Delft University of Technology

Identifying Logistical Fleet Strategies for Future Scenarios of Offshore Energy Innovations in the North Sea Region

MSc Thesis

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TU Delft

PETERSON

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by

S.F.A. Permana

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Preface

The research presented is conducted as a thesis graduation report in the context of the Master's program in Transport, Infrastructure & Logistics at the Faculty of Civil Engineering & Geosciences of the Delft University of Technology in The Netherlands. This thesis is written in cooperation with the Delft University of Technology and Peterson Den Helder B.V. and is carried out as part of the NSE5 research.

With the strong and steady support from the experts involved in this research, as well as friends and family, I managed to stay motivated and finish this research during my Master's studies. Thank you to Reinier Dick for guiding me throughout the process and referring me to other experts in the field who were able to help out a lot. Thank you to Jafar Rezae and Xiaoli Jiang, who put in a lot of effort in supporting me with my model and advising me on how to work as systematically and efficiently as possible during my thesis process and thank you to Rudy Negenborn for concrete advice on how to think critically.

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الحمد لله

S.F.A. Permana
Delft, December 2024

Executive Summary

Global and regional climate targets have been established to reduce the worldwide carbon footprint. The European Commission aims to reduce the net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels and reduce it even further to zero net emissions of greenhouse gases by 2050, according to the European Green Deal (European Commission, 2021). It is necessary that a transition takes place to a carbon-free energy supply, which can be enabled by offshore wind energy (European Commission, 2022). In combination with offshore wind energy, energy stakeholders in the North Sea region aim to implement Offshore Hydrogen and Carbon Capture Storage facilities in the North Sea Region. This research will dive into the changes in maintenance demand in the North Sea as a result of these new facilities such that decision-makers in offshore logistics can facilitate these new demands. This research will therefore look into these logistic requirements and determine what offshore fleet services have to be provided, in terms of fleet size and fleet mix, in order to accommodate the future scenario with the implementation of energy hubs and their corresponding facilities, in order to achieve the following research objective:

The goal of this research is to identify an optimal vessel fleet strategy for offshore activities in a future scenario with energy hubs and their corresponding facilities.

The three offshore facilities considered in this research are Offshore Wind Farms (OWFs), Carbon Capture Storage (CCS) facilities and a Hydrogen Power Plant (HPP). Some of the OWFs are already operational in the North Sea, whereas CCS facilities and the HPP are expected to be operational after 2030. Due to this, there is very limited research on CCS and HPP and their maintenance demand. The activities for this research for CCS and HPP have thus been acquired by expert interviews and are depicted in Table 1 for a yearly basis. These activities can be supported from one of three bases: Den Helder, IJmuiden, an offshore SOV acting as a base, or an energy island. Den Helder and IJmuiden are onshore bases whereas the SOV and Island base are located offshore. The activities in Table 1 have to be completed using three vessel types: CTV, SOV, and HLV, which can be chartered offshore for a certain amount of time. The Maximum Duration of Use (MDU) of the CTV is 12 hours, whereas SOVs and HLVs can stay offshore for a maximum of one week (168 hours). CTVs are primarily used for transporting technicians to (nearby) offshore facilities, whereas SOVs and HLVs also provide lodging facilities for the technicians. For wind farms further from the shore that require a larger travel time than 30 minutes to one hour maximum using a CTV, larger vessels have to be deployed.

Table 1: Operation & Maintenances Activities of Offshore Facilities

Location	Task name	Occurrence Rate	Duration	Technicians	Required Asset
OWF	Manual Reset	7.5	3 hours	2	CTV
OWF	Minor Repair	6.81	7.5hours	2	CTV
OWF	Medium Repair	3.35	22 hours	3	CTV
OWF	Major Repair	1.17	26 hours	4	SOV
OWF	Major Replacement	0.29	52 hours	5	HLV
OWF	Yearly Servicing	1	60 hours	3	CTV
CCS	Yearly Maintenance	1	21 days	20	SOV
CCS	Unplanned Maintenance	20	1 day	20	SOV
CCS	Painting	0.167	10 weeks	40	HLV
HPP	Cell Replacement	0.125	14 days	20	HLV
HPP	Daily Maintenance	365	1 day	20	SOV

A primary requirement for a logistics service provider is ensuring the availability of assets necessary to meet generated demand. This objective can be approached through various strategies, with the effectiveness of each evaluated through specific Key Performance Indicators (KPIs). In this research, two KPIs are emphasized which are in line with the system's primary objectives: (1) minimizing the number of vessels required in the fleet mix and (2) minimizing the total distance travelled. Cost-related KPIs are not included, as cost elements are highly stochastic and difficult to project accurately in future scenarios.

