description

In this section, the three candidate concepts are described in more detail. The physical and operational side of each concept is described before its merits are further assessed. The schedule for the SOV differs for each wind farm. For this research, it's first assumed that the SOV is in operation for the whole year. Later the effects of wind farm size and SOV occupancy are filtered in.

5.5.1 Lifting launch

The first concept, the lifting launch, differs the least from the current system. A davit will be used for L&R operations, only the capacity of the davit and deck are increased to carry the FOTV. The general layout of the configuration is shown in figure 5.15.

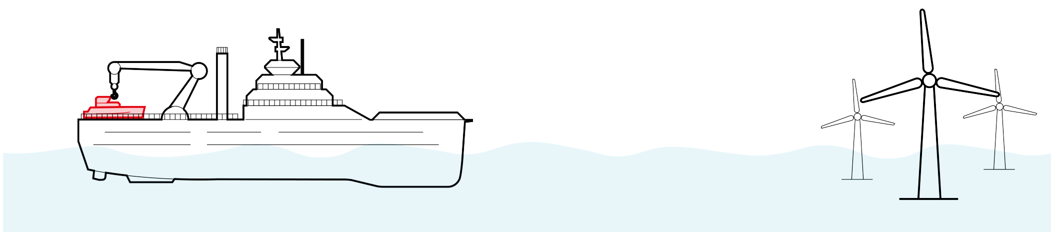

Figure 5.15: Configuration layout: Lifting launch

Physical concept description The location of the davit will either be on the port side or starboard of the SOV. This will be influenced by the preferences of the walk2work equipment. The davit will be placed as close to longitudinal midships as possible to decrease the effect of pitch motions on the L&R operation. There are currently no systems capable enough for the FOTV size and weight aimed for. But davit suppliers do deem it feasible. An engineering team of Vestdavit proposed explained that this is feasible but does not yet exist.

Operational concept description There is no crew shift needed for this concept. Similar to current practice with the DC, a crew is on standby during operating hours and sleeps during the night. When a call for unplanned maintenance is made, the weather is assessed for safe deployment. When a weather window is found based on the Hs limit and maximum wind speed, the equipment and crew are assembled and the FOTV is deployed. Before deployment, the vessel is oriented with the launch area in the lee of the SOV. If the Hs or wind speed limits are expected to be exceeded or the operation is finished, the FOTV returns to the SOV. The FOTV can also be used for equipment runs, crew changes of the SOV, or assistance in rescue missions. Resupply of fuel, freshwater, and disposal of black water is conducted at the end of the day with tanks stored on the SOV.

5.5.2 Connected to SOV boat landing

The second candidate concept has similar benefits as the first when it comes to interfaces with the SOV but still differs in both Physical and operational layout. The general layout of the configuration is shown in figure 5.16.

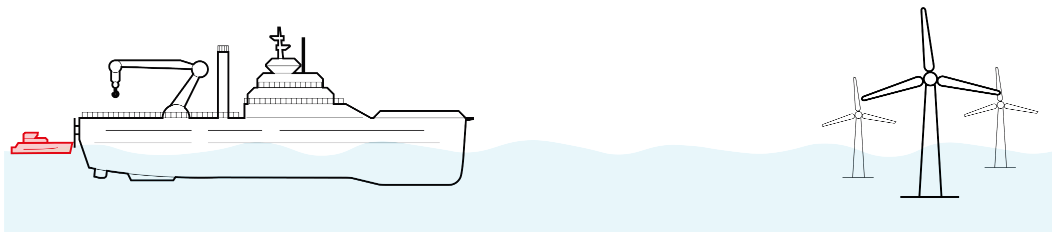

Figure 5.16: Configuration layout: Connected to the SOV boat landing

Physical concept description The SOV will be equipped with one or two boat landings. One at the stern and possibly one at one of the sides. In figure 5.17 a vessel with both boat landing positions is shown.

Figure 5.17: SOV with boat landing installed at the stern and starboard [Maritime, 2019]

The side placement will allow a more significant lee and there is more flexibility in the location. But the SOV can't transit with a FOTV connected to the side because of the large submerged area of the FOTV perpendicular to the direction of the SOV. If the SOV would accelerate with the SOV connected to one side, this would make the FOTV rotate in the direction of the stern of the SOV and both vessels will collide. Additionally, the direction of the SOV would be influenced and the resistance would be higher. Finally, the FOTV is not designed to have water flowing from the side of the vessel, it might heavily roll or capsize at higher SOV speed. If the SOV would accelerate forward while the FOTV is connected to the stern of the SOV, the strain on the connection would increase and the connection should be designed for this situation. But the FOTV is not expected to make unwanted motions or collide with the SOV. This provides the SOV with more freedom and therefore safety in comparison with the side boat landing. The SOV can also rotate and transit in DP mode, only full reverse is prohibited when the FOTV is connected to the stern.

The boat landings can be made retractable like the 'automatic boat landing system' from Kenc []. The advantages decrease when the FOTV is connected to the boat landing most of the time. Also, the system is not designed with the gripper system in mind, so it's only usable for push-on operation. The stern boat landing won't be made retractable but it could be an option for the side boat landing.

The SOV will also be equipped with a crane to lift cargo to and from the FOTV. The cargo operations are expected to be better when performed in the lee of a ship located at the side of the vessel. This would imply that the second boat landing is equipped and that cargo isn't transferred at the stern of the vessel.

The FOTV will be equipped with a gripper system like the Mobimar system previously described. This system will allow the vessel to stay connected to the SOV boat landing without using the propulsion system.

Operational concept description The crew operations of this candidate concept also works with one day shift and has the same limits dependent on the FOTV itself. What is different from the previous concept is the L&R operation. For a single boat landing system, the technicians will transfer at the stern. During transfer, the gripper system of the FOTV is put in grip mode, obstructing relative vertical motion between the boat landing and the bow of the FOTV. This is the basic procedure unless the SOV has a second boat landing at one of the sides and heavy equipment needs to be transferred. In this case, the crew will transfer at the stern, disconnect and connect again at the side of the SOV. Here the technicians board and the cargo is transferred by crane. During this operation the FOTV is in the lee of the SOV and grip mode is activated. Once the operation of the FOTV is concluded and both technicians are safe on the SOV, the gripper system of the FOTV is put into sliding mode remotely, to allow relative vertical motion. The resupply of fuel and consumables of the FOTV will be executed when it's connected to the stern. Here a set of hoses and pumps will be installed to transfer fuel, fresh water, and black water.

5.5.3 Moored to designated platform

The last candidate concept requires the most description because it differs the most from the predecessor system. Both in physical layout and operation, this concept offers new opportunities and challenges. The general layout of the configuration is shown in figure 5.18.

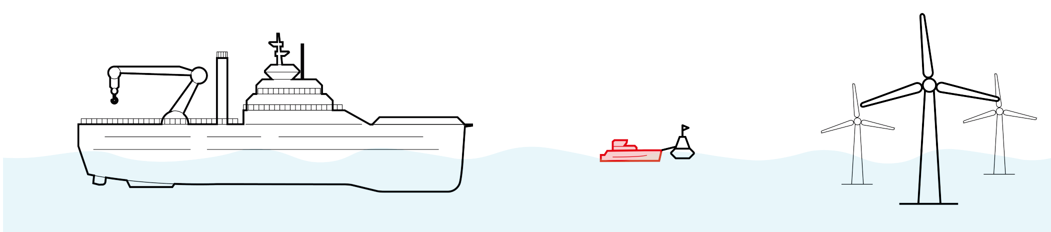

Figure 5.18: Configuration layout: Moored to a designated platform

Physical concept description The SOV is equipped with a boat landing at one of its sides. This way the FOTV can pick up technicians and equipment. The boat landing in this configuration can benefit from being retractable. The SOV will also need to be equipped with a crane for cargo transfer and tanks and hoses to resupply the FOTV.

The FOTV is equipped with a regular bow fender. The vessel is moored to a buoy in the center of the wind park when it's not in operation. The connection between Buoy and FOTV is just a double mooring line. Because both buoy and vessel will pivot in the dominating direction of the combination of wind, swell, and, current, there won't be any significant impact between buoy and FOTV. The mooring arrangement of the buoy must be designed to withstand the drifting wave load of both FOTV and Buoy combined.

Alternatively, if the propulsion of the FOTV is electric and the energy storage is in the form of batteries, the batteries could be charged directly from the wind farm.

Operational concept description In contrast to the other two candidate concepts, this concept uses two crew shifts per day. The shifts are 12 hours and the off-duty crew is on the SOV. So there is always a crew on board when the FOTV is in the wind farm. Twice per day, the FOTV must connect to the SOV to switch the crew. If within a two-hour range around the regular time of switching there is no suitable weather window to switch, the FOTV will return to port so the on-duty crew can rest. The next day, if the weather allows switching of the crew, the FOTV will return to the wind farm.

The connection to the buoy is done by positioning the bow of the vessel close to the buoy so that crew on deck can connect the lines to the buoy using a hook on a pole.

5.6 Performance characteristics

Following the systems engineering approach, the last step before validating the implementation concepts is deriving the right set of Performance characteristics. This is done in two stages: Performance analysis and effectiveness analysis. During performance analysis, a set of performance parameters is derived that characterizes each candidate concept. Afterward, the effectiveness analysis checks if each candidate meets the operational requirements and if not how it can be adjusted to do so [Kossiakoff et al., 2003].

5.6.1 Performance analysis

Depending on the complexity of the system, the performance characteristics overlap with the earlier defined performance requirements. Like many other systems, this system will base its performance characteristics partly on the performance requirements but more characteristics are added outside of the requirements. The three candidate concepts are:

1. Lifting launch
2. Connected to SOV boat landing
3. Moored to a designated platform

All three of these configurations will be assessed for three different FOTVs. The performance characteristics will reflect the accessibility performance, the logistic advantage or disadvantage, and finally the economic performance of the candidate concepts.

Accessibility performance The performance characteristic most linked to the performance requirements is also the most critical characteristic. Where the performance requirements go into the exact chance of certain vessel movements, the performance requirements limits the accuracy to experience. The significant wave height limit defined by the user of the vessel is taken as a base for accessibility. But this parameter only provides information on the FOTV. The weather condition and specific configurations also have an effect on accessibility. All three configurations have different logistics connected to their operations. For the lifting launch, if the L&R limit is higher than the transfer limit, the vessel can be deployed at any time there is a weather window. For the other two configurations, the FOTV crews must be able to switch the night- and day shifts with the SOV. This means that at specific moments during the day, a weather window is required. Otherwise, the FOTV transits back to port. This hinders the accessibility the next day as the FOTV has to return to the wind farm. These logistic limits, combined with the hindcast data of a specific wind farm and the Hs limit of the vessel will result in a percentage operability parameter which is used as a performance characteristic.

Logistic performance Each configuration differs in terms of the time required to deploy and recover from an unplanned maintenance mission. The Lifting launch will require the assembly of the technicians and equipment and the launching of the FOTV in the water. If the FOTV is connected to the SOV boat landing the 'launch time' is reduced for example. Finally, when the FOTV is moored to a buoy, the technicians and crew will have to be picked up from the SOV before the operation can start. The average time difference between the configurations will be used as a performance characteristic.

Economic performance The final performance characteristic covers the economic performance of the configuration. As a vessel user, Siemens Gamesa doesn't acquire the vessel but rents it from a vessel owner. The costs involved consist of a day rate and the fuel cost. The day rate includes the use of the vessel, the crew of the vessel, insurance, and maintenance of the vessel. There won't be any investment cost linked to the use of a FOTV. The configurations might require investment costs and operational costs. A complete overview of all costs will be constructed and given as a yearly expense for the next 20 years. A significant uncertainty is the effect of fuel price. This will have to be estimated and kept in mind when assessing the results.

5.6.2 Effectiveness analysis

This analytical check is introduced so no subsystem functions are neglected in the candidate concepts. The operational requirements developed in the work of Brans [Brans, 2021] shown in figure 5.19, are used for this analysis. These objectives were developed for the DC system, as this system aims to replace that very system, and the corresponding requirements must be met. Each primary objective is individually assessed below, secondary objectives of interest are discussed in the paragraphs.

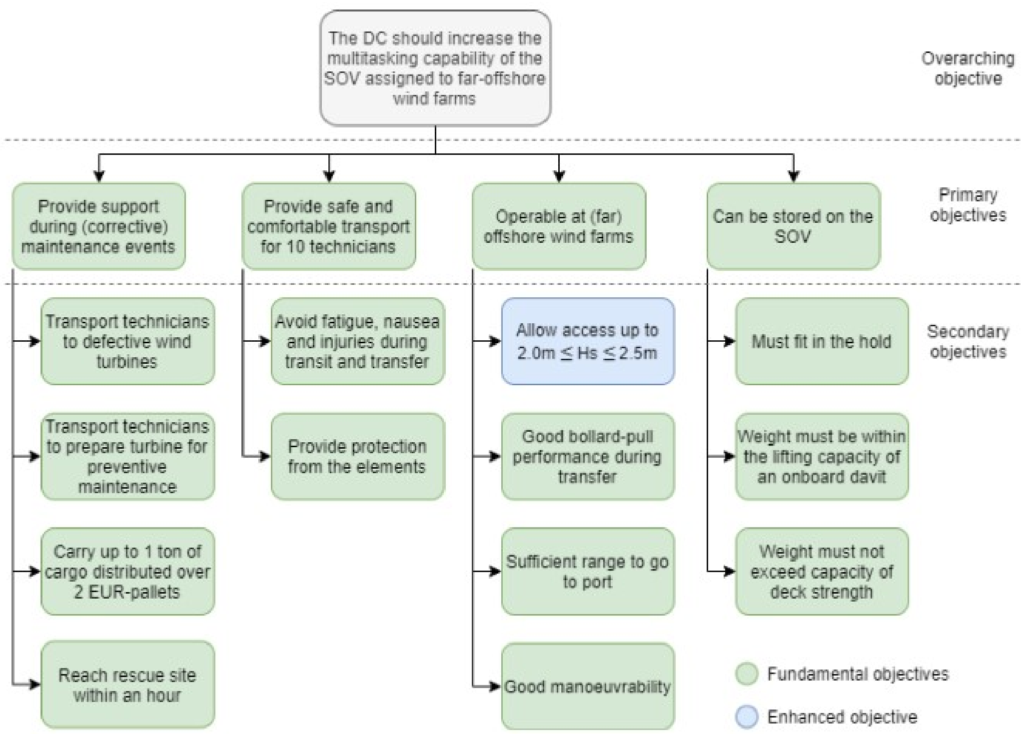

Figure 5.19: Operational requirements of daughter craft [Brans, 2021]

Provide support during (corrective) maintenance events Because the FOTVs will be the same vessels as CTVs, a lot is known about their operation. They have transported technicians to defective WTGs, transported technicians to prepare for preventive maintenance, carried 1 ton of cargo distributed over 2 EUR-pallets, and reached rescue sites within the hour. But most of these operations were close to shore. Because a few CTVs, like the Njord Zephyr, Umoe Firmus, and MSC Boreas, have operated beyond the 65km mark from shore the conclusion is drawn that even far offshore these objectives have been achieved with comparable vessels. When it comes to the effect of the candidate concepts, a closer look is required. The cargo restrictions are met by the crane installment next to the boat landing for the exposed concepts. The last secondary objective does imply that the speed of the FOTV must be enough to reach any technician in the wind park within an hour minus the time to deploy. This last restriction is most critical for the lifting launch as this concept has the longest deployment time.

Provide safe and comfortable transport for 10 technicians This requirement is hard to predict as has been shown in section 4.4. But what is for certain is that the acceleration on average is reduced for these larger vessels. In an interview with Jelte Bos summarized in appendix A, a motion sickness researcher at TNO, he pointed out two major factors for sea sickness:

1. Avoid motions with a frequency around 0,16 Hz.

2. People get used to a motion behavior, but this is disturbed if the behavior changes.

The first factor must be assessed for each SOV, FOTV, and WTG in every wind farm. The second factor gives insight into the difference in experience between the crew and technicians. Where the crew only alternates between SOV and FOTV and stay on this vessel for a longer duration, the technicians also enter the WTG with its own motions behavior and switch places more often than the crew. The FOTV is expected to result in less motion sickness than the DC but is not likely to eliminate it.

Operable at (far) offshore wind farms According to vessel users and owners, the Hs limit of 2.0m to 2.5m is not realistic with current CTVs. Multiple shipbuilders do claim similar performance but have not steadily proven these performances yet. The system improvement is taking the Hs limit from 0.9-1.2 to 1.5-1.8, this is expected to improve with better vessel design and improved prediction methods. The bollard-push performance is significantly better for FOTVs than that of DCs, although some concepts won't require this as the gripper will replace that requirement. The range to go to the port should always be preserved as the FOTV is expected to go back to port without the assistance of the SOV when the weather turns bad. Although the SOV is always close with fuel stores and has the ability to resupply the FOTV, autonomy is required to ensure safety. Finally, maneuverability is most critical during the approach of the boat landing. The vessel has been designed for this purpose and maneuverability has rarely been pointed out as lacking or reason to abort the transfer.

Can be stored on the SOV This objective only applies to the lifting launch as the other candidates won't require the FOTV to be stored on the SOV. The last two secondary objectives hold true and will be checked in each individual case.

5.7 Vessel selection

For all three configurations, a set of existing vessels is used. For each vessel a few criteria have to be met, which are listed below:

1. The day rate is known.
2. The fuel consumption, distance traveled and transfers made to WTGs is known for at least one year.
3. The performance limits in Hs are confirmed by both a user and supplier or owner of the vessel. This way the performance isn't artificially increased for marketing reasons.
4. The transfer performance is higher than 1,2m Hs.

These criteria were met by three vessels. To compare their performance to the status quo, a DC was chosen. Because of the sensitivity of the corporate data, after collection of the real data, the data is modified. The vessel data in this report is dummy data that is within realistic ranges and has a realistic distribution. The four vessels with their performances are listed below:

1. FOTV 1 - MCS Boreas - Twin axe bow
    - Loa: 25,75 [m]
    - Transfer limit: 1,50 [m]
    - Day rate: €3200
    - Fuel consumption a: 45 [l/nm]
    - Fuel consumption b: 15 [l/#]

Figure 5.20: MCS Boreas [Fleetmon, 2022]

2. FOTV 2 - Njord Zephyr - Z-bow
    - Loa: 27,0 [m]
    - Transfer limit: 1,60 [m]
    - Day rate: €4000
    - Fuel consumption a: 62 [l/nm]
    - Fuel consumption b: 18 [l/#]

Figure 5.21: Njord Zephyr [Njord offshore, 2022]

3. FOTV 3 - Umoe Firmus - surface effect ship
    - Loa: 25,6 [m]
    - Transfer limit: 1,75 [m]
    - Day rate: €4800
    - Fuel consumption a: 80 [l/nm]
    - Fuel consumption b: 25 [l/#]

Figure 5.22: Umoe Firmus [4offshore, 2022b]

4. DC - Allusafe 1150
    - Loa: 11,5 [m]
    - Transfer limit: 1,0 [m]
    - Day rate: €500
    - Fuel consumption a: 10 [l/nm]
    - Fuel consumption b: 6 [l/#]

Figure 5.23: Alusafe 1150 daughter craft [Maritime partner, 2022]

5.7.1 Fuel consumption

The fuel consumption of each vessel is seen as a function, see function 5.1, of the number of miles and the number of transfers made. The data of one operational year for the Njord Zephyr was used in a linear regression to obtain the dependency on miles and transfers. The R^2 value of the regression was 0,92 and so the outcome has a reasonable error. The data on the other vessels was deemed unreliable and so the fuel consumption is scaled based on the transfer limit. This is not physically correct but does allow for an interesting test case, where cost and performance increase simultaneously.

$$F_{fuelconsumption}(x, y) = ax + by \tag{5.1}$$

With:

x	- number of miles
y	- number of transfers to WTGs
a	- fuel per transfer to WTG [l/#]
b	- fuel per mile transited [l/nm]

These four vessels are used in the calculation to understand how the outcome changes with different vessel performances and costs. The parameters given for this calculation might not be exact, but they are all realistic values and so the outcomes make sense for real-world application. An important factor for transfer performance is the relative amount of buoyancy around the bow of the vessel. The vertical forces on the bow should be minimized by reducing the amount of forward buoyancy. This is more the case for the Njord Zephyr than for the MCS Boreas, on the other hand, does the axe bow shape improve the comfort during transit by keeping the forward surface piercing area constant during pitching motions. For this calculation, only the transfer performance is used.

5.8 Site selection

The calculation for the three configurations will be done for three different wind farms. This way the difference in impact can be assessed. These wind parks had to pass the following criteria:

1. The wind farm has to be in operation, to ensure the hindcast data for the exact location has been extracted.
2. The wind farm must be far offshore, at least 65 km from shore.
3. The wind farm should have more than 50 WTGs. A smaller wind farm is unlikely to justify the use of an expensive vessel like a FOTV.

The three selected wind farms are Gemini, Hornsea one, and Global Tech one. The wind farm locations are visible in figure 5.24 and the corresponding parameters are shown in table 5.2.

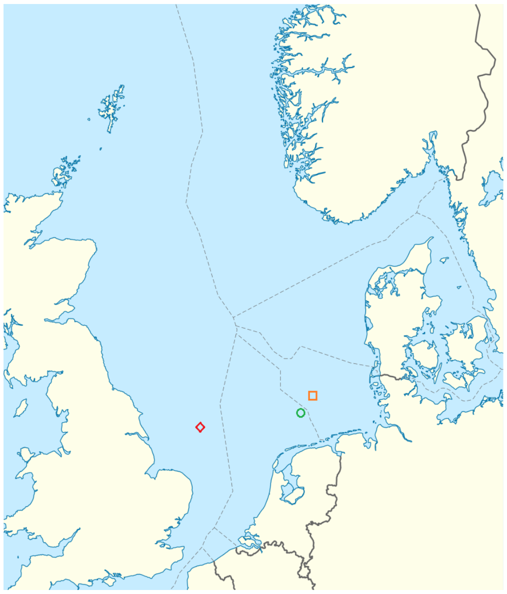

Figure 5.24: Wind farm location. Hornsea one (red diamond), Gemini (green circle), and Global Tech one (orange square)

	Number of WTGs	Distance to port [nm]	Inner-distance [nm]	Power per WTG MW
Gemini	150	48.6	2.9	4
Hornsea one	174	64.9	8.7	7
Global Tech one	80	37.8	2.2	5

Table 5.2: Overview of wind farm parameters

The number of WTGs, distance to port, and power per WTG of the three wind farms were provided by Siemens Gamesa. The inner-distance, average distance from central point in the wind farm to each WTG, was found using the wind farm layouts and area, both also supplied by Siemens Gamesa.

6 | Performance requirements validation

The fourth and final step of concept exploration is performance requirements validation. In this step, the performance characteristics integration is further developed in order to combine all performance characteristics into concrete results. These results will determine the ranking between the candidate configurations. This assessment is done by calculating the three main performance groups: Accessibility performance, logistic performance, and economic performance. These calculations are discussed in sections 6.2, 6.3, and 6.4 respectively. First, the data set is explained in section 6.1. All calculations are done in the Matlab environment. The results are discussed later in chapter 7.

6.1 Input data

There are three forms of input data. First the hindcast data, further explained below. Secondly the wind farm and vessel parameters, explained in 5.8 and 5.7. Finally the individual paremeters shown in figure 6.1.