A Vessel Fleet Size & Mix Problem has been formulated in order to find the optimal fleet for the activities presented in Table 1. The constraints of the problem are related to the demand requirements, route limitations, and vessel capacities. The problem is then modelled using Mixed-Integer Linear Programming (MILP) and solved using Gurobi, as this method can generate strategic insights that are applicable over extended periods, thereby providing valuable guidance for long-term planning. A synopsis of the methodology, its inputs and its outputs are illustrated in Figure 1. Due to computational limitations, the input data of activity demand has been structured on a daily basis for CTVs and a monthly basis for SOVs and HLVs.

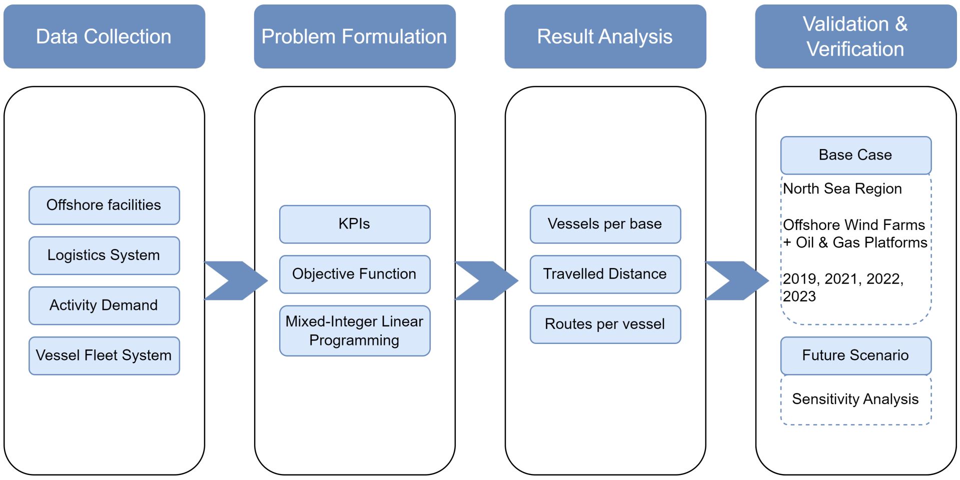

Figure 1: Methodology Synopsis

The model incorporates three objective functions for comparison: minimizing the number of routes, minimizing the distance travelled, and minimizing the number of vessels required. Results from the model indicate a fleet composition of 27 CTVs, 14 SOVs, and 25 HLVs. The model allocates all CTVs to the IJmuiden base, which aligns with operational expectations since CTVs primarily service wind farms, and IJmuiden is the closest base to these locations. For SOVs, vessels are allocated across all bases as they service all three facility types. Notably, when minimizing the number of SOVs, the model forces all vessels to be allocated to the Island base, reducing the required fleet by one vessel compared to the minimization of either routes or total distance. Although this configuration results in the highest total distance travelled, it aligns all activities with the HPP facilities located near the Island base, optimizing the fleet size. For HLVs, both the route- and distance-minimizing objectives yield identical outcomes in terms of activities, routes, vessels, and total distance. However, when minimizing the number of HLVs, the route allocation to the bases significantly shifts, maintaining the same number of routes but requiring one less vessel to complete the activities.

The results are compared to a base scenario using data collected from a logistics service company for the years 2019, 2021, 2022, and part of 2023. This data primarily focused on vessel activities rather than specific offshore tasks, and it was only available for SOVs. However, approximately 54–59% of these activities each year indicated offshore tasks. During these years, 20 to 30 vessels were employed annually, with about 12 unique vessels active per month. Based on these percentages, this equates to an estimated 4 to 10 vessels used specifically for offshore activities, with an average of seven vessels per month.

The model encompasses CTVs, SOVs, and HLVs, yet the validation is conducted solely with SOV data due to limitations in data availability. Despite this, validating with SOVs provides valuable insights since these vessels operate across all offshore facilities, in both the current and future cases. Although each scenario has distinct activity demands, a comparison of vessel requirements highlights differences in operational needs. Model validation against the base scenario shows that future vessel needs are about double in the model's results, largely due to the model's assumption that all periodic activities must occur within a single month and that vessels are not shared across bases. This projected increase is consistent with expectations, as future offshore operations will likely involve heightened demand across OWFs, hydrogen plants, and CCS platforms, all of which require greater vessel availability to support more frequent and complex activities.

To analyze the model's behaviour, several scenarios were tested based on the potential of future capacities of turbines and the HPP plant. The capacity of the turbines depends on upcoming innovations, as the largest turbines currently operating in the North Sea are around 14 MW, while other regions, such as China, are already advancing turbines with capacities exceeding 20 MW. For the HPP plant, capacity remains uncertain as stakeholders have yet to reach consensus on optimal levels. Thus, the sensitivity analysis includes two scenarios for wind farm capacity, two for HPP capacity, and an extension of the MDU parameter to assess its impact on model outcomes. Since CTVs are exclusively used for wind turbines, their sensitivity analysis focuses solely on turbine capacity, excluding MDU and HPP capacity.

Some of the key takeaways from the results, combined with the sensitivity analyses are:

- A key reason for the higher fleet estimate for CTVs is the model's sequential scheduling of tasks, which limits simultaneous activities and overlooks operational efficiencies achieved with real-life technician capacity. The model assumes only two technicians per CTV, but each vessel could potentially carry up to 12 technicians, allowing for significantly higher task throughput and reducing the number of routes needed by threefold or more. With a Maximum Duration of Use (MDU) of 12 hours, this capacity could further increase, allowing for up to 24 manual resets per route without considering travel time.
- For SOVs, the model estimates a monthly fleet size of 14-15 vessels, considerably higher than the average of seven vessels typically required per month in the base scenario. This is due to the model's assumption that nearly all maintenance and operational activities are scheduled to occur within the given month and the model's constraints, which limit vessels to single bases.
- The model estimates that 25-26 HLVs are needed to complete scheduled activities, largely due to the high visitation rates required by CCS and HPP facilities. However, this demand is likely overestimated, as the model assumes all CCS tasks must be completed within a single month—including a major painting job typically scheduled only once every six years. Practical operations for extended tasks, such as CCS painting, which typically require 10 weeks, would be spread over multiple months, unlike the model's approach that compresses tasks within one month by using multiple vessels. Distributing long-duration tasks across a longer period, rather than within a single month, would lead to a more operationally feasible and cost-effective schedule, making the current model results conservative. For example, if CCS platforms are painted once every six years with each one of the five platforms painted annually, the HLV fleet requirement would decrease substantially. Limiting CCS painting to one job per month would cut total routes by approximately 40%, lowering the vessel requirement from 39 to around 23 vessels. Even with this reduced CCS demand, over 60% of routes would still serve HPP facilities, indicating that their ongoing maintenance needs continue to drive a substantial HLV demand.
- The sensitivity analysis for SOVs and HLVs shows that extending the MDU increases the fleet requirement, whereas variations in wind turbine capacity at the IJmuiden Ver wind farm have minimal impact on fleet sizes of the HLVs due to the low maintenance frequency. The different sizes considered for the HPP capacities show a linear relation to the number of activities, routes, and vessels allocated to each base.

Based on the results, validation, and verification of the model, one can conclude that this model provides a foundational tool for decision-makers in offshore logistics to optimize their vessel fleet strategies effectively. The model's insights reveal key dynamics in fleet composition, fleet size, and allocation, offering a flexible approach that can adapt as offshore energy hubs expand their facilities and demands evolve. By examining critical factors such as maintenance schedules and fleet composition, logistics operators can use this model to make informed decisions on optimal vessel numbers, routes, and maintenance strategies. As real-time data becomes available from emerging offshore activities, decision-makers can refine the model's inputs to align fleet allocation closely with actual demand, ensuring that vessel resources are available as needed. With this, the main research question as related to the project goal can be answered:

How to establish an optimal vessel fleet mix, that satisfies the requirements of offshore activities to facilitate energy hubs and their corresponding facilities?

To determine an optimal vessel fleet mix, it is essential that logistics service providers stay well-informed about the decisions and developments made by other stakeholders involved in the maintenance activities of offshore facilities. These stakeholders play a critical role in defining facility capacities and operational needs, which directly impact vessel requirements. In an assumed scenario where offshore wind farms will have a maximum turbine capacity of 14 MW each and the hydrogen plant will operate with eight platforms of 1 GW each, logistics service providers can consider an initial upper bound of 39 CTVs, 13 SOVs, and 26 HLVs to meet operational demands. However, these estimates represent a conservative upper limit; the actual number of vessels required could be reduced when accounting for (1) the capacity constraints of technicians on each vessel, keeping in mind a drop-off and pick-up system and (2) the consideration of vessel overlap, where two vessel types can be used simultaneously.