6.1.1 Hindcast data

For each of the three wind farms, the hindcast data of the last 21 years is used. The first data point is 01/01/00 at 00:00 and the last data point is 31/12/20 at 23:00. Three different sets of data are used, each one specific to one wind park. The hindcast significant wave height data is not very accurate on single data points according to experience within Siemens Gamesa, appendix A. However, the averages over longer periods of time are more accurate. Therefore all predictions based on the hindcast data will use the entire 21 years of data to improve accuracy. When using the hindcast data to evaluate a certain weather window, a column is used that displays in each cell n, the maximum value of [n, n+1, ..., n + win], where 'win' is the window length in hours.

6.1.2 Other input

The individual parameters have varying origins. The shift times and length are examples of parameters taken from the current practice at example wind farms. 'hour' and 'stop_perc' are both used as a stop for the statistical method. Although the 'hour' limit is never reached, the syntax required a limit. Furthermore the parameters that are expected to vary over time are inputted: configuration limits, fuel prices, amount of transfers, operational rating and energy price. These parameters are further evaluated in the sensitivity study in section 7.8. Finally the minimum amount of port calls is inputted in case the weather isn't the most limiting factor but logistics are.

```
%% ---Parameters---

Start_shift =           7;                          % starting time of operations
End_shift =             17;                         % time after which no operation can be executed
win =                   4;                          % maximum time window

hour =                  2000;                       % maximum amount of hours - Statistic method
stop_perc =             0.99;                       % percentage the iteration stops at - Statistic method

config_limit_l =        4;                          % maximum significant wave height for SOV to stay in wind farm
config_limit_c =        2;                          % maximum significant wave height for the FOTV to stay connected to the SOV
config_limit_m =        2;                          % maximum significant wave height for the FOTV to stay moored to the buoy

fuel_price =            890;                        % fuel price [€/ton]
fuel_price_l =          fuel_price * 0.84 / 1000;   % transform to liter price [€/liter]
CTV_transfers =         6.54;                       % yearly amount of WTG transfers of example CTV per WTG
unplanned_perc =        0.7;                        % percentage of transfers for unplanned maintenance
Energy_price =          0.07;                       % energy selling price [€/kWh]
Operational_rating =    0.65;                       % average output per turbine [%]
Minimum_port_calls =    2;                          % minimum amount of part calls per month

Months =                transpose(1:12);            % set up an array for the amount of months
H_s_data =              H_s_data_combined(:,win);   % match data set to window length
```

Figure 6.1: Input parameters Matlab

6.2 Accessibility performance

This research finds three main approaches to calculating the accessibility: A statistical approach, a direct historical approach, and a simulation approach. The statistical approach can operate with fewer input values and is a less expensive and elaborate model. The simulation approach on the other hand has the capability to give more specific results and allows to study the distribution of occurrence instead of only the averages. The direct historical approach is an expensive model that does allow for accurate results and the study of result distribution. For the current research, a statistical approach is tried first and compared to the results of the simulation. Afterward the direct historical approach is assessed as an alternative and also compared with the simulation. Siemens Gamesa already had built a statistical approach and was in the process of developing the simulation approach parallel to this research, appendix A.

The model description is supported by flowcharts to visualize the Matlab model. In figure 6.2, the first flowchart is shown, an overview of all calculations. Each part of this overview will be discussed in this section, moving from top to bottom, starting with the accessibility performance and concluding with the economic performance.

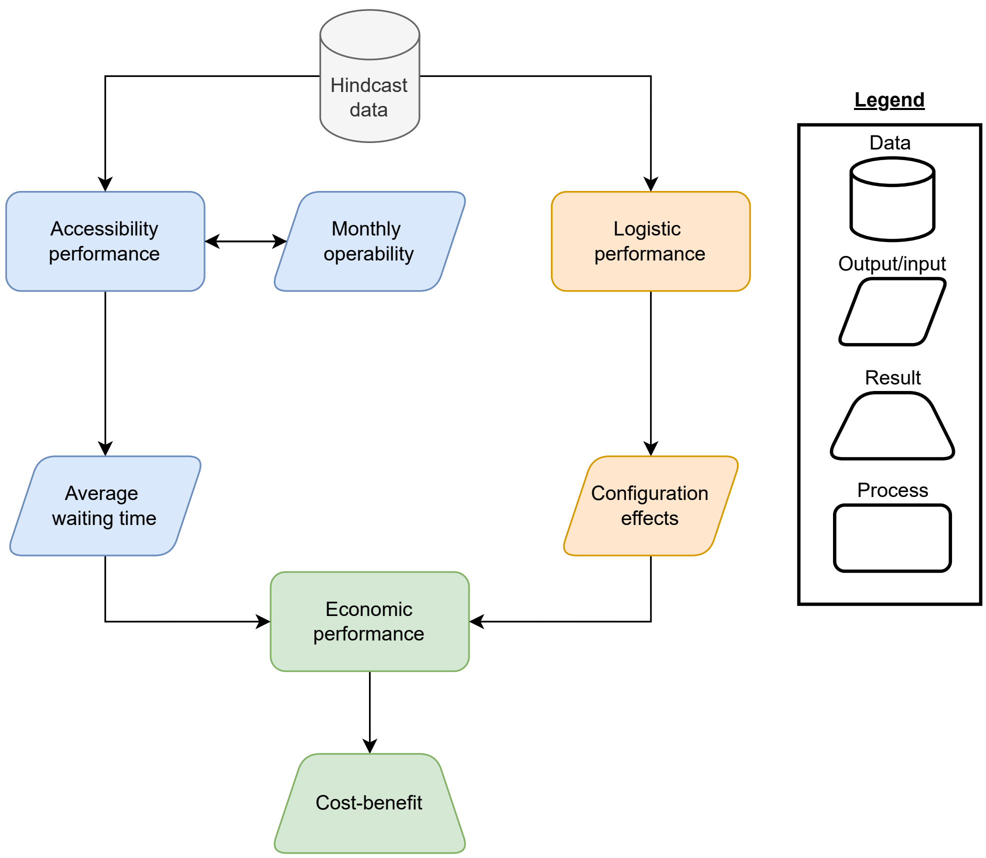

Figure 6.2: Model overview

6.2.1 Statistical approach: Monthly operability

The goal of this part of the calculation is to first find the average operability specific to each weather window length, location, and vessel limit per month. Secondly, this operability is used to calculate the average waiting time. In figure 6.3 the calculation flowchart for monthly operability is displayed. Compared to the existing statistical model of Siemens Gamesa, a few expansions were made and the level of detail was increased. Instead of assessing only each day for accessibility, the statistical model of this research assesses time segments with a length of one weather window. This weather window can be altered from one to five hours in length.

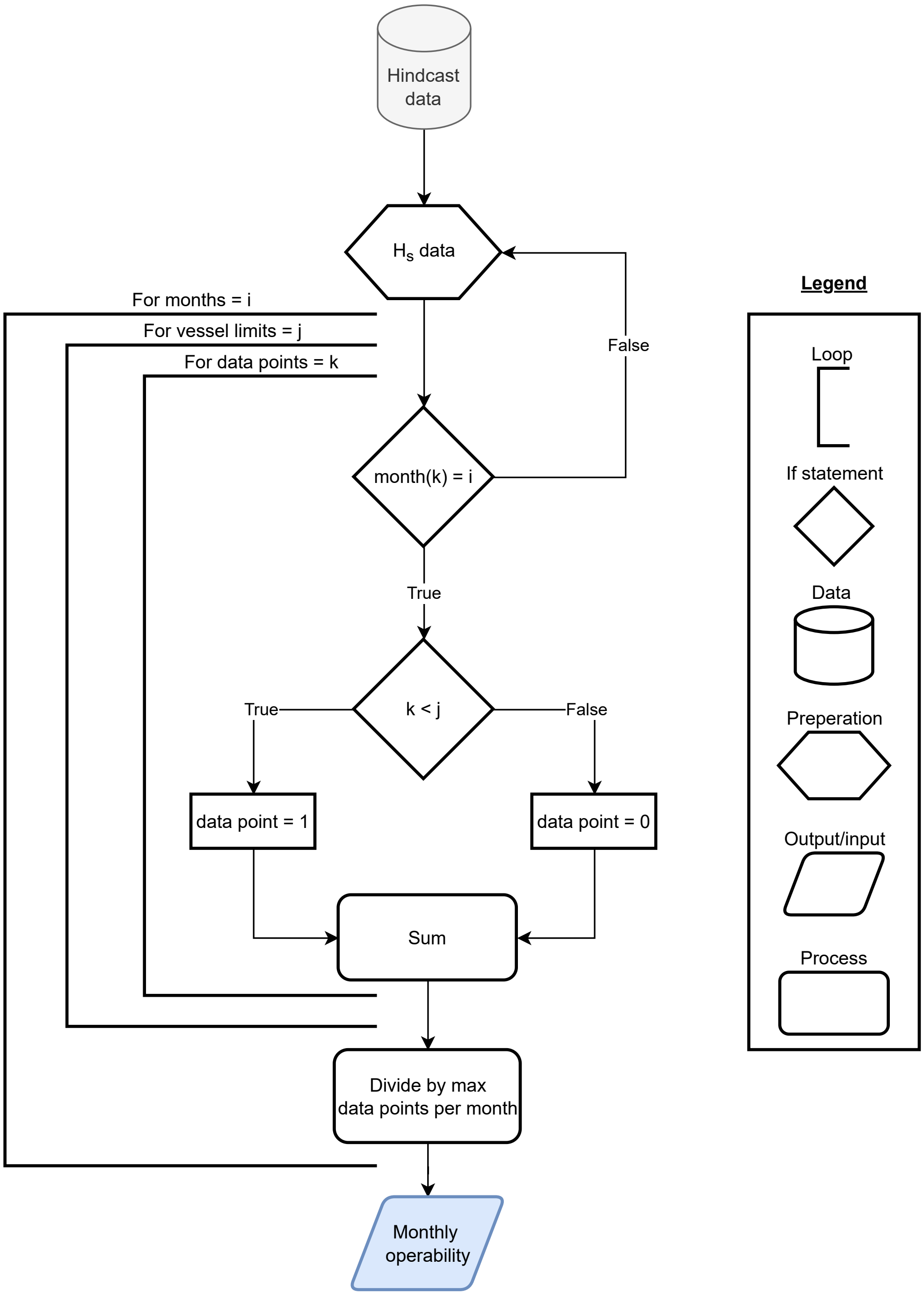

Figure 6.3: Accessibility calculation: Monthly operability

Indices & Sets

i	index for months	$i \in I$
j	index for vessel limits	$j \in J$
k	index for data points	$k \in K$
{1, 2, ..., 12}	set of months	I
{1.5, 1.6, 1.75, 1.0}	set of vessel limits [m]	J
{1, 2, ..., 188448}	set of data points [m]	K

Data preparation

From the hindcast data, the significant wave height data is modified for each weather window length. The corresponding month for each data point is retrieved for the outer loop.

Loops

This calculation is looped over three indices. First, all data points are run through the calculation, each for every hour in the 21 years. Then this calculation is repeated for the set of vessel limits, expressed in significant wave height. Finally, this whole calculation cycle is done twelve times to identify the differences per month.

If-statements

Two if-statements or requirements are present in this calculation. The first one checks if the data point corresponds to the current month, and the second requirement checks if the data point is higher or lower than the current vessel limit.

Processes

When the number of data points below each limit is summed for each month, this sum is divided by the maximum amount of data points for that month.

Monthly operability

This calculation results in twelve matrices, each for every month. Each matrix displays the amount hours that the significant wave height has gone under the vessel limit. By dividing this number by the maximum amount of data points in each month, the monthly operability is found. This operability can be seen as the chance for each hour in a specific month to remain below a specific limit for the length of one weather window.

So for example, in the Global Tech wind farm for the month of December and a vessel transfer limit of 1.5m, the number of hours that are below the limit is 4290 hours. Then the total amount hours in the 21 months of December are counted and summed, resulting in 15624 hours. By dividing the data points below the limit by the maximum amount of data points the operability is found: 27.46%.

6.2.2 Statistical approach: Average waiting time

The operability gives a broad idea of how often it's deemed safe for a specific vessel, month, and location to operate for a certain window length. But it doesn't directly show what this means for the availability of the WTGs. The availability of the WTGs depicts the amount of time the WTG is available for operation. This is influenced by the number of breakdowns the WTG experiences and the amount of time it takes to solve these breakdowns. The latter of these influences is made up of the average time to fix a problem once the technicians are on sight and the time it takes to get the technicians there. This last factor is influenced by the proposed configurations and is called accessibility. To calculate this accessibility the operability has to be transformed into an average amount of waiting time. This is done by the following calculations.

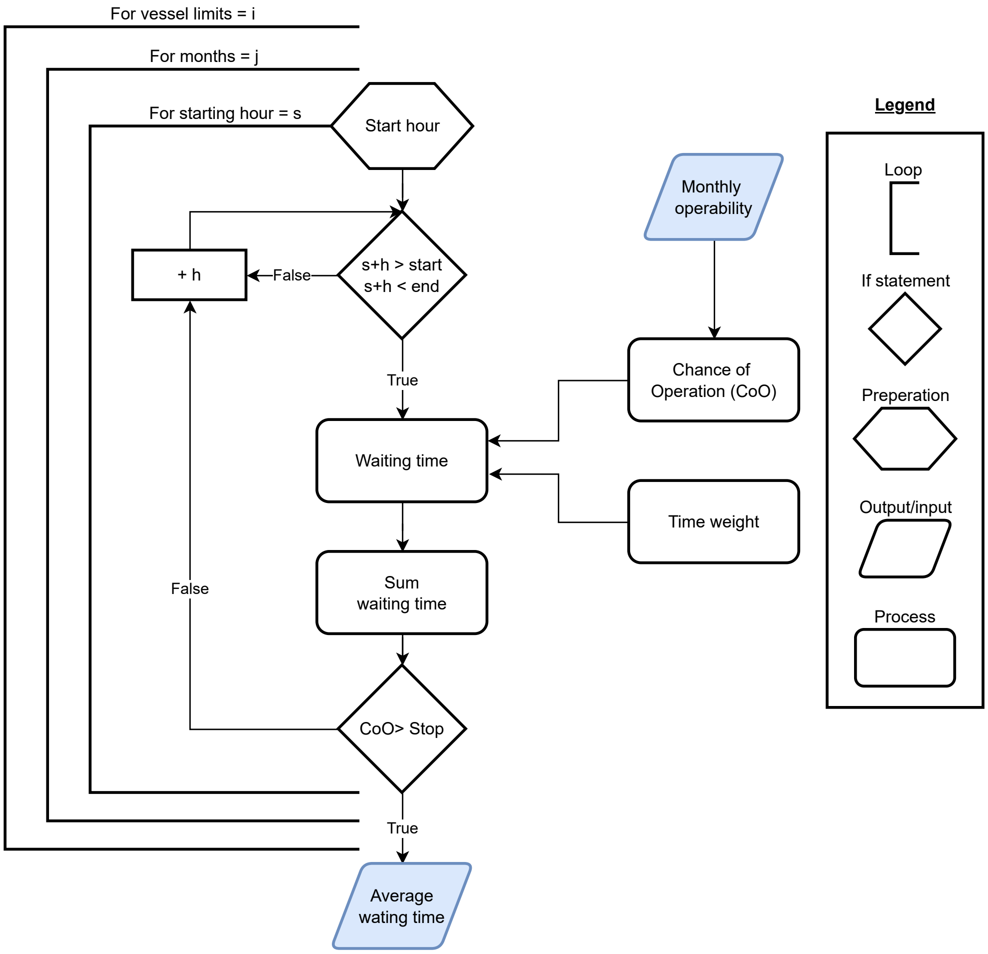

Figure 6.4: Accessibility calculation: Average waiting time

Indices & Sets

i	index for vessel limits	i ∈ I
j	index for months	j ∈ J
s	index for starting hours	s ∈ S
{1.5, 1.6, 1.75, 1.0}	set of vessel limits [m]	I
{1, 2, ..., 12}	set of months	J
{0, 1, ..., 23}	set of starting hours	J

Parameters

$Start_{shift}$	Hour of start day shift	[hours]
End_{shift}	Hour of end day shift	[hours]
h	window length	[hours]
stop	desired stopping percentage	[%]

Loops

This calculation is looped over three indices. First, the calculation is run for every starting hour of the day. This is important because a WTG can break down at any moment, but it can only be fixed within operating hours. Secondly, all calculations are done for every month and every vessel limit.

If-statements

Two if-statements or requirements are present in this calculation. The first requirement checks if the starting hour plus an amount of window lengths is within operating hours. If the requirement is met, the iteration is continued to the first process, this is a successful iteration. If the requirement isn't met, one window length is added to the time and the same requirement is checked again. To be exact, this requirement checks for a certain time if: An operation can be started within a time period of one window length from now, which can be concluded on this day. So when working hours are from 7 to 15 and the window length is 4 hours, the iteration continues for all values from 4 to 13. An operation starting at two in the afternoon for example wouldn't have a full window length to conclude its operation. On the other hand, when a WTG breaks down at 4 in the morning, an operation can be started within one window length so the iteration is continued. The second requirement is developed to stop the iteration for this starting hour when the desired chance of operation is achieved. If a WTG reports an error at 4 in the morning, the first iteration is successful because the operation can be started within 4 hours. The second iteration, one weather window length further in time, is also successful because between 8 and 12 is within operating hours. The third operation is also successful because between 12 and 16 is also within operating hours. The fourth iteration, however, is not successful because four hours from 16 is outside operating hours. Then the fifth(20-24) and sixth(0-4) are also unsuccessful because they are outside of operating hours. But the seventh iteration is successful again, just like the first.

Processes

Four major processes are present in this calculation. In this paragraph, they are explained in chronological order.

Chance of operation The chance of operation is a percentage that increases over each operation within operating hours. In the first successful iteration, the corresponding operability is the percentage. Because the chance that an operation can be performed is exactly that percentage for that month and vessel limit. The next iteration assesses the percentage that is left, so $1-$ chance of operation. This is then multiplied by the operability and the result is added to the previous chance of operation. So this percentage has a diminishing increase for each successful iteration until it exceeds the desired stopping percentage.

For the previous example starting at 4 in the morning with a global operability of 40% this means that at the first iteration the chance of operation is 40%. Then for the second iteration, which is also successful, the 60% of chance left in the previous operation is multiplied by the global operability 40% times 60% is 24%. This percentage is added to the chance of operation of the previous iteration resulting in 40% plus 24% is 64%. For the third iteration, the chance of operation becomes 40% times 36% plus the previous chance of operation which results in 78.4%. For the fourth, fifth, and sixth this percentage stays constant because the iterations are unsuccessful. Then for the seventh iteration, the chance of operation increases again. This process is repeated until the chance of iteration is above the desired amount, which is set at 99%.

Time weight For every successful iteration, a time weight is constructed. This time weight depicts the distance in time between the starting hour and the middle of this iteration. So if the starting hour of this iteration was two in the morning then the time weight of the second successful iteration is the average of eight and twelve, which is ten. The first successful iteration is more complicated in this example. The average between four and eight is six, but no operation can be started at this time. For this edge case, the average of the operational time window is taken. That means the average is between seven and eight which is seven and a half.

For the example of starting at 4 in the morning, the time weight of the first iteration is 3.5 hours. This is the average of the start of the operational time, which is three hours from the starting time, and the end of the first iteration, which is 4 hours from the starting time. The time weight for the second iteration is 6 hours, this is the average between the start and end of the second iteration. The third iteration has a time weight of 10 hours, this is the average between 8 and 12 hours from the starting time.

Waiting time For each successful iteration, the chance of operation and corresponding time weight are multiplied to find the weighted chance of operation. This depicts for each iteration the chance that an operation can be started that amount of time from the starting hour.

For the example of starting at 4 in the morning, the first iteration has a weighted chance of operation of 40% times 3.5 hours which results in 1.4. The second iteration has a weighted chance of operation of 24% times 6 hours which results in 1.44. The third iteration has a weighted chance of operation of 14.4% times 10 which results in 1.44.

Sum waiting time After each successful iteration, the waiting time is added to the previous sum. This is done for every starting hour, month, and vessel limit. The sum is final when the second if-statement is true and the desired chance of operation is reached.

For the example, all weighted chances of operation are summed and the total represents the total weighting time for that starting hour. When combined with all other 23 starting hours, the average waiting time is found.

6.2.3 Direct historical approach: Average waiting time

The alternative of the statistical approach is the direct historical approach. In this model, for every hour in the data set, the time is until the next weather window is found. These values are then collected per month and vessel limit. The averages of these limits are presented as the average monthly waiting time. The flowchart in figure 6.5 gives an overview of the calculation.

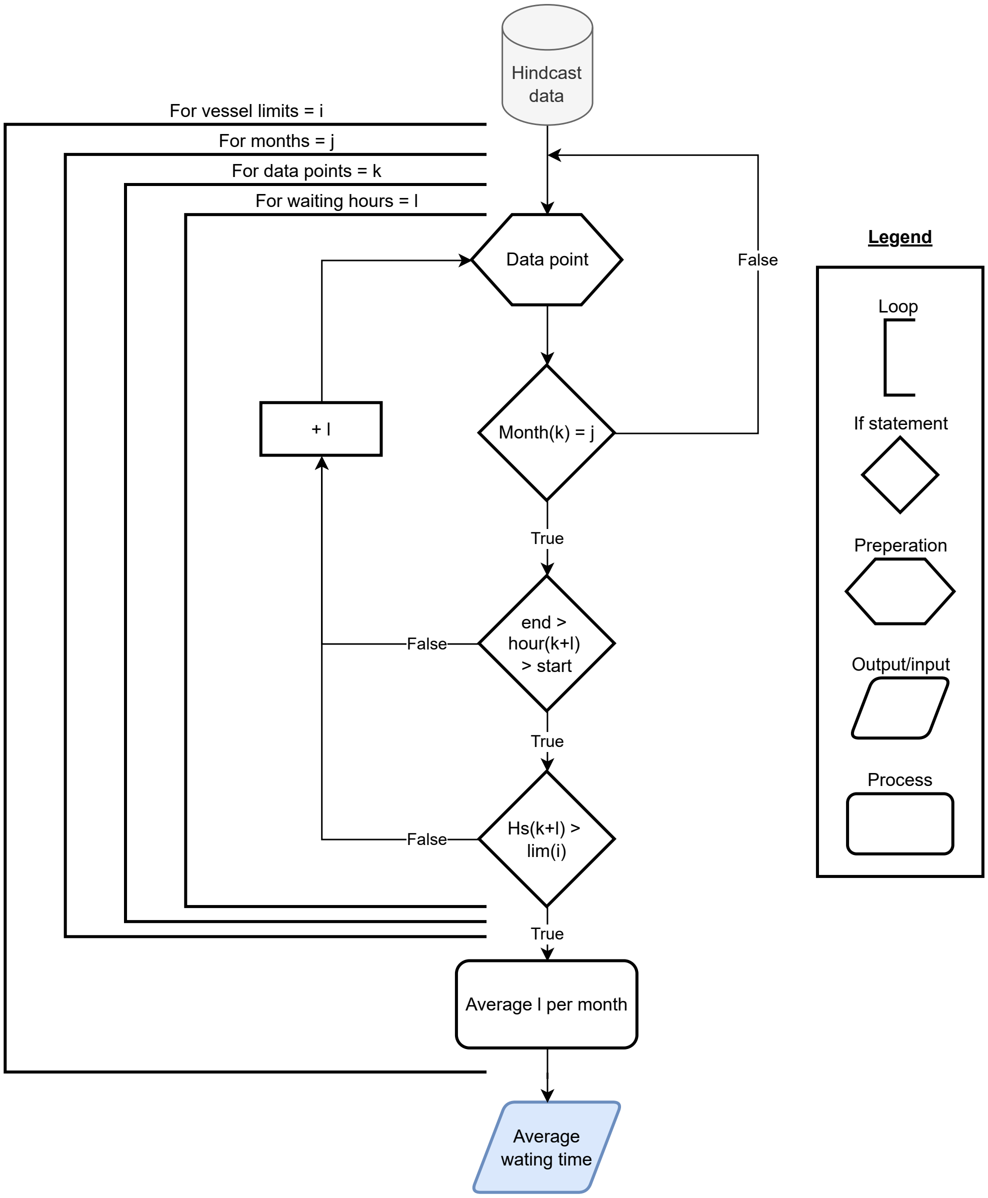

Figure 6.5: Direct historical approach: Average waiting time

Indices & Sets

i	index for vessel limits	$i \in I$
j	index for months	$j \in J$
k	index for data points	$k \in K$
l	index for waiting hours	$l \in L$
$\{1.5, 1.6, 1.75, 1.0\}$	set of vessel limits [m]	I
$\{1, 2, ..., 12\}$	set of months	J
$\{1, 2, ..., 188448\}$	set of data points [m]	K
$\{0, 1, ..., \infty\}$	set of waiting hours	L

Parameters

$Start_{shift}$	Hour of start day shift	[hours]
End_{shift}	Hour of end day shift	[hours]

Loops

This calculation is looped over four indices. First, the calculation is run for every starting data point in the data set. For each data point, the limit is checked for every amount of waiting hours until the first weather window within operation hours is found. Furthermore, the calculations are run per month to assess the difference between them. Finally, the calculation is repeated for all four vessel limits.

6.2.4 Data preparation

For each data point, a number of parameters are retrieved from the hindcast data set. First, the significant wave height, which represents the highest value of the three next values and its own. For each data point, the corresponding month and hour are also retrieved.

If-statements

The first if-statement checks if the data point is in the right month, if not, the data points are skipped until the current month is reached again. The second if-statement checks if the assessed weather window is within operating hours, if not, the waiting time is extended and the next weather window is assessed. Finally, the third if-statement checks if the assessed weather window stays below the required limit.

Processes

The only process is situated at the end of the calculation. The individual waiting times are collected for every month and limit. Then the averages are taken per specific combinations of month and limit.

6.3 Logistic performance

The goal of these calculations is to add the effects of each configuration. Every configuration has different limits concerning its ability to keep the FOTV in the wind farm. For the lifting launch configuration, the FOTV is stored on the SOV so as long as the SOV is safe to stay in the wind farm, the FOTV doesn't have to return to port. For the connected to the SOV configuration, the FOTV is exposed to the elements when connected to the boat landing of the SOV with its gripper. A lower limit is selected for this configuration. The same lower limit is used for the moored to a dedicated platform configuration, but here a second limit is added. Because in this configuration the crew must change twice per day, the weather must allow a transfer to the SOV around this time. So at the start and end of shift, the vessel limits may not be exceeded.

The effects of going back to port are discussed in economic performance.

6.3.1 Logistic performance: Lifting launch & connected to SOV

The lifting launch configuration is only limited by the ability of the SOV to stay in the wind farm. A calculation is run to identify how many days the SOV will have to return to port for a set of SOV limits and specific for each month. The flowchart for this calculation can be found in figure 6.6. For the connected to the SOV the same calculation is done but a lower limit is used. The calculation is very similar to that of the monthly operability only now the number of days instead of the amount of data points or hours are counted.

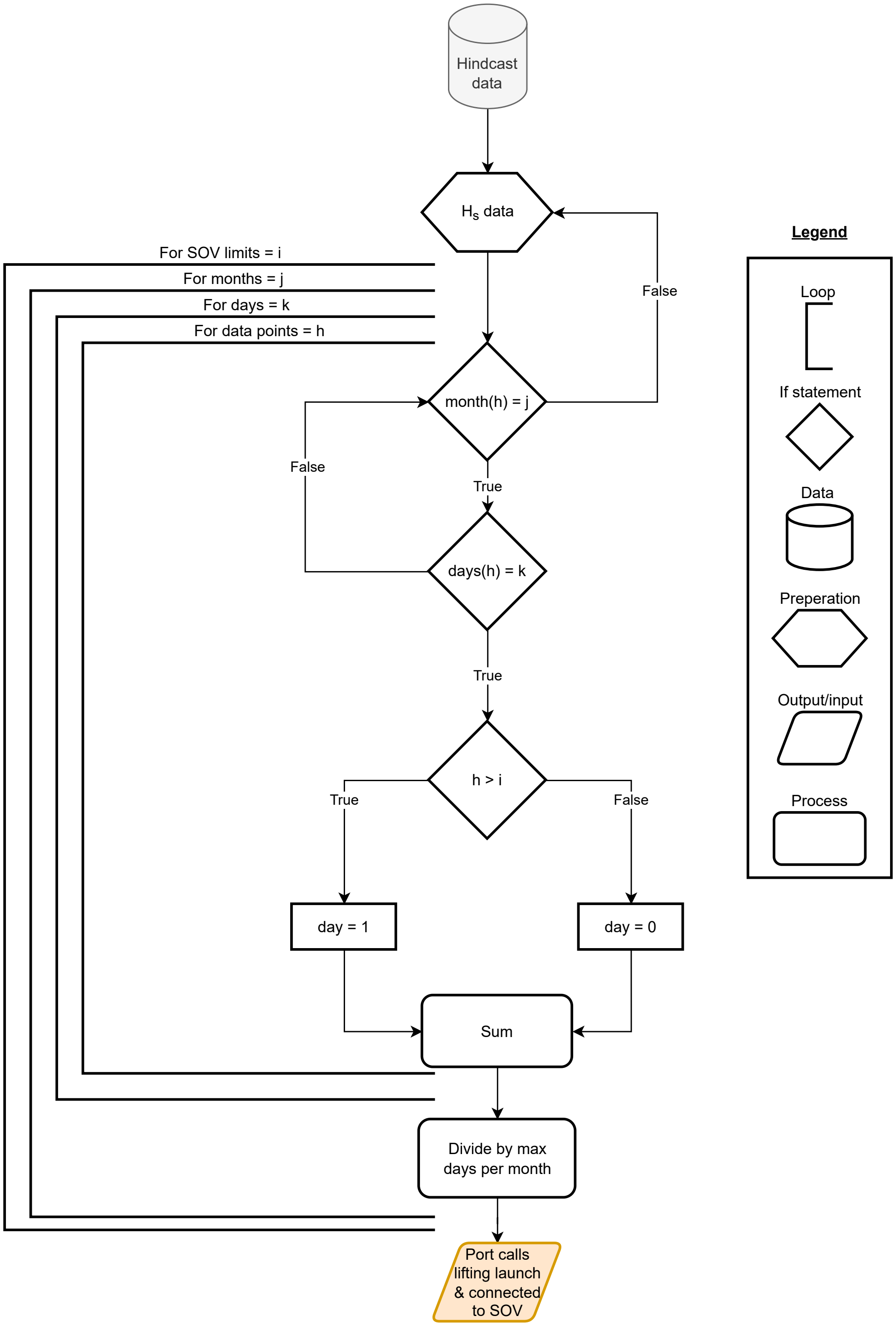

Figure 6.6: Logistic calculation: Lifting launch & connected to SOV

Indices & Sets

i	index for SOV limits	$i \in I$
j	index for months	$j \in J$
k	index for days	$k \in K$
h	index for data points	$h \in H$
$\{2.0, 2.1, ..., 4.0\}$	set of vessel limits [m]	I
$\{1, 2, ..., 12\}$	set of months	J
$\{0, 1, ..., 29/30/31\}$	set of days	K
$\{1, 2, ..., 188448\}$	set of data points [m]	H

6.3.2 Logistic performance: Moored to designated platform

The moored to designated platform configuration needs to meet two requirements to stay in the wind farm. Both requirements are visible in the flowchart in figure 6.7.

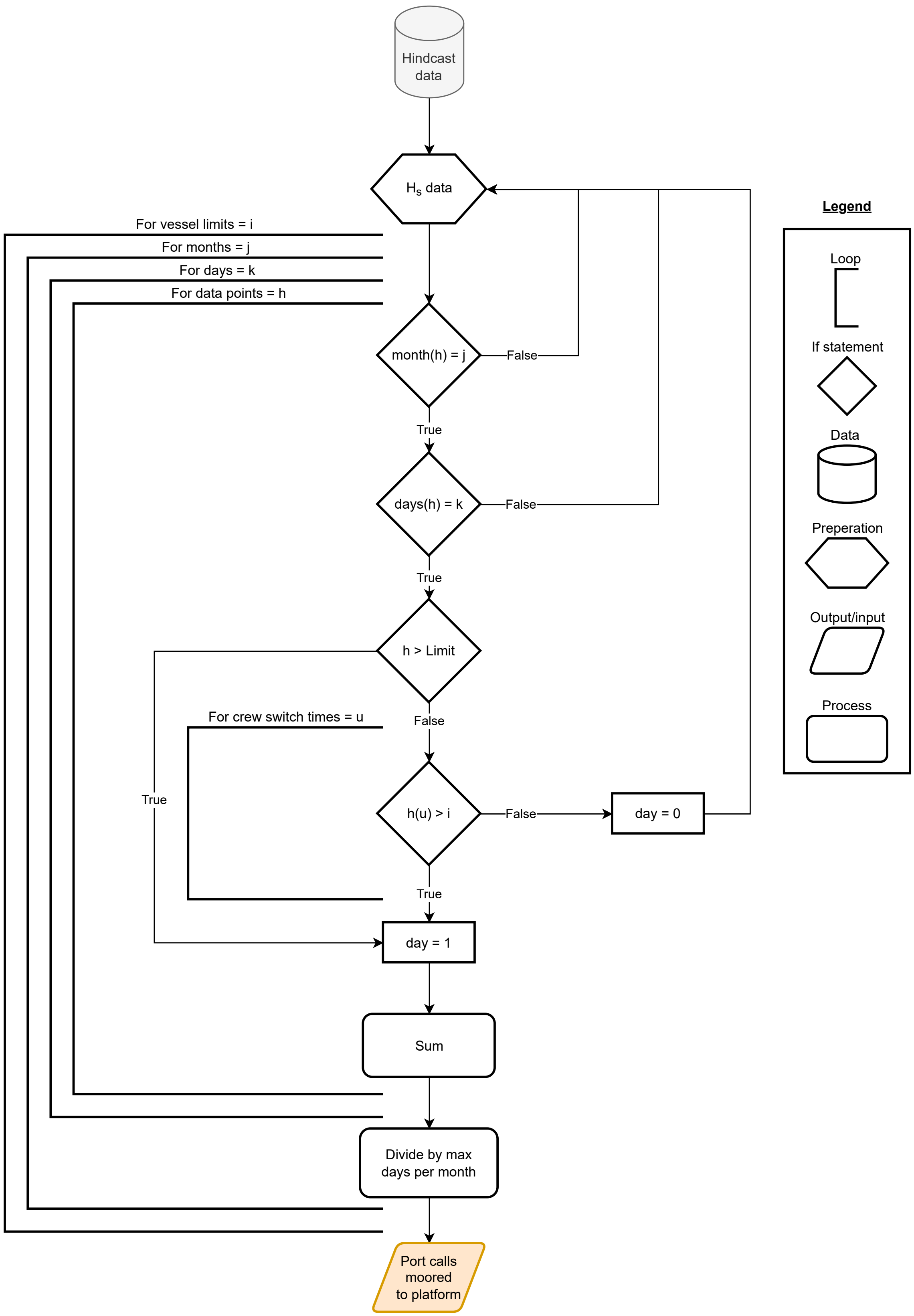

Figure 6.7: Logistic calculation: Moored to designated platform

Indices & Sets

i	index for SOV limits	$i \in I$
j	index for months	$j \in J$
k	index for days	$k \in K$
h	index for data points	$h \in H$
u	index for data points	$u \in U$
{2.0, 2.1, ..., 4.0}	set of vessel limits [m]	I
{1, 2, ..., 12}	set of months	J
{0, 1, ..., 29/30/31}	set of days	K
{1, 2, ..., 188448}	set of data points [m]	H
{start shift, end shift}	set crew shift times [hours]	U

Parameters

$Start_{shift}$	Hour of start day shift	[hours]
End_{shift}	Hour of end day shift	[hours]

Data preparation

From the hindcast data, the significant wave height data is modified for each weather window length. The corresponding month and day for each data point are retrieved.

Loops

This calculation is looped over five indices. The month, day, and data point loops ensure that every data point is filtered in the right month and that only one result per day is given as output. The most inner loop facilitates the final requirement to be run twice, for both the first and the second daily crew change. Finally, the whole cycle is repeated for every FOTV limit.

If-statements

Four if-statements or requirements are present in this calculation. The first two filter out the data points that don't match the current month and day of the cycle. The third loop checks the first requirement if the limit to stay moored to a buoy is exceeded at any point during this day. If this requirement is met, the day will be counted as a port call and the next iteration is started. If this requirement isn't met and the data point stays below the limit, the second requirement is checked. The fourth if-statement checks the second requirement. First, the data point at the start of the day shift is compared to the vessel limit. If the data point is larger than the vessel limit, the day is counted as a port call. If not, the data point at the end of the day shift is assessed. If this data point is larger than the vessel limit the day is counted as a port call. If it's also lower than the vessel limit, the vessel stays in the wind farm and a new iteration is started.

Processes

When the number of days below each limit is summed for each month, this sum is divided by the maximum amount of days for that month.

6.4 Economic performance

The economic performance consists of five parts: Fuel cost, day rate, configuration cost, port call losses, and economic effects of increased availability. All five parts will be discussed in this section.

Fuel cost

Fuel cost is calculated per vessel and configuration. An overview of the calculation is given as a flowchart in figure 6.8.

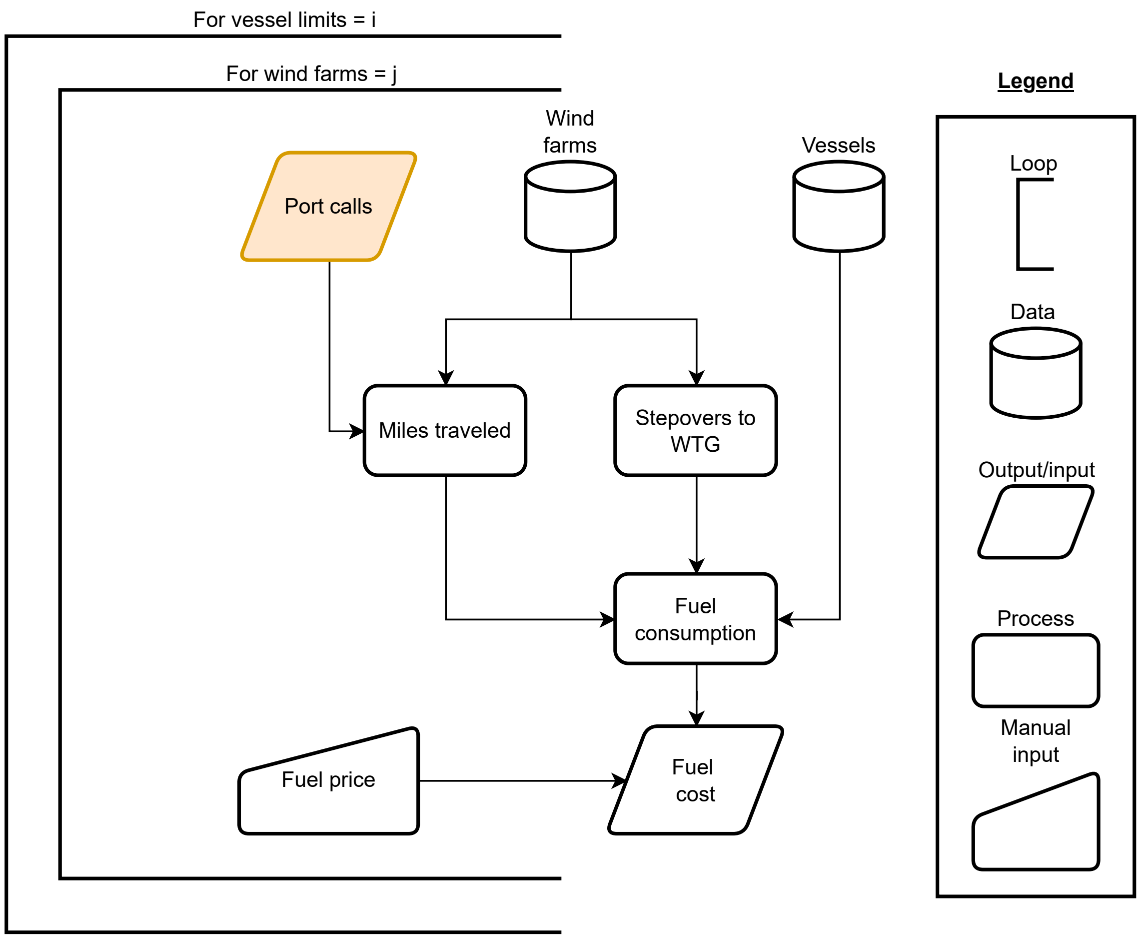

Figure 6.8: Economic calculation: Fuel cost

Indices & Sets

i	index for vessel	$i \in I$
j	index for wind farm	$j \in J$

Parameters

$fuelprice$	price of fuel	[€/ton]

loops

This calculation is looped over all vessels and wind farms. Because the port calls are specific to each configuration, the results will also differ per configuration.

Processes

Four sub-calculations make up the complete calculation to predict the fuel cost. All four are elaborated upon in this paragraph.

Miles traveled The number of miles a vessel will travel per month is based on two factors. First the number of transfers to WTG it makes monthly times the average distance to get there. And secondly, the amount of port calls times the distance required to transit to and from the port.

Stepovers to WTG The amount of stepovers is seen as a function of the amount of WTGs in the wind farm and is based on historical vessel data.

Fuel consumption The fuel consumption is predicted by using the vessel-specific consumption, the miles traveled, and the number of transfers to the WTG. The formula representation is shown in paragraph 5.7.1.

Fuel cost The consumption is multiplied by a fixed fuel cost of €890 per ton to calculate the fuel cost. The fuel price is very volatile and will be further discussed in the sensitivity study.

Day rate

The largest source of cost is the FOTV day rate, these can be found in section 5.7. These day rates include the use of the vessel, the crew wages, and insurance. The day rate is multiplied by a full year, 365 days, to calculate the cost.

Configuration cost

All three of the configurations have investment costs and operating costs. The FOTVs are excluded as they are not to have investment costs attached nor are they influenced by the configurations.

Lifting launch For the lifting launch configuration, the investment is the highest. The cost of the L&R equipment is estimated at € 3.5 million. This investment is depreciated over a 25-year period. Furthermore, the maintenance of this equipment will cost an additional € 50,000.- yearly. The consequence of systems failure is high, so to keep risk at a minimum, the chance of failure has to remain as low as possible.

Connected to the SOV The only investments needed for this configuration are the boat landing on the SOV and the gripper on the FOTV. A single, stern-mounted, boat landing is chosen as the base. Although most SOVs already have this boat landing, the investment is added to the configuration coast because of how crucial it is. The cost of the boat landing is set as a €50,000 investment. The gripper will cost around € 500,000 and needs around € 10,000 in yearly maintenance. Both investments are depreciated over 25 years.

Connected to designated platform The buoy that holds the FOTV in place when it's not in operation costs €43,000 per year. This included both maintenance and investment cost.

Port call losses

When a FOTV has to return to port, it will have reduced operability the next day. When returning from the port, the transit time must be added to the expected waiting time. in figure 6.9 the calculation overview is shown.

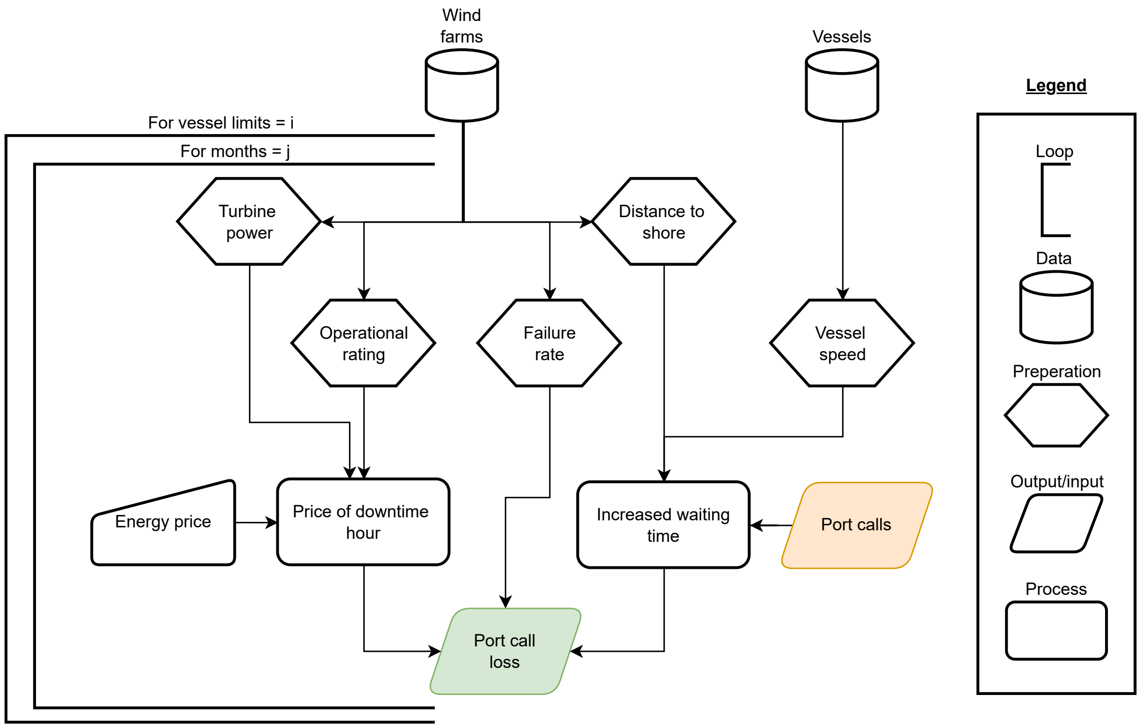

Figure 6.9: Economic calculation: port call losses

Indices & Sets

i	index for vessel	$i \in I$
j	index for wind farm	$j \in J$

Parameters

Energyprice	selling price of electricity	[€/kWh]

loops

This calculation is looped over all vessels and wind farms. Because the port calls are specific to each configuration, the results will also differ per configuration.

Processes

Three sub calculations make up the complete calculation to predict the port call losses. All three are elaborated upon in this paragraph.

Price of one downtime hour The cost of one downtime hour of a WTG is calculated by multiplying the power of the WTG with the operational rating and energy price. This makes for an economic value that is also used in the economic effects of increased availability.

Increased waiting time The effect the port calls have on the waiting time is calculated by first dividing the distance to shore by each vessel's speed and multiplying that by two. With this time lost per port call the waiting time is calculated by multiplying by the number of port calls.

Port call loss The final result is found by multiplying the price of one downtime hour by the increased waiting time per WTG and the amount of WTGs that fail.

Economic effects of increased availability

The goal of deploying FOTVs is to reduce the losses due to WTG downtime, so as to increase availability. This is quantified by the following calculation, shown in figure 6.10.