Finally, this research uncovers new opportunities and generates additional research directions for future investigation in the following ways:

- The mathematical model could be refined to better represent technician and time capacities by incorporating technician allocation constraints. This would enhance scheduling outcomes and reflect real-world scenarios where technician resources are critical, ultimately improving offshore logistical operations.
- The current model relies on deterministic input data, which overlooks the unpredictable nature of offshore logistics. By integrating stochastic elements like weather uncertainties and variable costs, the model could account for disruptions and enhance its applicability for strategic decision-making.
- This study does not consider the overlap in vessel usage, which could enhance efficiency. Using SOVs as mother vessels with CTVs as daughter vessels for crew transport could optimize vessel assignments and reduce operational expenses, calling for further investigation into this approach.

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1 Introduction

Global and regional climate targets have been established to reduce the worldwide carbon footprint. The European Commission aims to reduce the net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels and reduce it even further to zero net emissions of greenhouse gases by 2050, according to the European Green Deal (European Commission, 2021). It is necessary that a transition takes place to a carbon-free energy supply, which can be enabled by offshore wind energy (European Commission, 2022). The North Sea is expected to play a vital role in this transition due to its relatively shallow waters, favourable wind climate, and proximity to great ports and energy consumers (Government.nl, n.d.). Aside from wind energy, other sustainable energy sources such as solar energy and biomass energy are also required. One of the many challenges of these renewable energy sources is their dependency on weather conditions, causing fluctuations in their energy supply due to intermittency, variability, and uncertainty (Wang, Palazoglu, and El-Farra, 2015).

With the increase in energy demand and expansion of offshore energy wind farms, the availability of space in the North Sea is getting more scarce. Close-to-shore locations are lower in cost to build offshore wind farms, but these spaces have been occupied by early developers. This led to wind farms being built further from the shore, where higher wind speeds result in the generation of more energy and thus lower wind power variability (Fernández-Guillamón et al., 2019). The disadvantages of increasing the distance to the shore are the increase in costs due to the larger wind turbines needed to sustain the increased wind power capacity, more complex foundation types in deeper water, and more transmission infrastructure (Ørsted, n.d.; European Environment Agency, 2009; IEA, 2013). Larger wind turbines are being built compared to the ones that will be decommissioned by 2030 and multiple scenarios for the energy transition for the period of 2030 to 2050 project a shift towards decentralized and intermittent renewable energy generation (Nortier et al., 2022). One of the innovations that are taking place in the offshore industry, recently proposed by Tennet, is the development of energy hubs, or 'Power Hubs' (TenneT, 2020). Energy hubs consolidate several activities in the North Sea as they will serve as offshore power plants gathering and distributing green electricity from hundreds of wind turbines surrounding the hubs directly to consumers in European countries surrounding the North Sea. Energy hubs have the potential to expand their services or increase in scale by building additional facilities near or on the hubs (DW, 2021). Because of the consolidation of several functions, an energy hub changes the logistics and transportation demands of offshore activities. It is expected that the functionality and frequency of the transport and logistics resources will need to be adjusted to accommodate the functionalities of the energy hubs efficiently.

This research will dive into different future scenarios of how the development of energy hubs will affect the activities and decision-making of a logistic service provider and provide a general model of how the logistic services can be performed. The range of operations of this research is limited to the Dutch territory of the North Sea Region until the year 2050.

1.1. Research Gap

A literature review was performed to assess previous research on the topic of energy transitions, wind farms, energy hubs, and offshore logistics. This review focuses on different scenarios of spatial planning in the North Sea Region and its effects on offshore logistics. Spatial planning can generally be described as a process of decision-making in which relevant stakeholders determine how a certain physical area is used (Jay, 2010). In the offshore industry of the North Sea Region, this includes the increase in the construction of offshore wind farms, the development of energy hubs, and all other activities that take place in the area. Energy hubs make the consolidation of several offshore activities possible, it brings together the production and warehousing of sustainable energy, as well as the energy distribution and management.

Table 1.1 presents a summarized overview of the literature reviewed and the topics that have been studied in the papers. The main topics that are relevant to this study are related to the activities that are consolidated in offshore energy hubs and (mathematical) models that have been developed to represent these activities and their corresponding logistic demand. The table shows that extensive research has been done on the O&M phase of wind turbines. However, this is not the case for offshore energy storage. The energy storage methods used for offshore wind hubs are relatively new fields of study, which explains the lack of research done on these subjects. Furthermore, the reviewed literature in the table shows that the research done on energy hubs usually does not consider logistical aspects nor does it contain a comprehensive analysis of the Operational & Maintenance phase of the overall hub.