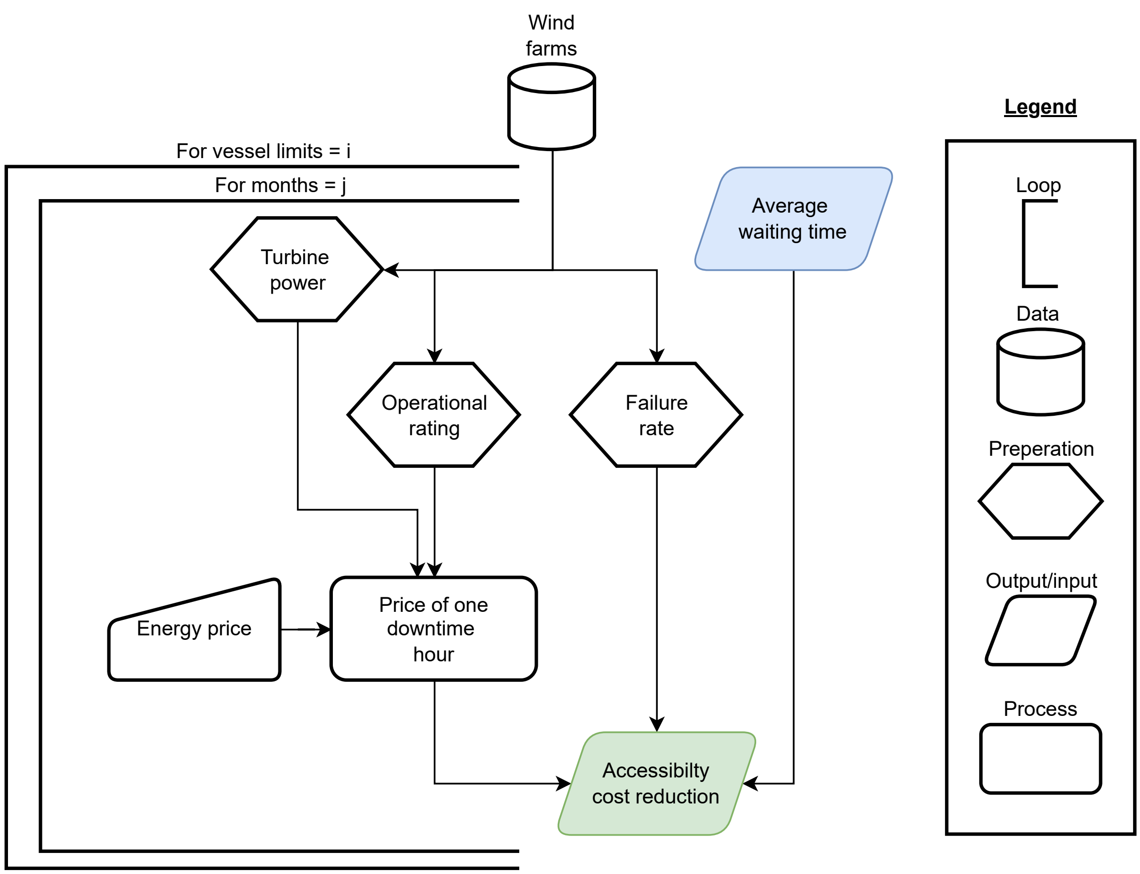

Figure 6.10: Economic calculation: Economic effects of increased availability

Indices & Sets

i	index for vessel	$i \in I$
j	index for wind farm	$j \in J$

Parameters

Energyprice	selling price of electricity	[€/kWh]

loops

This calculation is looped over all vessels and wind farms. The average waiting times are also specific to each vessel and wind farm.

Processes

Besides the calculation of the price of one downtime hour, the final calculation is explained below.

Price of one downtime hour The cost of one downtime hour of a WTG is calculated by multiplying the power of the WTG with the operational rating and energy price. This makes for an economic value that is also used in the economic effects of increased availability.

Accessibility cost reduction The average waiting time is split over the vessel. The DC waiting times are first multiplied by the price of one downtime hour and the failure rate. These relatively high costs are used as a baseline. The same is done for the other vessels and the difference between the results of the DC and the FOTVs are the economic benefits of the FOTV. These benefits depict the income increase resulting from decreasing the time to repair a WTG by increasing accessibility.

With the right model in place, the calculations are done for all vessels, wind farms, and configurations. The results are presented and discussed in the next chapter.

7 | Results

In this chapter, the calculation for accessibility, logistics, and economics results are presented and discussed in sections 7.1, 7.2, 7.4, and 7.5 respectively. In section 7.3 the results of the two different accessibility calculations are compared. Furthermore, in section 7.6 the differences in economic performances due to vessel choice are evaluated and in section 7.7 the difference per wind farm is presented and evaluated. Finally, in section 7.8, the values of some key variables are changed to assess the sensitivity of the outcome and the edge of feasibility is found to see for which circumstances the FOTVs are not feasible anymore.

The results shown in the following sections are based on a base input unless mentioned otherwise. The base parameters in short: the hindcast data of Global Tech One is used, the crew shift starts at 7:00 and ends at 17:00, the window length is four hours, and the H_s limit to stay in the wind farm is 4.0m for the lifting launch and 2.0 for the other two configurations. The full set of input parameters are shown in section 6.1.

7.1 Accessibility results: a statistical approach

The two outcomes of the statistical approach are the monthly operability and average waiting time. Both outcomes are presented below and discussed.

7.1.1 Results and comments

The results are shown in figure 7.1. The general behavior of both plots is as expected. The operability of the FOTVs, H_s limit 1.5m, 1.6m, and 1.75m, is higher than that of the DC, purple dashed-dotted line signifying an H_s limit of 1.0m, because of their higher transfer limits. Furthermore, the operability of all vessels is higher in the summer months than in winter because of the overall seasonal weather conditions. The average waiting time also behaves as expected for the differences in vessels and monthly weather conditions. There are a few phenomena that weren't expected before concluding the calculations.

1. The difference in operability between the vessels has a varying effect on the average waiting time.
2. There are a few discontinuities in the graphs, most significantly around November, December, and January.

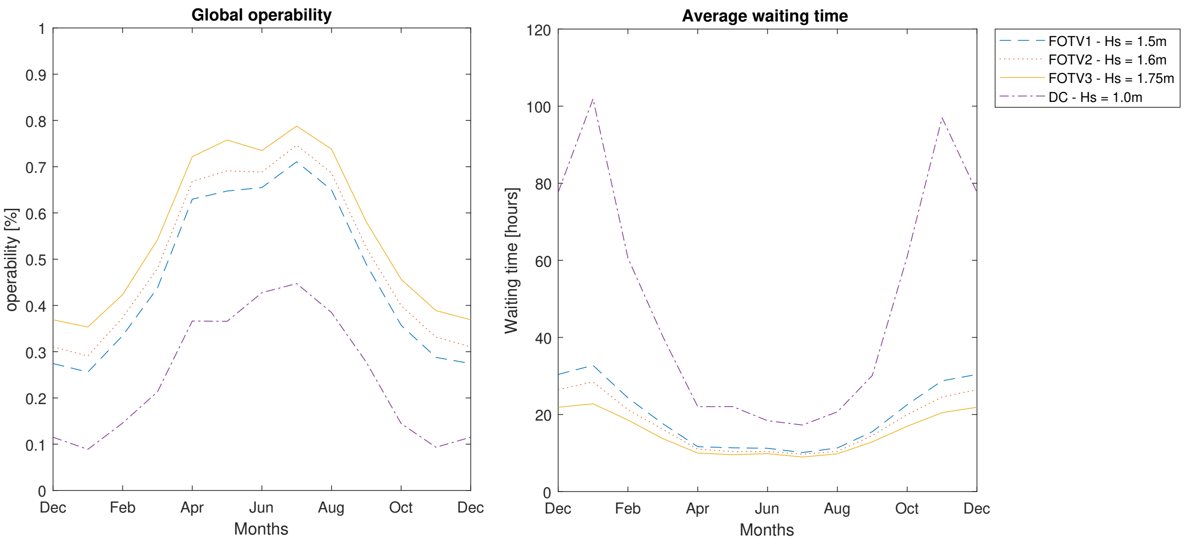

Figure 7.1: Results accessibility calculations, statistical approach. Left graph depicts Operability and right graph depicts the average waiting time for all four vessels. Wind park Global Tech One.

Relative effect of increased operability The difference in operability between the lowest-performing FOTV and DC in summer is around 22%. This is shown in figure 7.1 in the left graph, comparing the DC line in purple with the lowest performing FOTV line in blue (FOTV 1). The difference between the same two vessels during winter is around 16%. So in winter, the effect of an improved vessel seems lower than in summer based on the operability. But the difference between these vessels in terms of average waiting time, right graph of figure 7.1, has a very different dynamic. Here the difference in summer is around 10 hours of waiting time more for the DC compared to the FOTV. However, the difference in winter is 50 to 70 hours. In other words, the difference in operability does not solely determine the average waiting time. The reason for this phenomenon in the calculations is the effect of the relative difference in operability. The operability is used as a chance for a successful operation. The chance is repeatedly applied until the cumulative chance reaches 99%. This results in two effects, an example to illustrate these effects is given in table 7.1. In this table, an operability of 10% is compared to that of 20%. The first effect is seen in the two 'Cumulative' columns. Higher operability will increase the cumulative chance faster and therefore needs fewer iterations to reach the desired percentage. Secondly, the 'Increase' column shows that higher operability starts with a higher increase. However, at iteration 6 the lower operability surpasses the higher operability in terms of chance increase per iteration. This means that a larger portion of chance is distributed here compared to the higher operability and is multiplied with higher time weights. Because of the two effects, the relation between operability and waiting time becomes inverse exponential. In other words, an increase in operability has a larger effect on the average waiting time if the operability is low compared to when the operability is high.

Iteration	Cumulative	Increase	Cumulative	Increase
	0		0	
1	0.10	0.10	0.20	0.20
2	0.19	0.09	0.36	0.16
3	0.27	0.08	0.49	0.13
4	0.34	0.07	0.59	0.10
5	0.41	0.07	0.67	0.08
6	0.47	0.06	0.74	0.07
7	0.52	0.05	0.79	0.05
8	0.57	0.05	0.83	0.04
9	0.61	0.04	0.87	0.03
10	0.65	0.04	0.89	0.03

Table 7.1: Example for two different operability values over 10 iterations without time weights

In table 7.2 both operability values are increased with a flat 5%. This is a relatively higher increase for the lower operability mark. Because of the two effects the operability has on this distribution, the moment of surpassing is now later, at iteration 8. Moreover, the cumulative chance after 10 iterations has grown by 2% for the lower operability and by 1% for the higher operability.

Iteration	Cumulative	Increase	Cumulative	Increase
	0		0	
1	0.15	0.15	0.25	0.25
2	0.24	0.09	0.40	0.15
3	0.31	0.08	0.52	0.12
4	0.38	0.07	0.62	0.10
5	0.44	0.06	0.69	0.08
6	0.50	0.06	0.75	0.06
7	0.55	0.05	0.80	0.05
8	0.59	0.05	0.84	0.04
9	0.63	0.04	0.87	0.03
10	0.67	0.04	0.90	0.03

Table 7.2: Example for relative difference in operability

The effect of the relative difference in operability on waiting time is also explained by the physical reality. First, the distribution of significant wave height occurrence determines the correlation between vessel limits and operability. The relation between operability and waiting time is also determined by statistical dynamics. The chance to operate the next hour or day isn't influenced by the notion that it's possible to operate at this point in time. But there is certainly a relationship between the weather conditions of the time segment and the sequential time segment. This is something the statistical approach neglects wrongfully. The chance in the model is only influenced by the weather and the vessel limits, which is represented by operability. The higher the chance of operation, the shorter the average waiting time. Regardless of the time window that is examined, an increase of one percent has more effect on the waiting time for low operability than for high operability.

Discontinuities After close inspection of the hindcast data, it was determined that both discontinuities in winter and summer are representative of the data. A comparison with another model in paragraph 7.1.2 underlines this conclusion. This doesn't rule out the possibility that the data doesn't represent the reality correctly, but because of the size of the data set, this is deemed unlikely.

7.1.2 Verification

At Siemens Gamesa, a tool was developed parallel to this research. The tool predicts weather downtime and response time using a Monte Carlo simulation. It is used for CTV performance predictions and can be used in many other applications.

Operability To verify the accessibility calculations of this research the results are compared. First, the same data is loaded into the tool and analyzed. This shows that the discontinuities are also found in the data by this tool. In figure 7.2 the weather downtime is displayed for Global Tech one with a FOTV with an $H_s$limit of 1.75m. The weather downtime is not a parameter that is calculated in the method of this research. But the parameter is indicative of the occurrence of significant wave heights at a certain limit. In the month of June and December, the data differs over the course of the graph.

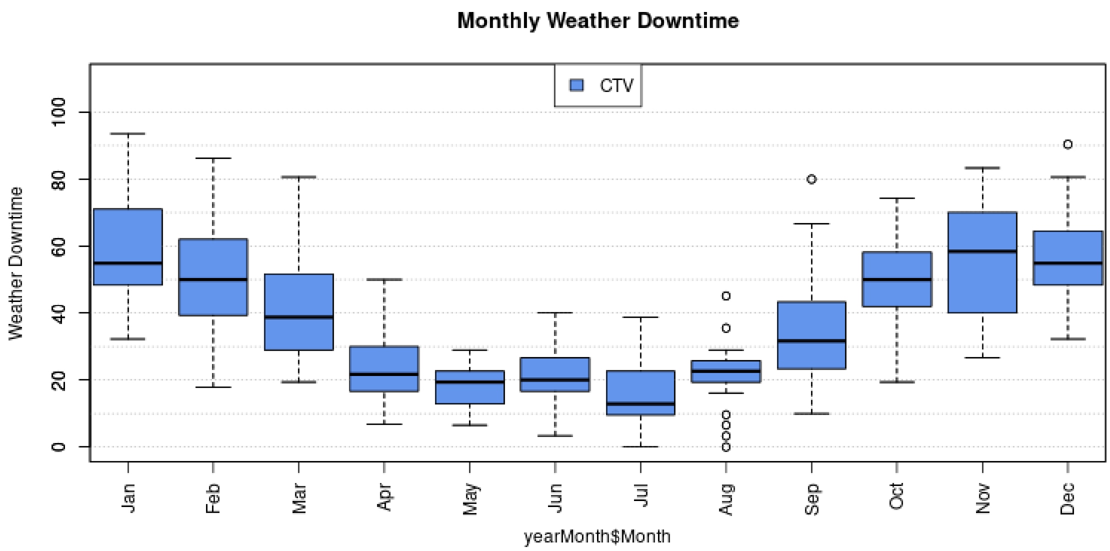

Figure 7.2: Weather downtime for Global tech one with 1.75m FOTV.

Waiting time The simulation of Siemens Gamesa calculates the mean monthly response time. This is comparable to the average waiting time calculated in the model of this research. The outcomes of the simulations for vessel limits 1.75m, 1,5m, and 1.0m are compared to the statistical model results in figures 7.3. The full results of the simulation approach are found in appendix C.

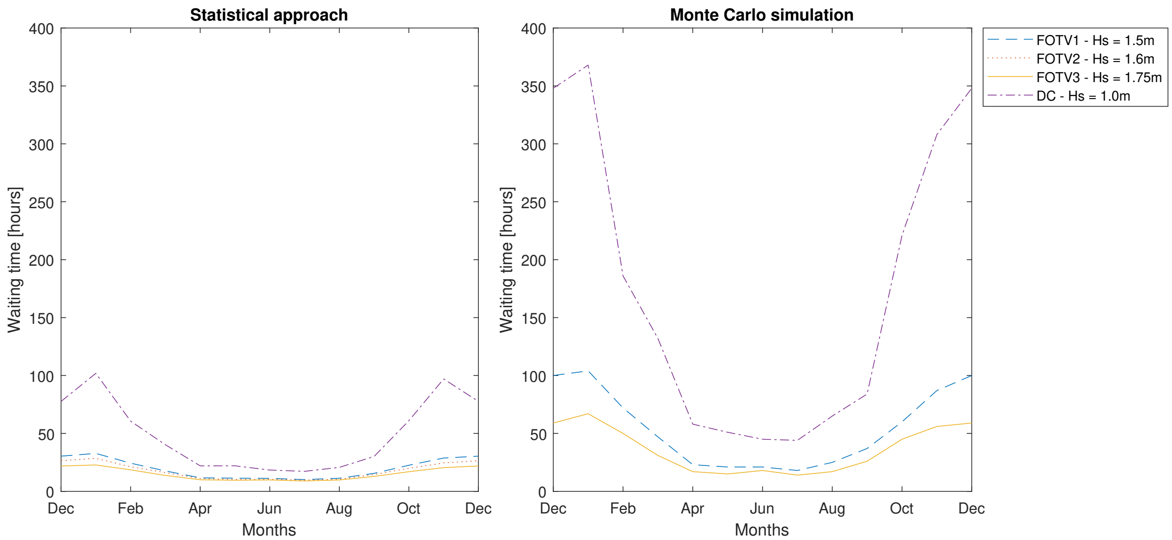

Figure 7.3: Results comparison between statistical approach and simulation approach

When results of the Monte Carlo simulation are compared to the results of the statistical model the results differ significantly. The course of the graphs is very comparable but the simulation results are higher across all months and limits. For the highest limit, the simulation results are roughly twice as high as the results from the statistical model, seen in the yellow solid line in both graphs. But for lower vessel limits this difference increases rapidly, comparing the purple dash-dotted line. This difference is in line with the relative effect of increased operability behaving in an inverse exponential manner. The difference between the outcomes comes largely down to the difference in the time segment that is assessed. For the statistical model, for every segment with the length of one weather window, the chance of operability is assessed. The Monte Carlo simulation assesses full days, so the operability is only applied once every day. In comparison, the statistical model is more detailed and allows for different situations per day. On the other hand, the simulation can more realistically mimic the weather conditions over a period of time, unlike the statistical model that uses a flat average per month. The question remains what a reasonable time segment is to assess. The most critical factor for this question is the coherence in weather conditions over time. The weather certainly changes from day to day, but it can also change after four hours. At this point, the results of this approach have to be deemed conservative in terms of waiting time and every calculation that is based on this waiting time.

7.2 Accessibility results: a direct historical approach

The direct historical approach calculates the average monthly waiting times. The results are shown in figure 7.4.

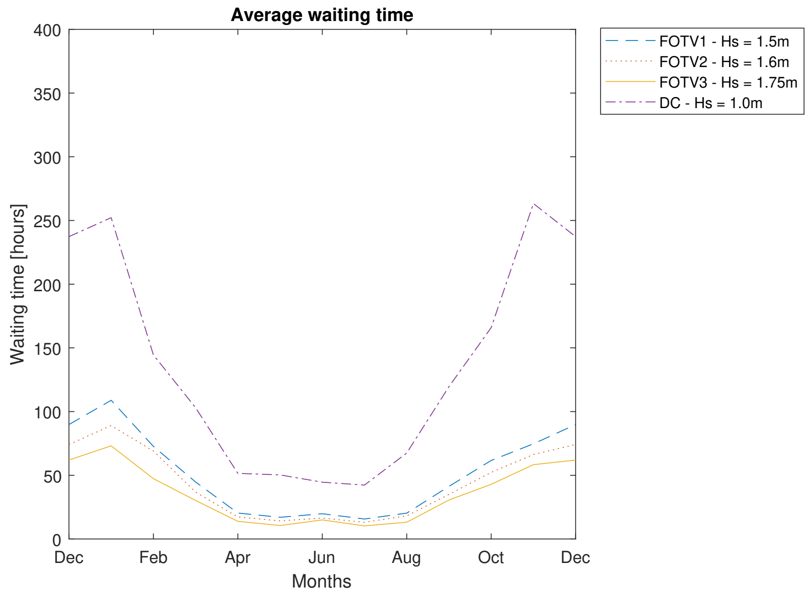

Figure 7.4: Results direct historical approach: Average monthly waiting time

These results are higher than the waiting times calculated with the statistical model. Two of the discontinuities from the statistical model are also prevalent in the results of the direct historical model. The slightly higher values in June and the lower values in December. The lower values in December are visible only for the DC and for the FOTVs only in comparison with January but not with November. This means that for Global Tech one, the December month has better weather conditions than January. When compared to November, December has more H_s values above 1.0m than November. But on the other hand, December has fewer values above 1.5m in comparison to November. This can be seen in the box plots of figure 7.2, the box of December is smaller for a 1.75m limit compared to November.

7.2.1 Verification

The results of the direct historical approach are compared to that of the simulation approach. In figure 7.5 the two graphs are shown next to each other. The results of the FOTVs are very comparable. But the results for the DCs do differ significantly. The DC has higher waiting times for the simulation model than for the direct historical model. This can be explained by the inverse exponential behavior that is present in this in the correlation between operability and waiting time. Because the direct historical model doesn't rely on operability, it can be concluded that the Monte Carlo simulation overshoots this effect for lower vessel limits.

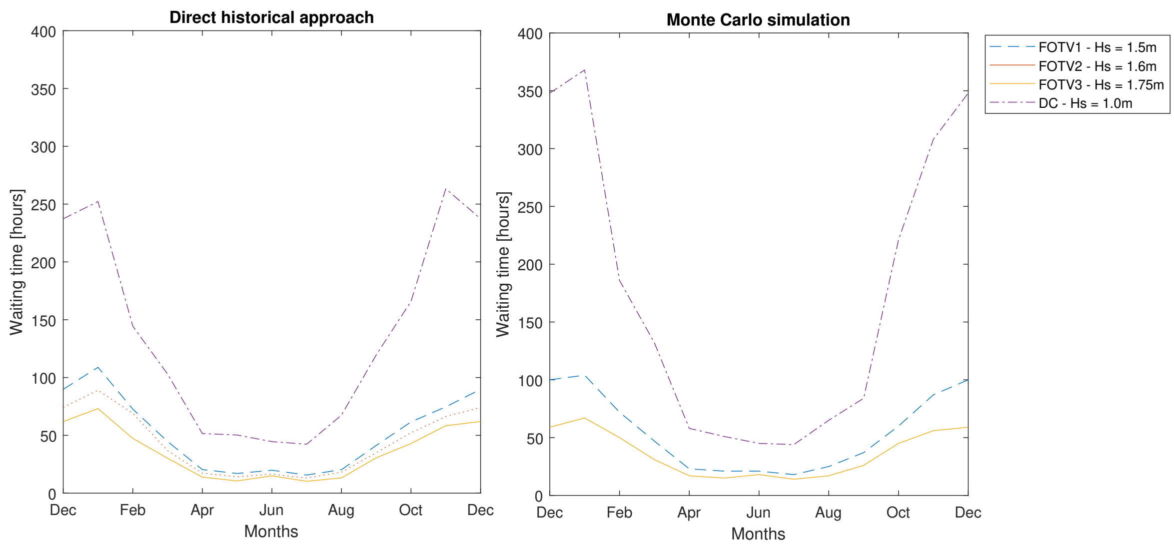

Figure 7.5: Results comparison between direct historical approach and simulation approach

7.3 Accessibility results: comparison

The average waiting times are used in the calculation as input to calculate economic effects. These results will differ depending on the approach of calculating the average waiting times. Therefore a decision has to be made on which results are deemed most realistic.The predicted waiting times according to each of the three methods are presented in figure 7.6.

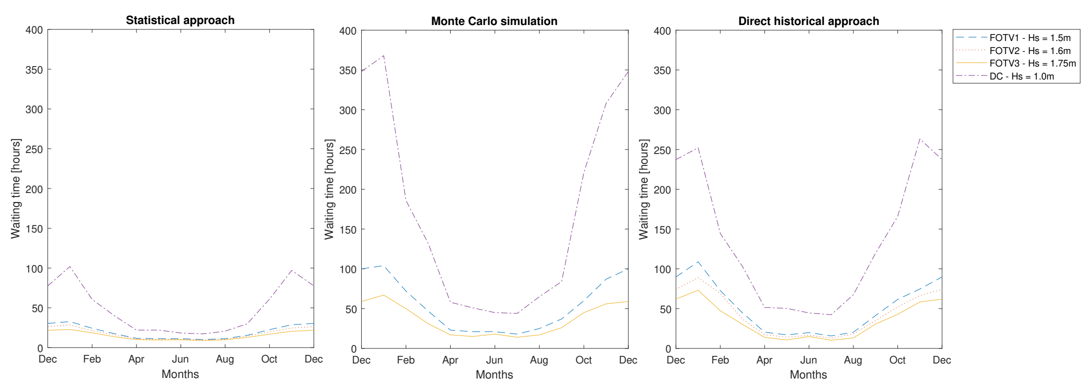

Figure 7.6: Results comparison between all three approaches

Because of the risk of mismatch in time segment usage in the statistical approach, this method is deemed least realistic and discarded. For the decision between the direct historical approach and the simulation, the difference in DC results is most significant.This can be seen when the purple dash-dotted line off the middle and right-hand graph are compared. The Monte Carlo simulation overshoots the inverse exponential dynamic between operability and waiting time. This research deems the direct historical approach most realistic and will continue to build on the results of this model.

7.4 Logistic results

The logistics results are meant to calculate the effects of all three configurations. Each configuration has its own corresponding limitations. The effects of these limitations are calculated in the form of port calls, and how often the FOTV is required to return to port. The effect of a port call is threefold. First, the added distance contributes to fuel consumption. Secondly, the time in transit is added to the waiting time and finally, the days that the FOTV stays in port are added to the waiting time. Two forms of limitations are present. First, an overall significant wave height limit, if at some point during a day this is exceeded, the FOTV must return to shore. This limit applies to all three configurations with varying amounts. The second limit only applies on the moored to designated platform configuration. Here the significant wave height during crew change needs to be equal to or lower than the vessel transfer limit. This way the crew can exchange with the other crow on the SOV. If this isn't possible, the FOTV must return to the port so the crew can rest. Both results are discussed below.

7.4.1 Overall significant wave height limit

In figure 7.7 the results are shown for the overall significant wave height limit. The graph behaves as expected. The conditions from April up to and including August are the best conditions. In winter months the highest significant wave height values are seen and the number of port calls goes up. The whole range between the limit of lifting launch (4.0m) and connected to the SOV (2.0m) is shown. While the limit increments are constant, the difference between each line is not constant. For the higher limits, the results are closer to each other than for the lower results. This shows the higher volume of wave height occurrences in the lower values compared to the higher, which correlates to the physical reality. The differences are very high. Where the first configuration has made 2 - 6 port calls per month, the second needs to do 8 to 20 per month. This research deems the lifting launch therefore feasible in this regard. For the connected to the SOV, the feasibility will depend on the limit. If the conservative limit of 2.0m is realistic, the number of port calls is too high in winter but workable during summer. If for example, the real limit of the connected to the SOV is 2.5m, the number of port calls goes from 8 - 20 to 4 - 15. For the continuation of the calculation, the limit of 2.0m is used.

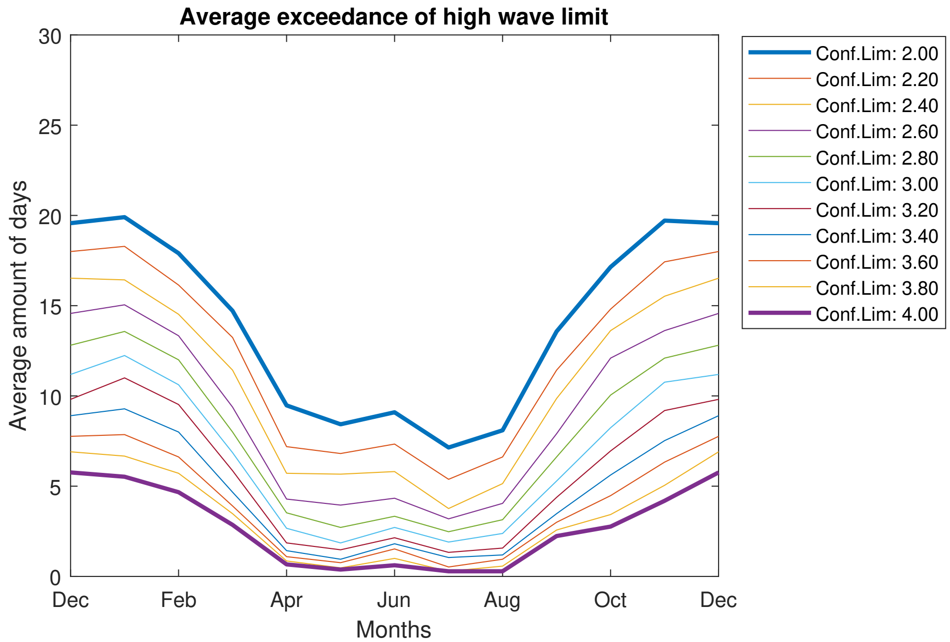

Figure 7.7: Results logistic assessment of high wave limit

7.4.2 Significant wave height limit at crew change

The third configuration, moored to a designated platform, has two requirements. The results are shown in figure 7.8. Both the overall limit of 2.0m and the transfer limit of the FOTV at crew change hours. If one of the requirements isn't met, the FOTV must return to port. In figure A the results of this dual requirement are shown. The limits corresponding to the lines in the graph depict the transfer limits of the vessels. Starting at the highest limit, which coincides with the overall limit, the line just shows the overall limit. Now for the transfer limit of 1.9m, the difference is very small compared to the previous line. This makes sense because it depicts that for the whole day no exceedance of 2.0m can occur but also that around 7:00 and 17:00, no exceedance of 1.9m can occur. This second requirement is not too significant when the first is already met. But when the transfer limit drops further, the second requirement gains influence. For the ranges of the FOTVs, the effect is not too significant, the difference between the 2.0m limit and the 1.5m limit stays within 3 days. But for the DC the difference is high, especially in summer. It can therefore be concluded that a vessel in this configuration must have a transfer limit of at least 1.5m.

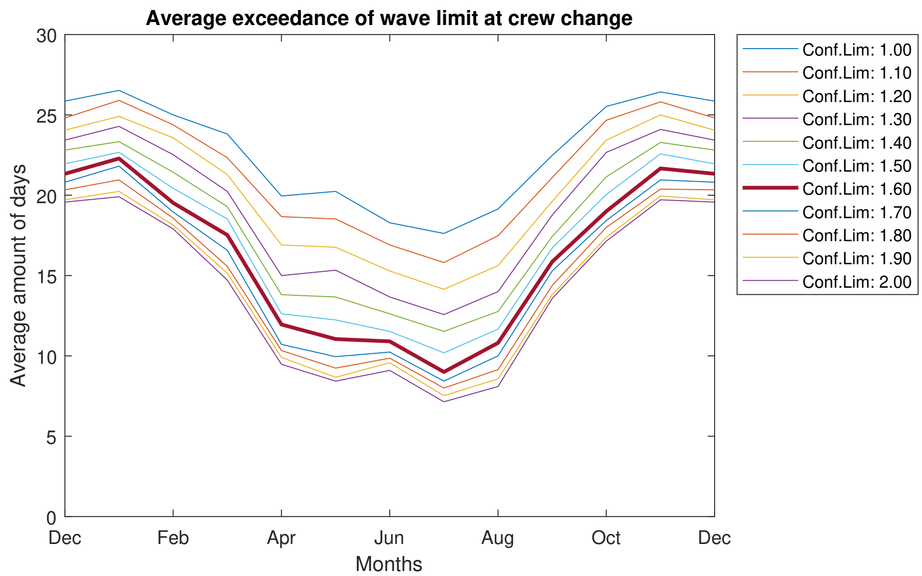

Figure 7.8: Results logistic assessment of high wave limit and crew change limit simultaneously

7.5 Economic results

The final part of the calculations translates the performance predictions of the previous calculations into economic parameters. There are five different economic parameters identified by this research. All parameters are calculated for every unique combination of FOTV, configuration, and wind farm. The parameters are expressed as yearly expenses for clarity. To assess the monthly effects, the previous calculations are used. In figure 7.9 all economic parameters are displayed for all three configurations and all four FOTVs. The results show that this research predicts that a FOTV deployment is deemed profitable for all configurations and FOTVs for the current input set. Every cost economic parameter is evaluated individually in this section.

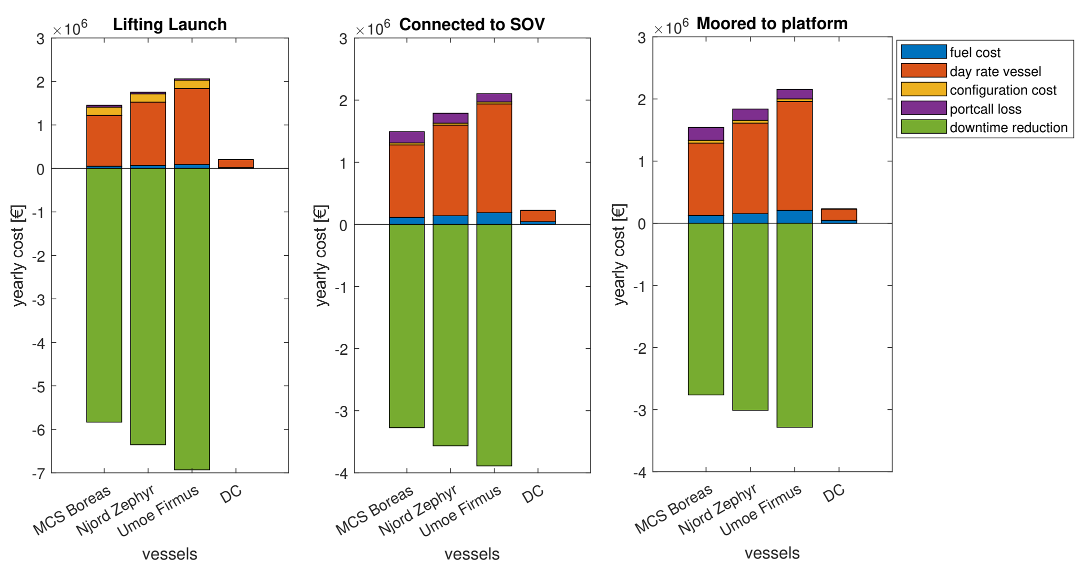

Figure 7.9: Economic results comparison for all three configurations

In table 7.3 the overall economic results are shown. In this table, the cost and downtime reduction are added together and so a negative number signifies a profitable scenario. Here two conclusions become clear:

1. The most profitable configuration is the lifting launch.

2. The most profitable vessel changes per configuration.

The most profitable configuration The difference in overall economics is large. This is mostly because of the difference in port calls and so in the difference in configuration limits. The port call losses and fuel consumption are lower for the lifting launch and the downtime reduction is higher in comparison to the other two configurations.

Vessel choice The impact of vessel choice differs per configuration. This is because of the relative impact of the constant cost factor day rate. When the vessel can operate less due to weather constriction, the relative impact of its higher transfer limit diminishes compared to the higher day rate. For the connected to the SOV configuration, this effect is at its tipping point. The highest performance vessel, Umoe Firmus, is the most profitable but the second-highest, Njord zephyr, is third. This is explained by the differences in day rate and transfer limits between the vessels. For the moored to a designated platform configuration, the impact of the day rate has surpassed the impact of the transfer limit.

	Msc Boreas	**Njord Zephyr**	**Umoe Firmus**	**DC**
Lifting launch	€ -4,381,891	€ -4,601,779	€ -4,870,413	€ 200,724
Connected to SOV	€ -1,781,691	€ -1,776,582	€ -1,785,634	€ 200,724
Moored to platform	€ -1,223,119	€ -1,173,352	€ -1,130,881	€ 200,724

Table 7.3: Overall economic results in yearly cost [€/year]

7.5.1 Fuel cost

The fuel cost is a minor part of the total cost. The isolated fuel cost results are shown in figure 7.10. Two trends can be seen in these results.

1. Influence of amount of port calls.
2. Influence of vessel choice.

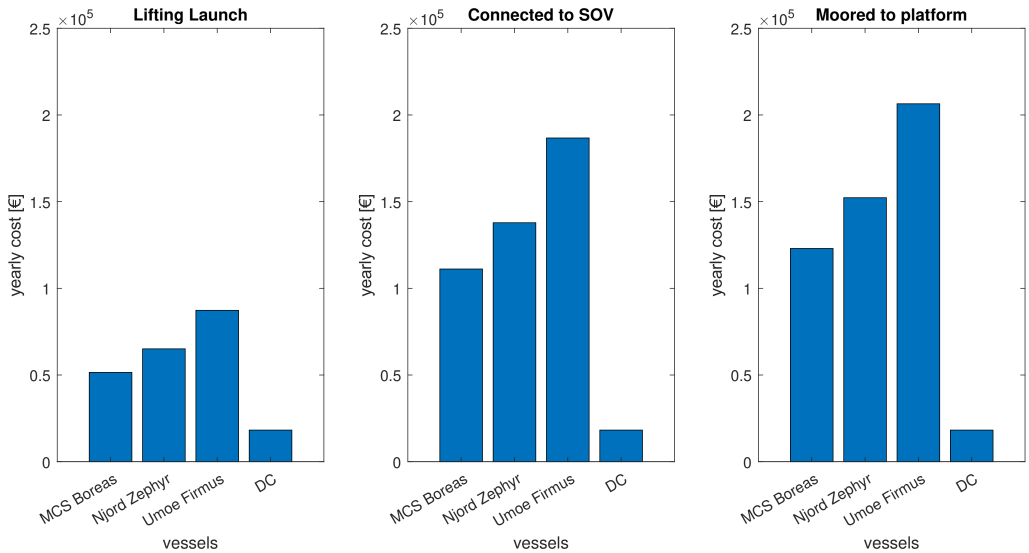

Figure 7.10: Economic results: fuel cost

Influence of amount of port calls The amount of port calls is determined by the configuration restrictions. Therefore, the lifting launch configuration has less fuel cost while the other two configurations have relatively high fuel costs. The effect of the crew change requirement for the moored to a designated platform is visible but not significant. The DC is affected in the same manner as the lifting launch configuration. This trend is a logical consequence of the way the port calls influence fuel consumption, both in terms of calculation and as a reflection of the physical reality. Because of the increase in transit distance stemming from a port call, fuel consumption increases.

Influence of vessel choice The vessels are given specific fuel consumption for the number of nautical miles traveled and specific fuel consumption for the amount of push-on transfers they perform. The amount of transfers is constant in a wind farm for all vessels and configurations. The number of nautical miles is constant for each vessel but differs per unique configuration and wind farm combination. The differences between the vessels in terms of fuel consumption are a logical result of the calculations. In comparison to the real world, the relative behavior is as expected and the results are close enough to historical data to be deemed realistic.

7.5.2 Day rate cost

The largest cost factor is the day rate cost. The day rate costs are shown in figure 7.11. These are fixed day rates that resemble the actual CTV day rates but have been altered because of the sensitivity of the data. The results are in line with expectations, both in their relative differences and the amount. It is clearly visible that the FOTVs will cost significantly more than a DC.

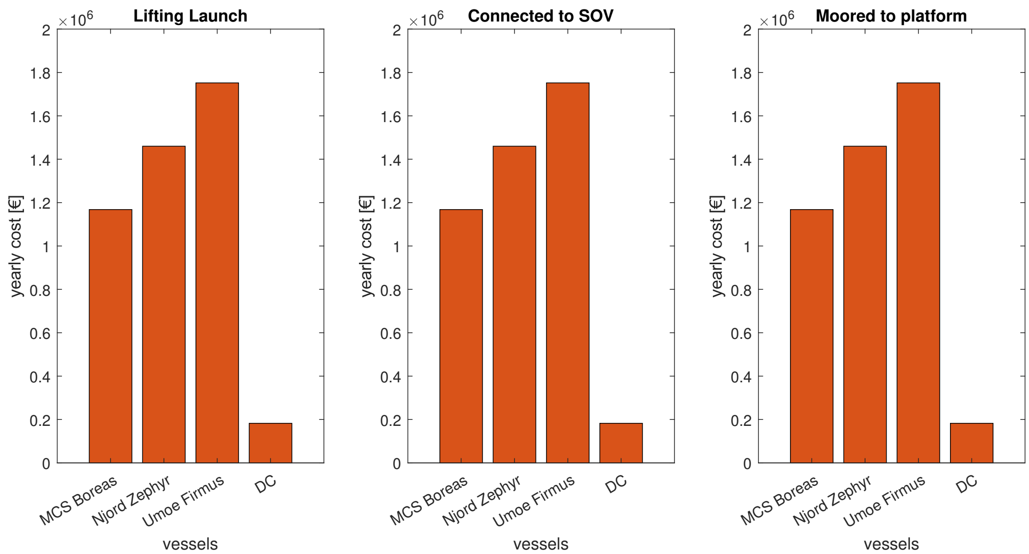

Figure 7.11: Economic results: Day rate

7.5.3 Configuration cost

The configuration-specific cost is based on the investment and maintenance needed to deploy and operate the configuration. The input for this cost can be found in section 6.4 and the results are shown in figure 7.12. These costs are relatively small compared to other cost factors for the connected to SOV configuration and the moored to a designated platform configuration. For the lifting launch configuration, the cost is in the same range as the fuel cost. The configuration cost is not influenced by either vessel choice or the wind farm. The results are as expected and are an estimation of the economic reality. Because the configuration cost is presented in yearly cost, the impact of investment is lost. For the lifting launch, a large investment is needed to deploy the configuration. Because of the uncertainty and volatility of the offshore energy sector, this is important information to evaluate when choosing a configuration.

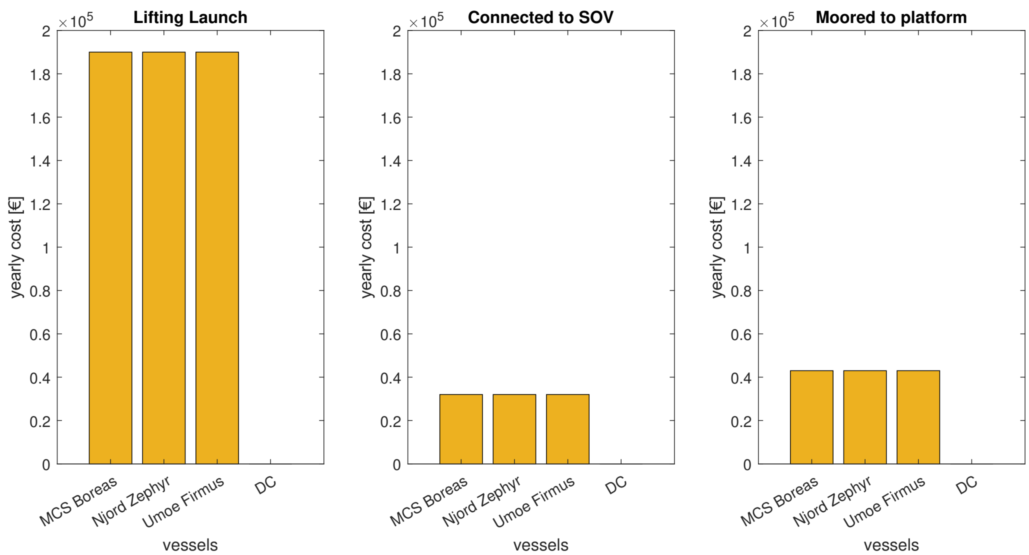

Figure 7.12: Economic results: Configuration cost

7.5.4 Port call loss

The port call losses are a product of the time lost by transiting to and from the port. The results are shown in figure 7.13. Similar to the results of fuel cost, two trends can be seen in these results. These costs are relatively low in comparison to the other cost factors.

1. Influence of amount of port calls.
2. Influence of vessel choice.

The most significant influence on these results is the number of port calls. Because of the difference in speed between the FOTVs, the time losses are less for the faster vessels. This is a logical result from the calculation and holds true in physical reality.

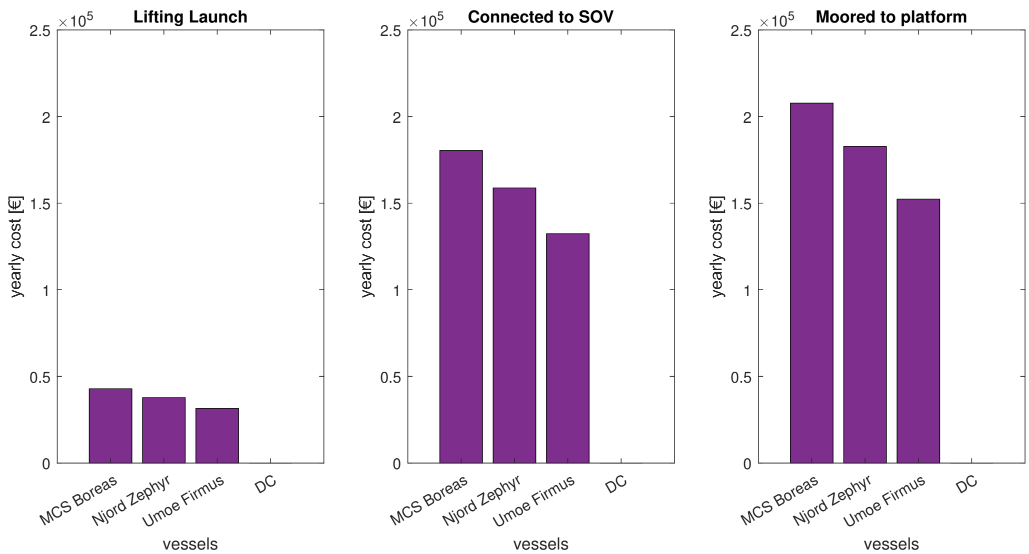

Figure 7.13: Economic results: Port call loss

7.5.5 Downtime reduction

Downtime reduction is the goal of implementing the FOTVs. The effect is translated to cost reductions and is visible in figure 7.14. These cost reductions are relatively high when compared with all other cost factors. Two trends can be seen in these results.

1. Influence of amount of port calls.
2. Influence of vessel choice.

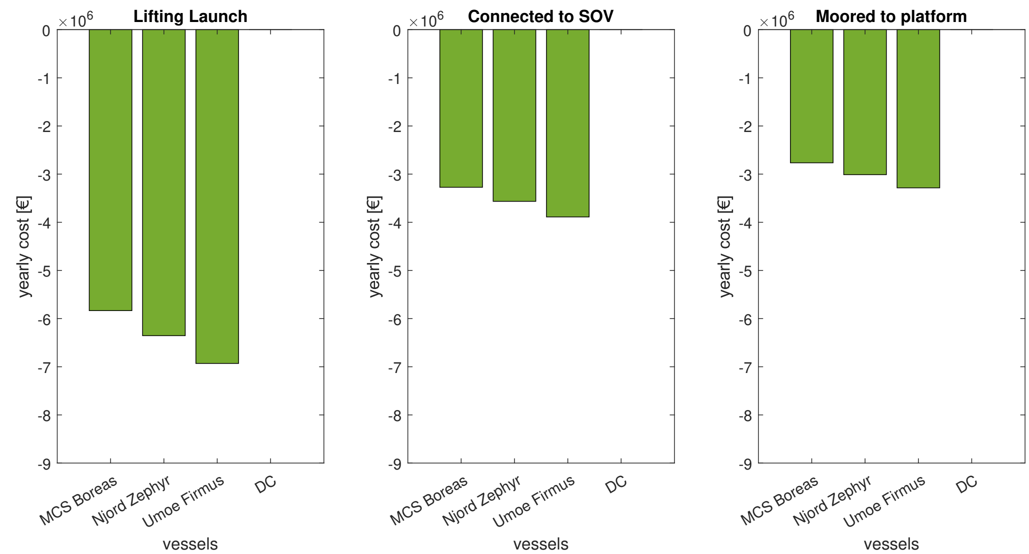

Figure 7.14: Economic results: Downtime reduction

Influence of amount of port calls The third effect of logistic results is found here, the number of port calls affects the realization of downtime reductions. If the combination of configuration and vessel is forced to return to port, the FOTV can't execute maintenance runs. The results show that the higher port calls for the second two configurations significantly reduce the capacity of the FOTV to reduce downtime. The DC is used as a base case and so has a reduction of zero.

Influence of vessel choice The difference in transfer limitation per vessel determines the amount of downtime reduction the FOTV can realize in comparison to the DC. The transfer limit values are not directly corresponding to the physical vessel but are in a realistic range. The effects therefore must be seen as indicative and can be used for implementation with real input values.

7.6 Performance behavior

To assess the overall effects of vessel choice, a larger example set of FOTVS is used for the model. The set is developed by linear extrapolation and is shown in table 7.4. These vessel parameters are realistic enough but assume a linear correlation between all parameters, which is often not the case.

Hs limit [m]	**Speed [knts]**	**Day rate [€]**	**a [l/#]**	**b [l/nm]**
0.9	14.1	€ 2,250.0	35.2	10.3
1	15.6	€ 2,500.0	39.1	11.4
1.1	17.2	€ 2,750.0	43.0	12.6
1.2	18.8	€ 3,000.0	46.9	13.7
1.3	20.3	€ 3,250.0	50.9	14.9
1.4	21.9	€ 3,500.0	54.8	16.0
1.5	23.4	€ 3,750.0	58.7	17.2
1.6	25.0	€ 4,000.0	62.6	18.3
1.7	26.6	€ 4,250.0	66.5	19.4
1.8	28.1	€ 4,500.0	70.4	20.6
1.9	29.7	€ 4,750.0	74.3	21.7
2	31.3	€ 5,000.0	78.2	22.9
2.1	32.8	€ 5,250.0	82.2	24.0
2.2	34.4	€ 5,500.0	86.1	25.2
2.3	35.9	€ 5,750.0	90.0	26.3
2.4	37.5	€ 6,000.0	93.9	27.4
2.5	39.1	€ 6,250.0	97.8	28.6
2.6	40.6	€ 6,500.0	101.7	29.7

Table 7.4: Example set of FOTV parameters

In figure 7.15, the economic performance of the set of vessels is shown for all three configurations in wind farm Global Tech one. From this graph a couple of conclusions can be drawn. First, for all three configurations, the increase in profits diminishes when vessel performance is increased. Shown by the diminishing gradient of all three lines. Secondly, every configuration has a stagnation point, where the decision for a higher-performing vessel will decrease the overall profits. For the lifting launch configuration, shown in the blue dashed line, this point is reached with the example FOTV corresponding to a 2.2m limit. But for the moored to platform configuration, shown in the yellow dash-dotted line, the stagnation point is already reached at 1.9m. The difference in stagnation points is largely due to the difference in added accessibility the configurations offer. Because the moored to designated platform has more port calls, it can't capitalize on the added accessibility as efficiently as the lifting launch configuration does. In conclusion, this clearly shows the preferred vessel for each combination of wind farm and configuration. In this case, a FOTV with a significant wave height limit of 2.2m and lifting launch configuration would be most profitable for Global Tech one.

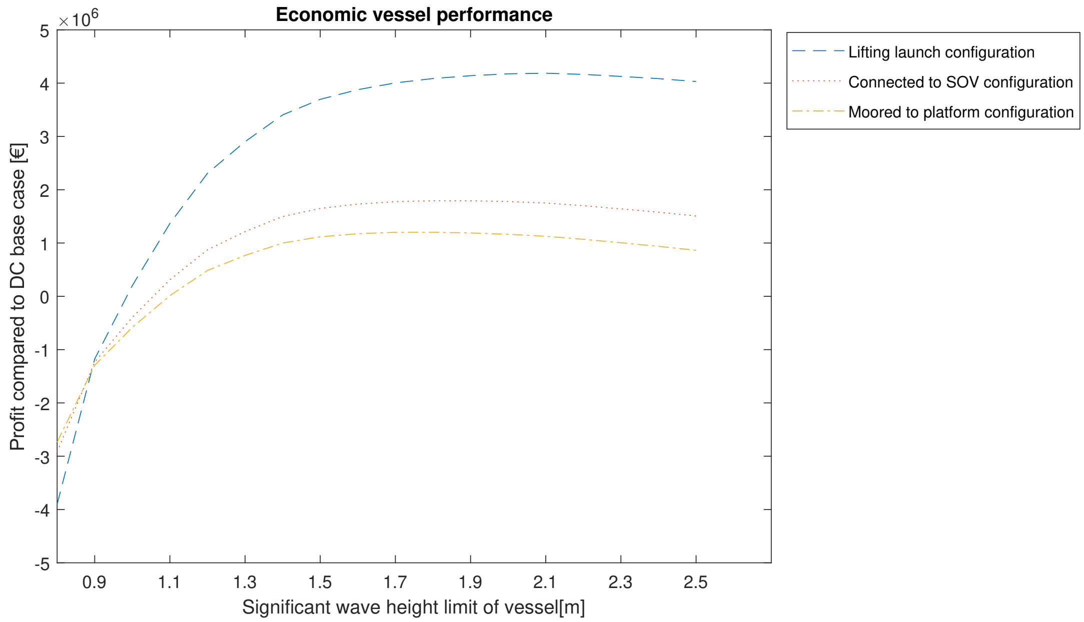

Figure 7.15: Economic vessel performance of example set FOTVs for all three configurations in Global Tech one

For higher-performing vessels, the day rate is not expected to behave linearly. Therefore an example set with exponential day rates is developed. The set is shown in table 7.5. The performance is shown in figure 7.16. Because the cost of higher-performing vessels has increased, the stagnation points for all three configurations have shifted to lower-performing vessels. The stagnation point for lifting launch configuration has shifted from 2.2m to 1.8m. For the moored to platform configuration, the stagnation point has shifted from 1.9m to 1.6m. The difference in outcomes shows that the model is very sensitive to changes in the day rate. It can be concluded that this model can only give reliable guidance when the input is certain.

Hs limit [m]	Speed [knts]	Day rate [€]	a [l/#]	b [l/nm]
0.9	14.1	€ 1,265.6	35.2	10.3
1.0	15.6	€ 1,562.5	39.1	11.4
1.1	17.2	€ 1,890.6	43.0	12.6
1.2	18.8	€ 2,250.0	46.9	13.7
1.3	20.3	€ 2,640.6	50.9	14.9
1.4	21.9	€ 3,062.5	54.8	16.0
1.5	23.4	€ 3,750.0	58.7	17.2
1.6	25.0	€ 4,000.0	62.6	18.3
1.7	26.6	€ 4,515.6	66.5	19.4
1.8	28.1	€ 5,062.5	70.4	20.6
1.9	29.7	€ 5,640.6	74.3	21.7
2.0	31.3	€ 6,250.0	78.2	22.9
2.1	32.8	€ 6,890.6	82.2	24.0
2.2	34.4	€ 7,562.5	86.1	25.2
2.3	35.9	€ 8,265.6	90.0	26.3
2.4	37.5	€ 9,000.0	93.9	27.4
2.5	39.1	€ 9,765.6	97.8	28.6
2.6	40.6	€ 10,562.5	101.7	29.7

Table 7.5: Example set of FOTV parameters with exponential day rate extrapolation

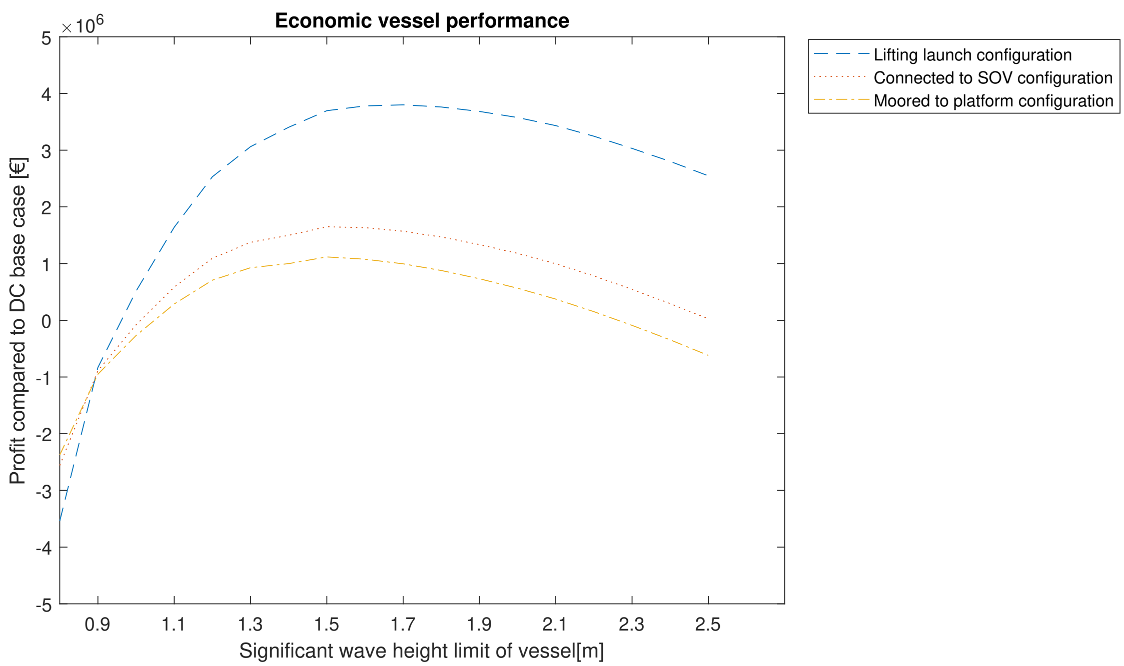

Figure 7.16: Economic vessel performance of example set FOTVs with exponential day rates, for all three configurations in Global Tech one

7.7 Wind farms

To test the applicability of the model, the whole calculation is done for two other wind farms and the results are compared and evaluated in this section. The model can load different sets of hindcast data and match corresponding wind farm data. The differences in input between the wind farms consist of significant wave height distribution, number of WTGs, maximum power of WTGs, distance to shore, and distance between WTGs.

7.7.1 Accessibility results

For the accessibility results, the direct historic approach is used to assess the hindcast data of each wind farm. The operability and waiting time results of all three wind farms are shown in figures 7.17 and 7.18 respectively. The only variable factor between wind farms for accessibility is the significant wave height distribution gathered from the hindcast data.

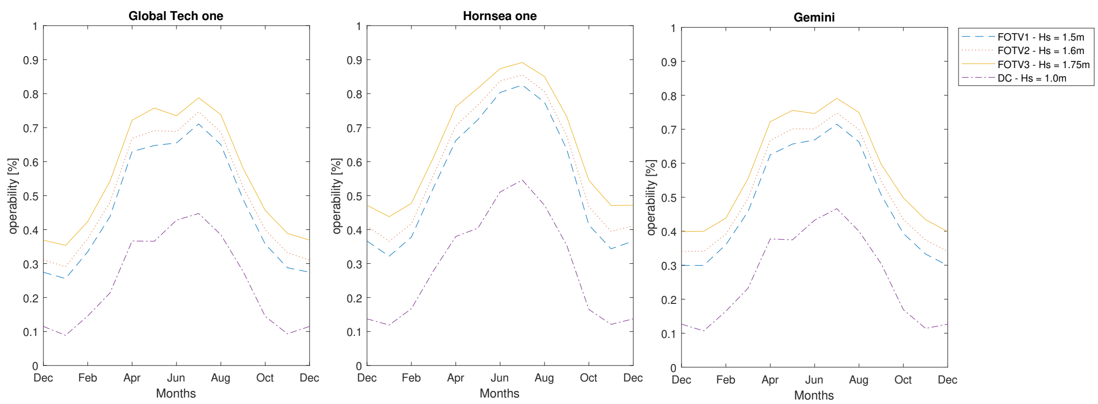

Figure 7.17: Wind farm comparison: Operability

Operability comparison At first glance, the results are similar in terms of range and behavior. However, across the three wind farms, the discontinuities differ. They all experience a slight dip in May for the DC but Hornsea one doesn't have the dip in June for the FOTVs. Hornsea one has the most different results, which is explained by the difference in location. As can be seen in figure 7.17. The weather conditions on average are better in Hornsea one than in the other two wind parks. Gemini wind park has slightly better operability than Global Tech one, which can be explained by the fact that Gemini is closer to shore and weather conditions are slightly milder on average.

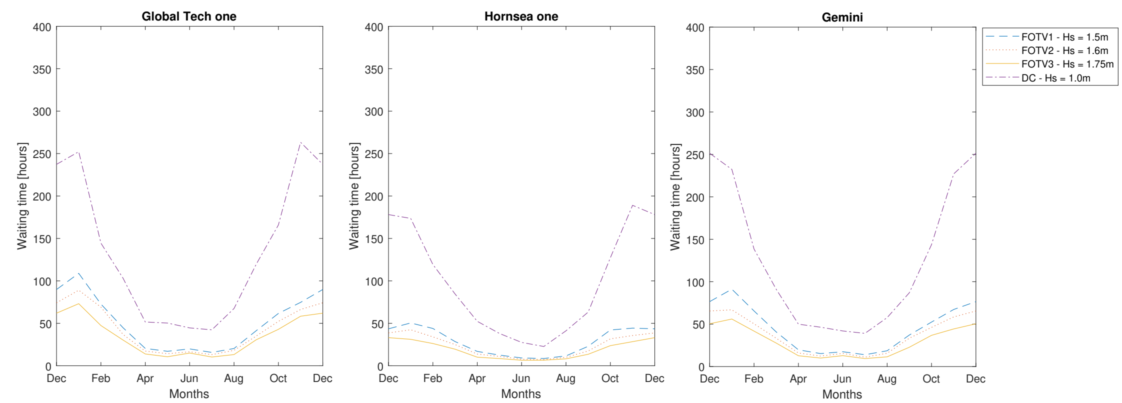

Figure 7.18: Wind farm comparison: Waiting time

Waiting times As for the operability, the results of Hornsea one are better than those of Global Tech one and Gemini. The performance of the FOTVs is significantly better in Hornsea one than for the other two wind farms. With the operability results in mind, the waiting time results behave as expected with one exception. The month of December for wind park Gemini has higher operability than the month of November and January but the opposite is true for the waiting times. The only explanation for this is that the waiting time takes operating hours into account and the operability doesn't. In other words, the month of December has significantly better conditions during the night than during the day when compared to other months. The same effect is seen when comparing the month of December and January for Hornsea one.

7.7.2 Logistic results

The logistic results for the three different wind farms are presented and discussed in this section. The results for the overall high limit are shown in figure 7.19. These results are very similar to each other. Similar to the previous comparison in accessibility, Hornsea one shows better results than the other two wind farms. In particular, the highest limits have significantly lower occurrence in Hornsea one. Moreover, Hornsea one shows better results for the lower limits in summer. When Global Tech one and Gemini are compared, the latter shows slightly better weather conditions.

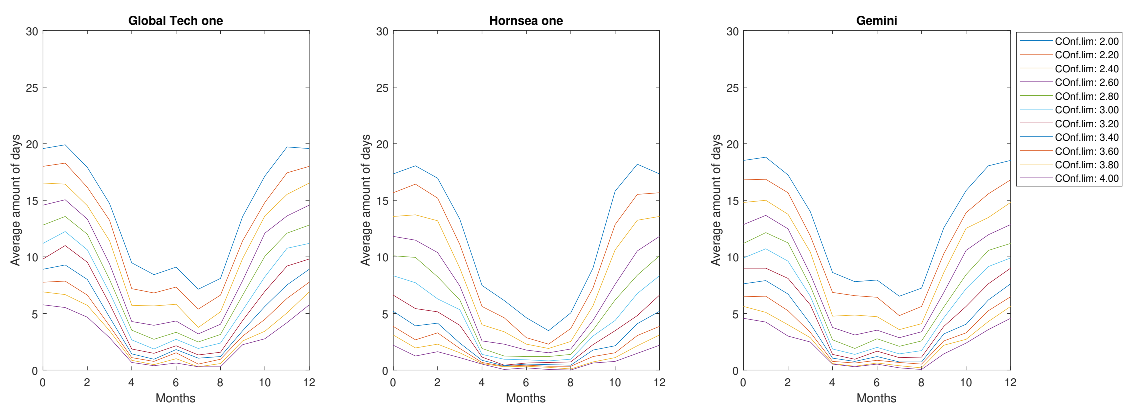

Figure 7.19: Wind farm comparison: High wave limit exceedance

In figure 7.20, the results are shown for the combination of an overall limit of 2.0m and a limit during crew change hours corresponding to the vessel transfer limit. The wind farms have similar results for the lower limits in winter. Apart from that, Hornsea one shows better results again.

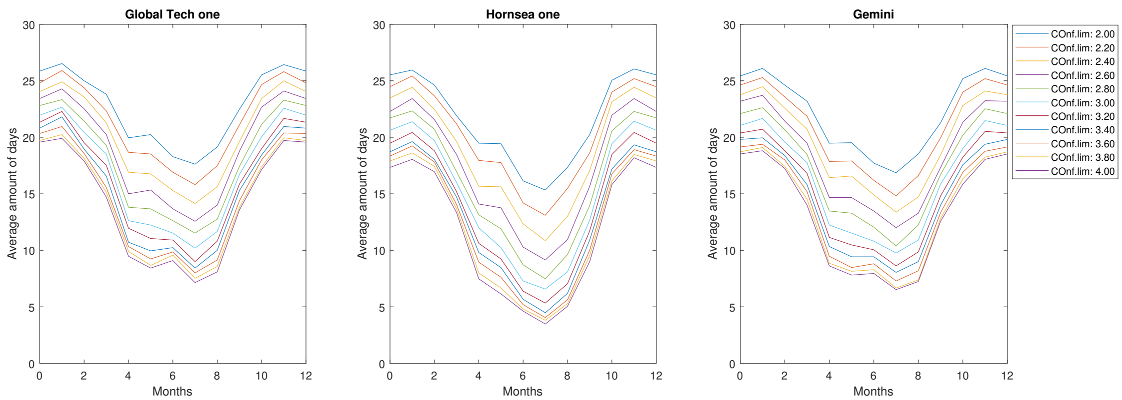

Figure 7.20: Wind farm comparison: Limits at crew change

7.7.3 Economic results

The last comparison between the wind parks is based on the economic results. All differences between wind parks have an influence on these results. The differences in weather at the site but also the amount and power of WTGs and the distance between WTGs and to shore. Each configuration will be calculated for all three wind parks and evaluated. Starting at the first configuration, lifting launch, which is shown in figure 7.21. Here it's clear that Hornsea one is the most profitable of all three wind farms. First the weather conditions in Hornsea one are better operable than the other two wind farms. Secondly, the installed power is higher because of the higher amount of WTGs and power per WTG. This increases the effect of downtime reduction because more power is generated per hour of downtime saved. On the other hand, the fuel cost and configuration cost are higher for Hornsea one because of the long distance to shore and distance between WTGs. The costs of Gemini and Global Tech one are very similar. However, the downtime reductions are higher for Gemini with similar weather conditions. This is explained by the fact that Gemini has a higher installed power which increases the economic effect of a reduced weather downtime. These phenomena are also seen in the other two configurations, shown in figure 7.22 and figure 7.23.

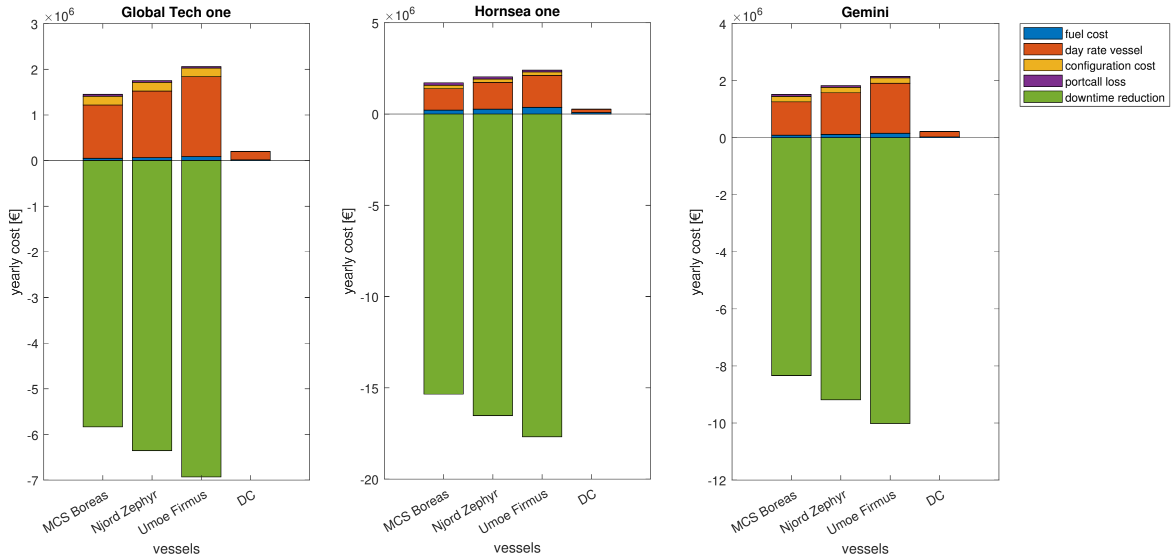

Figure 7.21: Wind farm comparison: Economic effects for lifting launch configuration

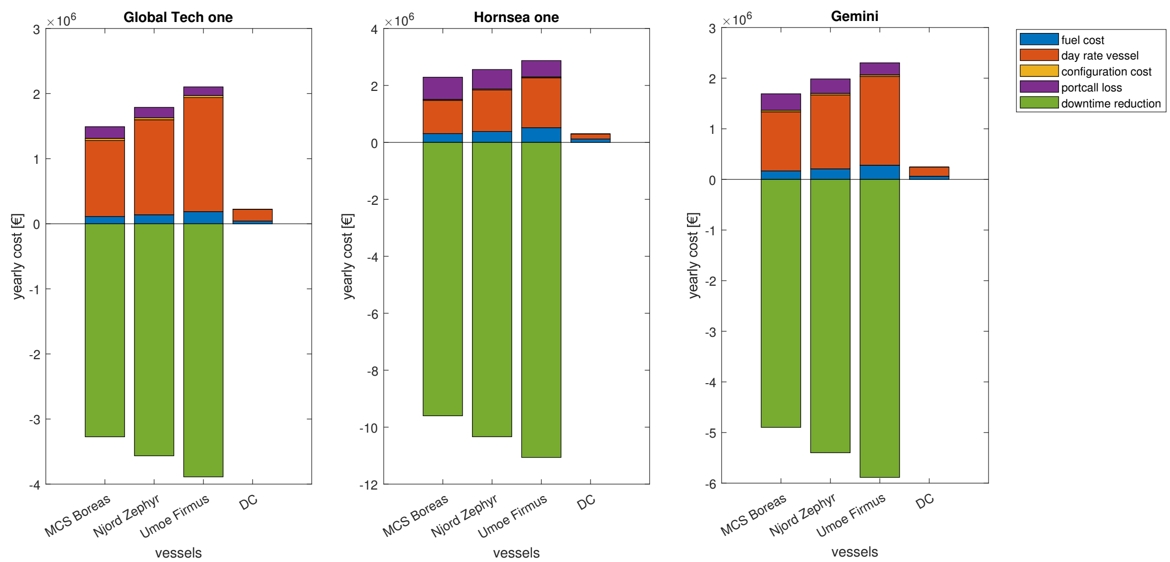

Figure 7.22: Wind farm comparison: Economic effects for connected to the SOV configuration

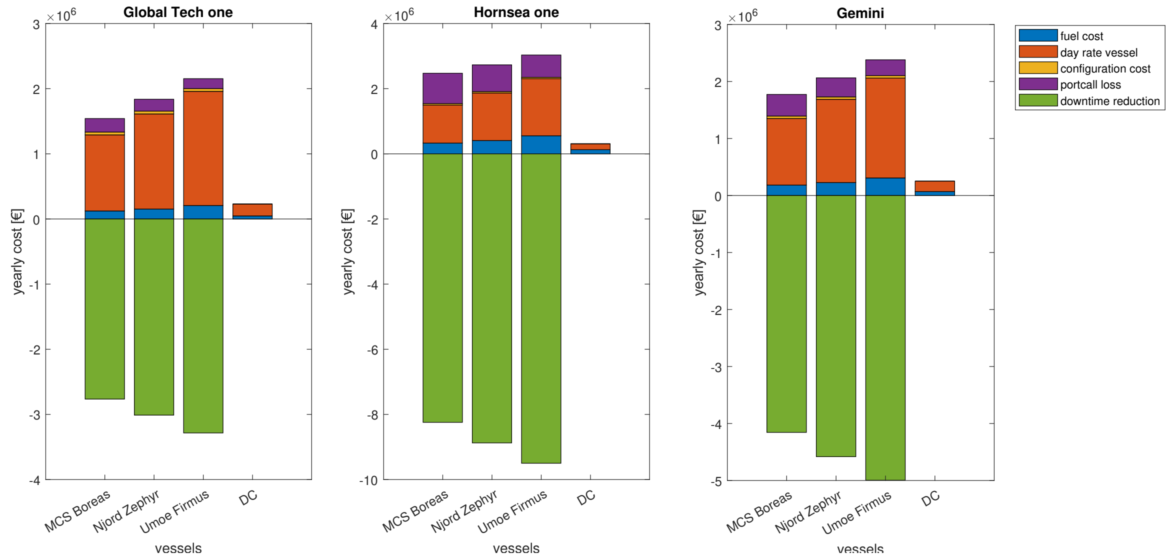

Figure 7.23: Wind farm comparison: Economic effects for moored to designated platform configuration

7.8 Sensitivity study

To assess the model even further, a sensitivity study is carried out on the four most relevant variables. These variables are expected to impact the outcome and more importantly are expected to vary in the coming years and decades. The four variables are listed below.

1. Electricity price
2. Fuel price
3. Configuration limits
4. Distance to shore

After the presentation and evaluation of the incremental changes to the variable, the variable is altered in such a way that the current conclusion on profitability becomes false. By assessing the edge case an insight is gained into how likely the conclusion will remain true for an extended period of time. Finally, a combined edge case is tested to find the boundary of the combined four variables.

7.8.1 Electricity price

The wind farm owner sells the generated electric energy according to the Power Purchase Agreement (PPA) with an energy company. This price can differ over time and is based on the volume and reliability of the power generation. The price is set at € 0,07 according to the price set in Germany [Ellen Thalman and Benjamin Wehrmann, 2021] for the last 20 years. By altering the value of energy price by relative increments the behavior of the outcome is modeled. Only the impact of downtime reductions is affected and this is done linearly. This means that an increase in energy price favors the choice of a high-performing vessel and a lower energy price favors the choice of a lower-performing vessel. Furthermore, the effects are higher for the configuration where the cumulative costs are closer to the downtime reduction. In other words, the impact of energy prices is higher for the lower-performing configurations. In table 7.6, the effects of a 10% increase and a 10% decrease in the electricity price are shown.

	Lifting launch		**Connected to SOV**		**Moored to platform**	
	Plus	**Minus**	**Plus**	**Minus**	**Plus**	**Minus**
Msc Boreas	13.1%	-13.1%	17.2%	-17.2%	20.6%	-20.6%
Njord Zephyr	13.6%	-13.6%	18.9%	-18.9%	23.7%	-23.7%
Umoe Firmus	14.1%	-14.1%	20.7%	-20.7%	27.2%	-27.2%

Table 7.6: Effect of electricity price change of 10% on the overall economics

Edge case study: Electricity price

The price of electricity is dropped to the point that the lowest-performing configuration isn't profitable anymore. This happens just above an electricity price of €0.04. First, the higher-performance FOTVs become unprofitable, and at just below €0.04, the lowest-performing FOTV becomes unprofitable too. By reducing the energy price to €0.02, all configurations become financially unattractive. The lower-performing FOTVs are still profitable but because of the high investment, these profits come at high risk. The chance of electricity prices reaching these low numbers is not likely with the steadily increasing demand for energy.

7.8.2 Fuel price

The fuel price of fuel is set at €890 per ton MDO [ship and bunker, 2019]. Because the impact of fuel cost on the economics is not that significant, the effects of incremental increases aren't either. However, the fuel price shows high volatility and therefore is worth assessing. In table 7.7 the effects of a 10% increase and a 10% for the overall economic results are shown.

	Lifting launch		Connected to SOV		Moored to platform	
	Plus	**Minus**	**Plus**	**Minus**	**Plus**	**Minus**
Msc Boreas	-0.1%	0.1%	-0.6%	0.6%	-1.0%	1.0%
Njord Zephyr	-0.1%	0.1%	-0.8%	0.8%	-1.3%	1.3%
Umoe Firmus	-0.2%	0.2%	-1.0%	1.0%	-1.8%	1.8%

Table 7.7: Effect of fuel price change of 10% on the overall economics

Edge case study: Fuel price

When the fuel price is increased to €7000 per ton MDO, the moored to designated platform configuration becomes unprofitable. For a fuel price of €60,000 per ton MDO, all configurations become financially unattractive and the low fuel consumption of the DC is the deciding factor. At that point, the decision to change to other means of energy carriers has long passed and both SOV and FOTV will have to sail on alternative fuels.

7.8.3 Configuration limits

The configuration limits are of high significance for the economic results. Only the overall configuration limits are changed, and the vessel transfer limits remain the same. In table 7.8 the effects of a 10% increase and a 10% decrease are shown for the overall economic results. A similar effect for the electricity price can be found, where the higher-performing configurations are relatively less impacted than the lower-performing configurations. This similarity can be explained by the fact that both the configuration limit and electricity price mainly influence the downtime reduction. When the costs remain constant, the relative effect is higher for the case where the downtime reduction is closer to the sum of the other cost factors. However, the moored to designated platform configuration behaves differently. The effects for both the increase and decrease are lower than for the connected to the SOV configuration and the effects of decrease and increase differ significantly from each other. This is because of the second configuration limit which is linked to the vessel transfer limits. When the overall limit is increased from 2.0m to 2.2m, the increase in operability is limited by the requirement that states that at crew change, the significant wave height must remain under the vessel transfer limit. The result shows the effect of the vessel limits, the higher-performing FOTVs are more affected by the change in configuration limit than the lower-performing vessels. The decrease in configuration limit for the moored to a designated platform configuration holds a higher effect because of the constant sum of other cost factors.

	Lifting launch		Connected to SOV		Moored to platform	
	Plus	**Minus**	**Plus**	**Minus**	**Plus**	**Minus**
Msc Boreas	4.4%	-6.2%	26.1%	-27.1%	6.0%	-11.2%
Njord Zephyr	4.5%	-6.4%	28.3%	-29.4%	11.7%	-17.7%
Umoe Firmus	4.6%	-6.6%	30.6%	-31.8%	17.6%	-24.3%

Table 7.8: Effect of configuration limit change of 10% on the overall economics

Edge case study: Configuration limits

First, the edge case study is performed for the lifting launch configuration. Around an overall limit to stay in the wind farm of 1.5m the configuration becomes financially unattractive. This limit is lower than any SOV limit in current practice and so holds no risk for the outcomes of this research. For the configuration limits of the second two configurations, the edge value of the overall limit is below the transfer limit of the lowest-performing vessel. Therefore these edge cases hold no risk for the outcome of this research.

7.8.4 Distance to shore

The final subject of the sensitivity study is the distance to shore. The effect of this variable is seen in both port call loss and fuel consumption and is shown in table 7.9. The effects are low but because of the trend of wind farms moving further from shore, it is of high interest. Like the previous sensitivity studies, the effects are higher for the lower-performing configurations. What is interesting is the difference in results per vessel for the connected to the SOV configuration. The effects of the vessel speed, day rate, and fuel consumption form a balance around the current input values. The increase in fuel consumption and day rate for a higher-performing vessel are compensated by the increase in speed and therefore the reduction in waiting time.

	Lifting launch		**Connected to SOV**		**Moored to platform**	
	Plus	**Minus**	**Plus**	**Minus**	**Plus**	**Minus**
Msc Boreas	-0.1%	0.1%	-1.5%	1.5%	-2.4%	2.4%
Njord Zephyr	-0.1%	0.1%	-1.4%	1.4%	-2.5%	2.5%
Umoe Firmus	-0.1%	0.1%	-1.5%	1.5%	-2.7%	2.7%

Table 7.9: Effect of the distance to shore change of 10% on the overall economics

Edge case study: Distance to shore

To find out if there is a maximum distance to port for which the conclusions remain true, the distance to port is increased. At around 8 times the current distance to shore, at a value of 300 nautical miles, the second two configurations become unprofitable. These configurations are more sensitive to this variable than the lifting launch configuration because of the number of port calls.

When the distance to port is increased 65 times, at a value of 2500 nautical miles, all configurations are financially unattractive. This is two-thirds across the Atlantic ocean from Rotterdam. There won't be any wind farm location in the world that is that far from a port. Therefore, the distance can increase over the years without these conclusions becoming untrue.

7.8.5 Combined edge cases

A combination of variable alteration is assessed for a more realistic scenario where the conclusions of this research become false. With the set of alterations shown below, the second two configurations are highly unprofitable. However, the lifting launch configuration is still financially attractive. If the electricity price is lowered even further to €0.035 per kWh, the lifting launch configuration is also unprofitable. The occurrence chance of one of these four variable alterations is quite low. The chance that all four alter in this direction is highly unlikely

Variable changes

Electricity price	from €0.07	to €0.05
Fuel price	from €890	to €1780
Configuration limits	from 4.0m and 2.0m	to 3.6m and 1.8m
Distance to shore	from 37.8 nm	to 378 nm

With all the results gathered from all calculations and the sensitivity study, the conclusions on this research can be drawn and are presented in the next chapter.

8 | Conclusion

In this chapter, the conclusions are drawn for the whole research. The research questions are answered one by one and comments are placed concerning the validity of every answer. The sub-questions are answered first, and the main research question is answered after.

What are the limitations in accessibility in far-offshore wind farms and to what extent do they hinder accessibility? The motions of the vessel induced by wind, current, but mostly waves, lead to two major limitations:

- The safety of technicians during transfer is reduced by vessel motions. The chance of falling overboard is increased when the vessel moves relative to the turbine ladder. A certain safety standard is necessary for operation. Therefore the severity of the weather determines if the operation is possible.
- The motions of the vessel during all three stages but especially during transit can make the crew fatigued, nauseated, or even cause physical harm. Heave, roll, and pitch motions are the main drivers behind these effects. The weather conditions have a significant effect on these motions. Because these are all three effects to be avoided, the weather determines if the operation is possible.

The combination of both limitations with the weather in far-offshore wind farms results in low accessibility, 0 to 10 days a month. Other limitations are the availability of technicians and the equipment capacity of the daughter craft.

How can the effectiveness of the DC(or other transport) be improved and what KPIs can describe this improvement? A set of performance requirements is developed, that function as KPIs. These requirements consist of general requirements, transfer safety requirements, and crew comfort requirements. These are far more elaborate than the current standard in the system which only uses significant wave height to define what weather conditions the system can safely operate in. This research finds that this deficiency in performance description hinders the accurate comparison between existing and future systems.
These requirements also compartmentalize the areas of improvement and in section 5.1 many system alternatives propose to improve on all different areas. Novel technologies or design alteration of the daughter craft can improve the seakeeping and therefore reduce limitations, the weather conditions could be reduced by floating breakwater systems or evaded by diving under the wave spectrum, and multiple methods exist to lower susceptibility to motion sickness.

Which improvement is expected to increase accessibility the most? The size increase of the DC is deemed most applicable to improve performance at this point. This so-called Far offshore transfer vessel (FOTV), proposes improvements to all of the accessibility KPIs. The other system alternatives could still pose significant improvement individually or in combination with the FOTV system. Most of these alternatives are less developed and therefore are expected to require relatively extensive research before the performance can be estimated.

What new challenges does this improvement introduce and what are their effects? The main challenge is storing the FOTV in the wind farm without damage to the vessel or risking the safety of the crew. This requires a solid interface with the SOV for exchanging crew and cargo between both vessels. Furthermore, the FOTV must be able to stay in the wind farm as often as possible to maximize its accessibility improvement.

How can these challenges be met? The solutions are divided into two principal concepts: The enlarged daughter craft concept and the exposed concepts. From these principal concepts, three configurations are deemed feasible by this research: lifting launch, connected to the SOV, and moored to designated platform.

How can the performance of these novel solutions be predicted? A statistical model is developed based on hindcast data of wind farms. Three methods of calculating average waiting time with the hindcast data have been identified: A statistical, direct historical, and a Monte Carlo simulation approach. The direct historical approach is deemed most applicable for this research because of the availability of data. The outcomes couldn't be verified because no accessibility data is available. The model predicts the accessibility performance, logistical performance, and economic performance of each combination of configuration, vessel, and wind farm.

How is the system expected to differ from the status quo? The FOTVs are predicted to improve accessibility and realize a profit for every configuration, wind farm, or choice of vessel. From the model results a few conclusions can be drawn:

- The model can calculate which existing vessel is most profitable based on the accessibility performance and cost of a set of vessels.
- The relation between vessel limits [H_s] and average waiting time is inverse exponential. So the relative effect of a better performing vessel decreases when vessel performance increases. This favors replacing the lower performing vessels first and profit increases are most significant in harsher conditions, e.g. during winter.
- The day rate is the highest cost factor for each FOTV.
- The logistical and financial results differ per wind farm and so does the most profitable vessel.

Finally, the model is based on a set of assumptions, which if proven false, undermine the results. Most significantly, the vessel parameters, energy price, configuration limits, and accuracy of hindcast data, significantly decrease the value of the results if assumed incorrectly.

8.1 Answering main research questions

How can the accessibility during unplanned maintenance of far-offshore wind farms be improved?

By deploying a FOTV with a lifting launch configuration, the accessibility can be improved significantly. Moreover, the costs of this vessel and configuration are more than compensated by the benefit of the increased accessibility. When due to market instability or lack of funds a preference for low investment solutions is present, the connected to the SOV configuration will also offer higher accessibility and ample compensation for costs. Finally, the moored to a designated platform is also deemed profitable but less so than the other two configurations.

8.2 Recommendations

Develop an inclusive method for describing accessibility performance in unplanned maintenance for far-offshore wind parks By doing so a framework can be created to assist the development of improved systems. Without such a method most improvements focus on one particular requirement without knowing if the design choices lower other KPIs. The method will help shipbuilders in their design process and maintenance suppliers such as Siemens Gamesa with the right fleet configuration.

Increase knowledge of hydrodynamics of small vessels in high-speed transit This can be done analytical or numerical by retrieving data from existing vessels and using machine learning to approximate the hydrodynamic relations. Either way, the comfort and safety of the technicians can only be predicted if the vessel motions are better predicted.

Increase knowledge of the long-term effect of high accelerations over time Because the current regulations are not yet set on the long-term effects of high accelerations on the brain, a risk is taken by exposing offshore personnel to these kinds of conditions. One way of finding out if this risk is tangible is by looking into subjects who have endured similar conditions in the past like the crew of small coast guard vessels or some professionals in the navy.

Collect data There is little data on CTV vessel motions and almost no data on daughter craft use. The challenges surrounding accessibility in unplanned maintenance for far-offshore wind parks would be made a lot clearer if the vessel motions of some CTVs and DCs had been monitored for the last year. This would allow validation of the calculations done in this research. Furthermore, structured data on transfer incidents and their causes and motion sickness incidents would be very insightful. Finally, captain reports that include every time the call is made that the weather is or isn't safe for use, would be very helpful. This data could be compared with weather data and the human aspect could be assessed.

Alternative systems The alternatives that weren't selected for further research still hold the potential for system improvement. Some envelop a larger scope that can be covered in a single graduation thesis but could be executed by a Ph.D.

Bibliography

[4offshore, 2022a] 4offshore (2022a). Esvagt wind 1.

[4offshore, 2022b] 4offshore (2022b). Umoe Firmus.

[Abdullah et al., 2019] Abdullah, L., Chan, W., and Afshari, A. (2019). Application of PROMETHEE method for green supplier selection: a comparative result based on preference functions. *Journal of Industrial Engineering International*, 15(2):271–285.

[Administration, 2021] Administration, U. S. E. I. (2021). Levelized Costs of New Generation Resources in the Annual Energy Outlook 2021. Technical Report February 2021.

[Alkhairi et al., 2019] Alkhairi, P., Purba, L. P., Eryzha, A., Windarto, A. P., and Wanto, A. (2019). The Analysis of the ELECTREE II Algorithm in Determining the Doubts of the Community Doing Business Online. *Journal of Physics: Conference Series*, 1255(1).

[Behzadian et al., 2010] Behzadian, M., Kazemzadeh, R. B., Albadvi, A., and Aghdasi, M. (2010). PROMETHEE: A comprehensive literature review on methodologies and applications. *European Journal of Operational Research*, 200(1):198–215.

[Bogdanov et al., 2021] Bogdanov, D., Ram, M., Aghahosseini, A., Gulagi, A., Oyewo, A. S., Child, M., Caldera, U., Sadovskaia, K., Farfan, J., De Souza Noel Simas Barbosa, L., Fasihi, M., Khalili, S., Traber, T., and Breyer, C. (2021). Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. *Energy*, 227:120467.

[Bos, 2004] Bos, J. (2004). How motions make people sick such that they perform less: A model based approach. *NATO RTO/AVT-110 Symposium on Habitability of Combat and Transport Vehicles: Noise, Vibration and Motion*, pages 1–11.

[Brans, 2021] Brans, S. (2021). *Applying a Needs Analysis to promote Daughter Craft for year-round access to far-offshore wind turbines*. PhD thesis, Delft.

[BSI, 1997] BSI (1997). BS ISO 2631-1 : 1997 BSI Standards Publication Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration Part 1 : General Requirements.

[BVG associates, 2021] BVG associates (2021). Wind farm cost.

[Cepowski, 2012] Cepowski, T. (2012). The prediction of the Motion Sickness Incidence index at the initial design stage. Technical report.

[Cooper et al., 2011] Cooper, W. W., Seiford, L. M., and Zhu, J. (2011). *Data envelopment analysis: History, models, and interpretations*, volume 164.

[Costa et al., 2021] Costa, A. M., Orosa, J. A., Vergara, D., and Fernandez-Arias, P. (2021). New tendencies in wind energy operation and maintenance. *Applied Sciences (Switzerland)*, 11(4):1–26.

[Craft, 2022] Craft, N. (2022). Suspension hull.

[Deepflight, 2022] Deepflight (2022). Falcon.

[Dewan and Asgarpour, 2016] Dewan, A. and Asgarpour, M. (2016). Reference O&M Concepts for Near and Far Offshore Wind Farms. Technical report.

[Dikis, 2018] Dikis, K. (2018). Development trends of offshore wind industry and effect on cost aspects.

[Drago et al., 2017] Drago, M., Del Guzzo, A., Vitali, L., and Bruschi, R. (2017). Weather stand-by assessment in offshore operations using motion limit criteria. *Proceedings of the International Offshore and Polar Engineering Conference*, (August):494–501.

[Ellen Thalman and Benjamin Wehrmann, 2021] Ellen Thalman and Benjamin Wehrmann (2021). What German households pay for power.

[Energy institute and G+ Global offshore wind, 2018] Energy institute and G+ Global offshore wind (2018). *Good practice guideline Working at height in the offshore wind industry Second edition In partnership with.*

[Fleetmon, 2022] Fleetmon (2022). MCS Boreas.

[G+ Global Offshore Wind, 2020] G+ Global Offshore Wind (2020). G+ Global Offshore Wind Health & Safety Organisation - Incident Data Report.

[Han et al., 2021] Han, X., Leira, B. J., Sævik, S., and Ren, Z. (2021). Onboard tuning of vessel seakeeping model parameters and sea state characteristics. *Marine Structures*, 78(January):102998.

[HiswateWater, 2022] HiswateWater (2022). Rotorswing.

[IPPC, 2021] IPPC, I. (2021). Climate Change 2021 The Physical Science Basis Summary for Policymakers. Technical report.

[Jansen et al., 2020] Jansen, M., Staffell, I., Kitzing, L., Quoilin, S., Wiggelinkhuizen, E., Bulder, B., Riepin, I., and Müsgens, F. (2020). Offshore wind competitiveness in mature markets without subsidy. *Nature Energy*, 5(8):614–622.

[Kok et al., 2018] Kok, R., Vrijdag, A., van 't Veer, R., and Abbink, D. (2018). Haptic assistance to mitigate damaging vertical accelerations of small ships in head waves.

[Kongsberg, 2022] Kongsberg (2022). Boat transfer system.

[Kossiakoff et al., 2003] Kossiakoff, A., Sweet, W. N., Seymour, S. J., and Biemer, S. M. (2003). *System engineering principles and practice.*

[Lai et al., 1994] Lai, Y. J., Liu, T. Y., and Hwang, C. L. (1994). TOPSIS for MODM. *European Journal of Operational Research*, 76(3):486–500.

[Liu, 2015] Liu, Z. (2015). *Supply and demand of global energy and electricity.*

[Marine, 2022] Marine, R. (2022). ok hull.

[Maritime, 2019] Maritime, B. (2019). VROON WALK-TO-WORK VESSEL COMPLETES TWO-YEAR CHARTER FOR MHI VESTAS.

[Maritime partner, 2022] Maritime partner (2022). Alusafe 1150.

[McCartan et al., 2015] McCartan, S., Moody, L., Thompson, T., and Verheijden, B. (2015). A SWATH MOTHERSHIP CONCEPT FOR THE FAR SHORE WIND FARMS USING THE ENVIRONMENTAL PSYCHOLOGY NETWORK MODEL. *EWEA Offshore Conference2015*, (December).

[McCradden and Cusimano, 2018] McCradden, M. D. and Cusimano, M. D. (2018). Concussions in sledding sports and the unrecognized "sled head": A systematic review. *Frontiers in Neurology*, 9(SEP):1–8.

[McTaggart, 2014] McTaggart, K. (2014). Hydrodynamic Interactions during Launch and Recovery of a Small Boat from a Ship in a Seaway. Technical report.

[Mctaggart et al., 2016] Mctaggart, K., Hendriks, S., Nimmo-Smith, I., Oydegard, A., Pattison, J., and Stuntz, N. (2016). Considerations in Development of Naval Ship Design Criteria for Launch and Recovery. Technical report.

[Mobimar, 2012] Mobimar (2012). Mobimar 18 wind.

[Nauti-craft, 2022] Nauti-craft (2022). Innovative Crew Transfer Vessel with Nauti-Craft Suspension System by Wallaby Boats.

[Njord offshore, 2022] Njord offshore (2022). Njord Zephyr.

[Opricovic and Tzeng, 2004] Opricovic, S. and Tzeng, G. H. (2004). Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. *European Journal of Operational Research*, 156(2):445–455.

[Opricovic and Tzeng, 2007] Opricovic, S. and Tzeng, G. H. (2007). Extended VIKOR method in comparison with outranking methods. *European Journal of Operational Research*, 178(2):514–529.

[Palfinger, 2022] Palfinger (2022). PALFINGER MARINE SLIPWAY AND STERN ENTRY SYSTEMS SLIPWAY AND STERN RECOVERY SYSTEMS.

[Pavić and Novoselac, 2013] Pavić, Z. and Novoselac, V. (2013). Notes on TOPSIS Method. *International Journal of Research in Engineering and Science*, 1(2):5–12.

[Prozero, 2021] Prozero (2021). PROZERO 11M DCW CREW TRANSFER VESSEL.

[Prozero, 2022] Prozero (2022). ASV Technology.

[Qcollar, 2022] Qcollar (2022). Qcollar.

[Quick, 2022] Quick (2022). MC² X7 DC.

[Ramirez et al., 2019] Ramirez, l., Fraile, D., and Brindley, G. (2019). Offshore wind in Europe.

[Ramirez et al., 2020] Ramirez, L., Fraile, D., and Brindley, G. (2020). Offshore Wind in Europe.

[Ren and Lützen, 2017] Ren, J. and Lützen, M. (2017). Selection of sustainable alternative energy source for shipping: Multi-criteria decision making under incomplete information.

[Riis, 2019] Riis, M. (2019). SPARTA-Portfolio-Review-201819. Technical report.

[schlomer, 2019] schlomer, S. (2019). Technology-specifi c Cost and Performance Parameters. pages 1329–1356.

[Sheinberg et al., 2003] Sheinberg, R., Minnick, P. V., Beukema, T. G., Kauczynski, W., Silver, A. L., Cleary, C., Allan, R. G., Werenskiold, P., De Kat, J. O., Byers, D. W., and Lin, W. M. (2003). Stern boat deployment systems and operability. *Transactions - Society of Naval Architects and Marine Engineers*, 111(M):1–32.

[ship and bunker, 2019] ship and bunker (2019). Rotterdam bunker prices.

[Ship spotting, 2022] Ship spotting (2022). Esvagt Aurora - IMO 9594042.

[Smith, 2010] Smith, T. C. (2010). Launch and Recovery System Literature Review. (December).

[Tudem and Livgård, 2011] Tudem, U. S. and Livgård, T. K. (2011). Air Supported Vessel (ASV) Monohull Demonstrator. Design development, testing at sea and results proving the Concept. Technical report.

[Ulstein, 2021] Ulstein (2021). State-of-the-art service vessels for offshore wind.

[Vakilipour et al., 2021] Vakilipour, S., Sadeghi-Niaraki, A., Ghodousi, M., and Choi, S. M. (2021). Comparison between multi-criteria decision-making methods and evaluating the quality of life at different spatial levels. *Sustainability (Switzerland)*, 13(7):1–36.

[Valpy et al., 2017] Valpy, B., Hundleby, G., Freeman, K., Roberts, A., and Logan, A. (2017). Future renewable energy costs:
}Offshore wind.

[Vestdavit, 2020] Vestdavit (2020). F Type.

[Wertheim et al., 1999] Wertheim, A. H., Bos, J. E., and Bles, W. (1999). Contributions of roll and pitch to sea sickness. Technical report.

[Wiser et al., 2016] Wiser, R., Jenni, K., Seel, J., Baker, E., Hand, M., Lantz, E., and Smith, A. (2016). Expert elicitation survey on future wind energy costs. *Nature Energy*, 1(10).

[Zhao et al., 2019] Zhao, X. L., Ning, D. Z., Zou, Q. P., Qiao, D. S., and Cai, S. Q. (2019). Hybrid floating breakwater-WEC system: A review. *Ocean Engineering*, 186(June):106126.

A | Interviews with industry experts

Interviews were held throughout the whole duration of the literature study. There are no recordings of the interviews to maintain an open environment for sharing information and brainstorming. Below the summary of the notes is presented with the date of the interview. The text presented in this appendix is not an exact account of the interview but written notes of the interviews. Furthermore, not all meetings are represented here. Most of the weekly update meetings are not shown in this overview.

Employees Siemens Gamesa
Fernando Sanchez Santiago, Principal naval architect
Rene Wigmans, Global head of offshore service logistics
Hugo Cook, Vessel asset manager
Robert Deen, Maintenance supervisor
Florian Hoffman, Deputy site manager
John Snaith, Program manager - logistical sales support
Malene Juul Rasmussen, data science and availability model specialist
Ingmar Bos, Senior technician
Zak Brockman, project manager external

Other
Mark Paalvast, Co-founder MO4
Jaap Gelling, lecturer ship design TU Delft
Harleigh Seyffert, ship hydromechanics TU Delft
Jelte Bos, researcher TNO
Daniel Flato, marine superintendent BSM
Kai Gjerde, sales manager Vestdavit
Helge Hestø Andersen, sales manager Umoe Mandal
Per Christian Mogster, Innovation manager Vestdavit
Pauli Immonen, Mobimar

Interviews taken by author: Huug Kamerbeek

R. Wigmans: [22/10/2021] *Orientation meetings with Siemens Gamesa* I'd like you to zoom out and not limit yourself to the DC design. Look at other options to improve accessibility.

F. Santiago: [22/10/2021] *Introduction in the subject during first orientation meetings* The two critical phases are highlighted: transfer and transit. These both pose different challenges that haven't been resolved to this point in time.
A size increase of the DC would probably help but is restricted by the SOV.
I'm interested in the KPIs of accessibility such as vertical acceleration. If I know what influences accessibility, I can configure the maintenance fleet more adequately. Currently, we only discuss the maximum significant wave height that the DC can handle according to the vessel supplier. The real performance of the DC then seems to vary enormously between locations and crews.
The most critical phase seems to be the transfer phase, as the safety of the technicians is more at risk during transfer and therefore is more limiting when it comes to adverse weather conditions.

H. Cook: [24/11/2021] *The main goal of the meeting is getting a general understanding of what influences the decision of deploying a DC* Other reasons than weather restrictions for a DC not to sail can be related to the lack of technicians, not enough capacity for equipment onboard the DC or planning restrictions.
SGRE plans the use of the DC but the captain of the SOV and the captain of the DC determine if it's safe.
I agree with Fernando that the transfer phase is most critical but the transit phase is dangerous too and can be very uncomfortable. Especially when there is a high current, it's hard

to make a connection to the boat landing of the turbine.

R. Deen: [01/12/2021] *The goal of this meeting was retrieving historical maintenance data* The highest significant wave height successfully endured by DCs is between 1.0m and 1.2m.
Algae growth on the secondary steel of the turbine can increase the slip chance during transfer.
An unplanned service call is often handled the next day because the technicians are already booked on that day. Only when five turbines or more are down, a second troubleshooting team is assigned. This happens around three times per year.
The DC is a valuable asset in the eyes of the planner. But experience tells us that in the best months(summer) a DC can only be used in one-third of the days. CTV on the other hand has significantly higher accessibility.

F. Hoffman: [06/12/2021] *The goal of this meeting was to understand the perspective of the team onboard the SOV* The relative wave angle to the DC is very important for the transfer phase.
I think the low accessibility is a huge problem for our maintenance strategy and most down-time could be solved with a better performing DC.
I don't take seasickness into account when deploying a DC, just the significant wave height. But this can be a limiting factor for the crew of the DC. The windows of a DC are higher than that of a CTV which doesn't allow the crew to see the horizon all the time.
I would be helped a lot by a more complete method for predicting accessibility. Significant wave height is not complete enough.

M. Paalvast: [17/12/2021] *The meetings main subject was the alternative safety prediction that MO4 offers instead of significant wave height* We have made a slip model and magnitude model for the transfer phase based on physical models and a series of assumptions. Our test results for slip occurrence match the real live tests adequately.
One of the difficulties for predicting slip during transfer is that there is no single wave train but at least two: swell and wind.
The transit phase motions are more difficult to predict. This is also influenced by the water depth.

R. Wigmans: [23/12/2021] *During the weekly update meeting* There is a difference between the captain of the DC and the technicians. The latter is probably less resistant to heavy weather, but you have to take into account that they have a different task. Seasickness will have different outcomes for different tasks.

J. Snaith: [25/01/2022] *The meeting revolved around the current practice of accessibility prediction and how the results were used in the company.* The prediction tool is based on hindcast data from the year 2000 until now. The (Matlab) tool further requires a time window and vessel limits. The tool is made by Siemens Gamesa and a newer version is just being rolled out these months. The output of the model is an accessibility percentage that we can use to form our proposal to a client.

M. Rasmussen: [28/01/2022] *The goal of this meeting was to understand the calculations behind the in-house tool for accessibility prediction* The hindcast data that we use is not very accurate. The significant wave height and wind speed are mandatory inputs but there are many more possible limitations available in the tool. The tool will calculate the most optimal boat landing direction if directional preferences of the asset are given as input. This is for example the case for SOVs.

F. Santiago: [16/02/2022] *This meeting was held to discuss the right way to approach the complexity of non-linearity in vessel motion prediction of high-speed transit* The decision between a time domain or frequency domain simulation comes to the non-linear components of the system and the calculation time you can afford. Then either a wave spectrum or wave parameters are needed.
A positive trend in our relationship with vessel owners is that new agreements can be made based on availability per year instead of incomplete vessel performance.

I. Bos: [17/02/2022] *The goal of the meeting was to find data that could help validate any accessibility prediction improvements.* The MORS system might not be your best source of information as the system can also close matters on its own and doesn't specify which vessel is used. And the matters described in the file might not be the main error. The SRP system is better suited for your inquiries as this does register DC usage. The launch or recovery of a DC prohibits the SOV to work on something else. Another interesting source of info for you might be the HSE complaints filed for DC usage. There are in theory four parties that decide if the DC is used, first the site office puts in the request if they deem it safe and necessary, then the bridge of the SOV checks it, then the DC captain could still deem it unsafe and finally the technicians can break off the operation at any point they feel unsafe.

M. Paalvast: [10/03/2022] In this meeting it became clear that the implementation of the MO4 software for this research wasn't a perfect match. We did conclude that both vessel motions of CTVs and DCs during transfer could be predicted with reasonable accuracy, but that external factors didn't allow the implementation for this research. Also the inner workings of the software where briefly discussed.

H.C. Seyffert: [15/03/2022] Inquiry in different methods to predict vessel motions in high speed transit for small vessels.

J. Gelling: [16/03/2022] Discussed the implementation of FASTSHIP for predicting the motions of small vessels in high speed transfer. Many ship design aspects to take into account in this sector.

J. Bos: [22/03/2022] The interview became an elaborate lecture on motion sickness. Two major factors in sea sickness are frequency and amplitude of the accelerations. People can get used to a certain frequency but only to one frequency, this is probably the dominating SOV frequency in this case. Furthermore, a large range of solutions to and ways of predicting seasickness are discussed.

D. Flato: [31/03/2022] The interview focused on the current operation and regulations surrounding DC deployment. Short wave periods decrease the operable Hs limit. The DC is usually deployed in the lee of the SOV. Most accidents happen during L&R, but not because of the weather but just because of the effect when the lifting system fails. The crew and licence of a CTV/FOTV is more expensive than that of an DC.

K. Gjerde: [19/04/2022]This was one of the interviews concerning the capabilities of cranes, davits and stern ramps. Kai mentioned that the sector is demanding larger capacities every year. 80 ton is currently the max, theoreticaly. Vestdavit is looking at the 100 ton range.

H. Cook: [19/04/2022] Discussed the possibilities of leaving a CTV out in an offshore wind park for multiple days. Also looked at the case of the Njord Zephyr.

P. Immonen: [22/04/2022] Email contact on information request gripper system. There is no direct limit on duration of holding onto the boat landing. Both sliding and gripping mode don't require power except for the hydraulic power pack standing on standby which needs just a few KW per hour. The system can be fitted to different vessels but need to be redesigned for the corresponding loads. A decent price range is 500,000 for the system.

R. Wigmans: [24/4/22] Decision to keep the exposed configuration: connected to SOV, in the scope.

H.H. Andersen: [03/05/2022] Discussion about the performance of Wave Craft CTVs.

P.C. Mogster: [04/05/2022] Interview on future capabilities of Vestdavit products. Specific set of parameters for SOV and FOTVs was established.

Z. Brockman: [05/05/2022] Confirmation on regulations prohibiting leaving the FOTV unattended when moored offshore.

M. Rasmussen: [20/06/22] Meeting on new prediction tools within Siemens Gamesa and comparison of results. The old statistical model does daily calculations, using predefined operability. The simulation model uses the same operability for a Monte Carlo simulation.

B | Example VIKOR method

To illustrate the way VIKOR works a simple example is set up. Three virtual technologies with virtual parameters and virtual weights are put together, as can be seen in Table B.1. Additionally, a set of weights is assigned to the parameters. The parameter will later be noted as f_{ij}, the weights as w_j. J is the number of technologies j = 1, 2, 3,.. ,J and n is the number of parameters, i = 1, 2, 3,.. ,n.

Weights	9	8	7	6
	0,30	0,27	0,23	0,20
Technology\Parameter	Initial cost	OPEX	Emission cut	applicability on fleet (0-5)
One sail	100	20	500	4
Two sails	180	30	800	3
slow steaming	0	-10	600	5

Table B.1: Virtual data as an example for the VIKOR method

Then to determine the range of each parameter the best (f_i^*) and worst(f_i^-) are added to the Table B.2. This of course depends on whether a high or low parameter is preferred. For the cost, a low value is preferred but for emission cut, a high value is preferred.

Weights	9	8	7	6
	0,30	0,27	0,23	0,20
Technology\Parameter	Initial cost	OPEX	Emission cut	applicability on fleet (0-5)
One sail	100	20	500	4
Two sails	180	30	800	3
slow steaming	0	-10	600	5
Best (f^*)	0	-10	800	5
Worst(f^-)	180	30	500	3

Table B.2: Virtual data as an example for VIKOR, with f^* and f^-

Now two values have to be found for each parameter and technology. The S_J value, as shown in formula B.1, and its maximum for each technology, the R_J value, shown in formula B.2. The S_J value is the first step to a score by dividing the distance of the individual parameter to the optimum, by the maximum distance found in that parameter and multiplying this with the weight for that parameter.

$$S_j = \sum_{i=1}^{n} w_i * (f_i^* - f_{ij})/(f_i^* - f_i^-) \tag{B.1}$$

$$R_j = Max[w_i * (f_i^* - f_{ij})/(f_i^* - f_i^-)] \tag{B.2}$$

With:

w_i) - Weight corresponding to that parameter i, is a input of the decision maker [-]
f_{ij}) - Value for technology j for parameter i [-]

The lower the S_J value is, the lower the distance to the optimum every respective parameter for this technology is. So the S^* value depicts the lowest and therefore the best score. The same is true for the R_J value, as it depicts the lowest S_ij value for the technology and so the highest-performing parameter of the respective technology. The S^- and R^- values depict the opposite, so the highest value and because of that the lowest-performing. The results for this example are shown in table B.3.

	Initial cost	OPEX	Emission cut	Applicability on fleet (0-5)	S_j	R_j
One sail	0,17	0,20	0,23	0,10	0,70	0,23
Two sails	0,30	0,27	0,00	0,20	0,77	0,30
slow steaming	0,00	0,00	0,16	0,00	0,16	0,16
S^*,R^*					0,16	0,16
S^-,R^-					0,77	0,30

Table B.3: Virtual data as example for VIKOR, the f_{ij} values are replaced by S_{ij} values and the S_J and R_J Values are added

Finally, the Q_J value is formulated for every technology. This value combines all data in a final score with the following formula:

$$Q_J = \nu * (S_J - S^*)/(S^- - S^*) + (1 - \nu) * (R_J - R^*)/(R^- - R^*) \tag{B.3}$$

With:

ν - Weight for the strategy of maximum group utility [-]
$1 - \nu$ - Weight of the individual regret [-]

As can be seen in the formula, the score consists of two parts. The preference of the score towards the group utility (S) or to the individual regret (R) is defined by ν, initially, this value is set on 0,5 for an even division. The score divides the distance from the respective technology to the optimum by the maximum distance to the optimum. If a technology has the highest score, the value will be zero. Consequently, the lowest Q value results in the highest rank for the technology.

	Initial cost	OPEX	Emission	Applicability	s_J	R_J	Q_J	Rank
One sail	0,17	0,20	0,23	0,10	0,70	0,23	0,714685	2
Two sail	0,30	0,27	0,00	0,20	0,77	0,30	1	3
Slow steaming	0,00	0,00	0,16	0,00	0,16	0,16	0	1
S*,R*					0,16	0,16		
S-,R-					0,77	0,30		

Table B.4: Virtual data as example for VIKOR, the f_{ij} values are replaced by S_{ij} values and the S_J , R_J, Q_J Values and ranks are added

In this example the third technology, Slow steaming has the highest rank assigned. Which isn't surprising when looking at the example data. It scores best on 3 of the four parameters, two of which are the most important parameters. This example does give insight into how the reductions in speed can only be accounted for in the last parameter and therefore increases the sensitivity.

Conditions

There are two conditions built in the VIKOR method to test the outcome. The first condition is called 'Acceptable advantage' and is described by the following formula:

$$Q(A^{(2)}) - Q(A^{(1)}) \geq DQ \tag{B.4}$$

$$DQ = 1/(J-1) \tag{B.5}$$

With:

$Q(A^{(2)})$ - Q value of the second ranking alternative [-]
$Q(A^{(1)})$ - Q value of the first ranking alternative [-]
J - Number of technologies [-]

In short, the higher the amount of alternatives, the smaller the difference in score is allowed between the first and second in rank.

The second condition is 'Acceptable stability in decision making'. It dictates that the highest-ranked alternative must have the best score for R and/or S too.

If both conditions are met, the highest-ranked alternative is the preferred solution. If one of the conditions isn't met, a set of alternatives is preferred. The conditions can be used to decide how convincingly the first ranked outranks the other solutions.

C | Results Monte Carlo simulation

The full results from the Monte Carlo simulation model by Siemens Gamesa are shown below.

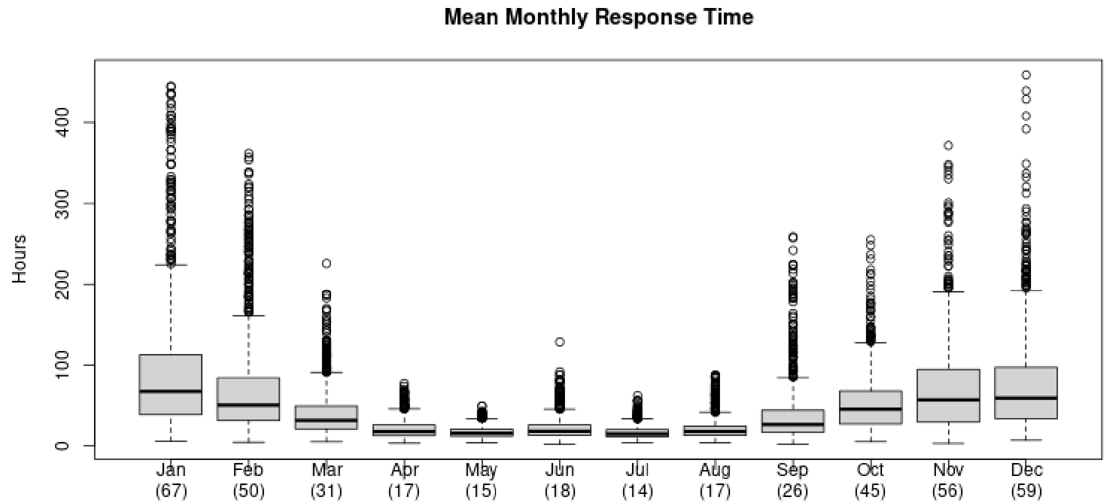

Figure C.1: Mean monthly response time for Global tech one with 1.75m FOTV.

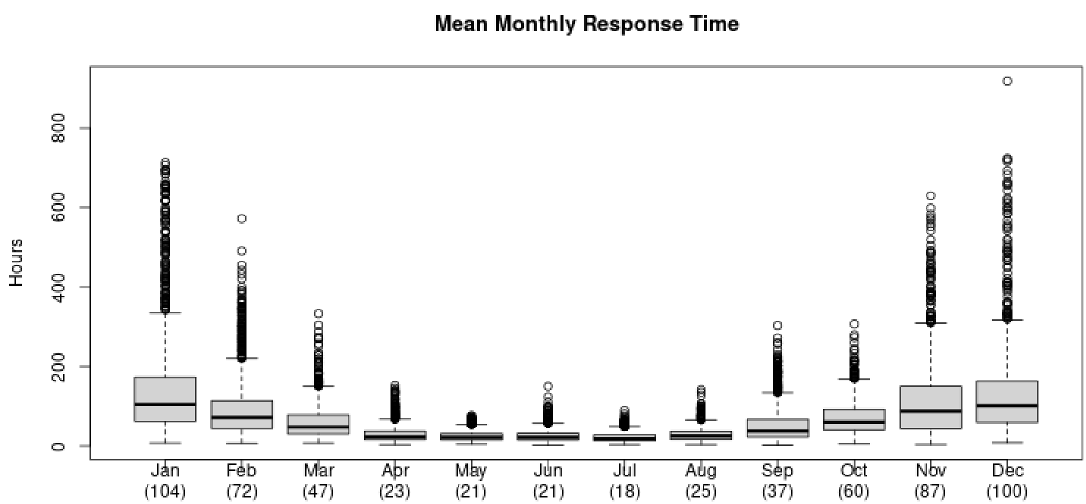

Figure C.2: Mean monthly response time for Global tech one with 1.5m FOTV.

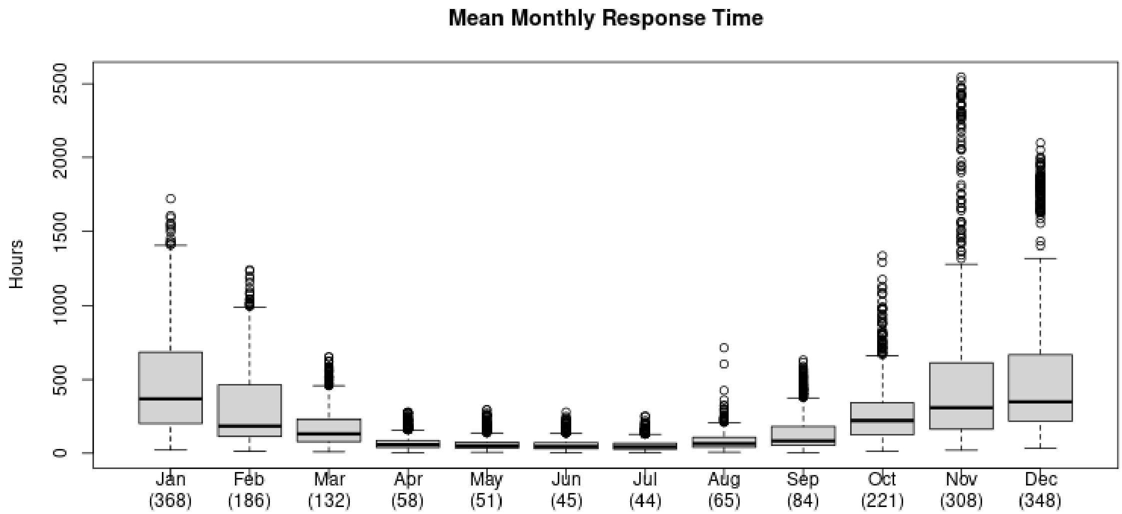

Figure C.3: Mean monthly response time for Global tech one with 1.0m FOTV.