With the upcoming changes in offshore logistic demand, the supply has to be adjusted accordingly. Bittencourt et al. (2021) presented a good-quality framework of solutions that can potentially enhance offshore service levels, reduce fleet requirements, and decrease operational costs. This paper provides a lengthy overview of previous solution methods found in the literature to approach similar problems. The reviewed literature lacks the consideration of energy hubs, in particular in vessel fleet problems. A vessel fleet is a number of service vehicles grouped together to reduce logistic costs in the O&M phase of offshore facilities.

This study focuses on the potential adjustments in the mix of vessels that are required to facilitate the future, additional activities in the North Sea Region. Furthermore, this research will add to the research done by Pejman Shoeibi Omrani et al. (2022) on logistic challenges in future scenarios in the Dutch North Sea Region. Pejman Shoeibi Omrani et al. (2022) analyzed the potential benefits of shared, optimized logistics between offshore Oil & Gas and wind sectors by comparing various scenarios. Similarly to the study done by Pejman Shoeibi Omrani et al. (2022), this study will also contribute to the NSE5 research. The NSE5 is the fifth stage of a public-private research programme that investigates the North Sea's potential for an integrated energy system.

1.2. Project Goal

A generous amount of literature exists on the topic of various offshore activities. Plenty of research has been done on offshore wind farms and how to optimize their logistic activities during installation, O&M, and decommissioning. For energy hubs, however, there is little to no literature due to the fact that this is still an innovative concept. This also means that the literature lacks research on the structure of energy hubs, where energy from offshore wind farms will be consolidated with warehousing facilities on the offshore hub platforms. The demands of each activity may not vary much from the current situation, but the logistic requirements will have to be reshaped to accommodate the future scenario. This research will therefore look into these logistic requirements and determine what offshore fleet services have to be provided, in terms of fleet size and fleet mix, in order to accommodate the future scenario with the implementation of energy hubs and their corresponding facilities, in order to achieve the following research objective:

The goal of this research is to identify an optimal vessel fleet strategy for offshore activities in a future scenario with energy hubs and their corresponding facilities.

1.3. Research Questions

The research goal mentioned above can be achieved by answering the following main research question:

How to establish an optimal vessel fleet mix, that satisfies the requirements of offshore activities to facilitate energy hubs and their corresponding facilities?

The main research question can be divided into the following sub-questions:

1. What are the logistic activities and requirements of the consolidated facilities on the offshore energy hubs?
2. How can the pool and sharing system of the mixture of fleet assets be modelled and what are the Key Performance Indicators?
3. How to develop a model that represents the mixture of fleet assets in a future scenario, incorporating the offshore energy hubs and their corresponding facilities?
4. How to verify and validate this model?
5. How can the model be used by decision-makers in logistic services?

1.4. Project Scope

To address the research gap mentioned in Section 1.1, this study will dive into the logistic aspects of offshore energy hubs. Energy hubs consolidate several offshore activities: produced energy will be transported to the hubs, where they are stored. This process reduces the variability of renewable energy production, as energy can be stored offshore in times of low energy demand or distributed in times of high demand. There are multiple methods to store energy and distribute it, but due to the time limit of this research, the scope is limited to energy storage through electrolysis and hydrogen production. Experts recognized great potential in this method for offshore energy storage, as they can be combined with the development of energy hubs. As for renewable energy production methods, this research will be limited to wind energy. Finally, to limit the carbon emissions in the North Sea, several O&G platforms are planned to be transformed into Carbon Capture Storage (CCS) platforms. These CCS platforms will also be considered in this research as these platforms will also play a significant role in the energy transformation towards 2050.

The focus of this study will be on offshore logistic activities and how they will change in the next 10-30 years, as a consequence of the implementation of energy hubs in the North Sea region. Most activities are related to either of the three life phases of offshore facilities: installation, O&M, or decommissioning. Because each life phase does not require the same logistic activities as any of the other life phases, this study will only take one life phase into consideration. Installation and decommissioning demand similar activities and can be carried out in the same amount of time, while the O&M period is expected to last tens of years. The operational phase will thus last the longest and the logistic activities during these years are expected to stay relatively consistent. For the distribution of energy in the form of hydrogen, the assumption is made that this process is integrated with the existing pipeline infrastructure in the North Sea.

Pejman Shoeibi Omrani et al. (2022) describes several scenarios in their study for the three hubs that are considered in the NSE5 research: Hub West, Hub East, and Hub North. This study will be limited to three scenarios outlined for Hub West as the base location for technicians - at the shore in IJmuiden, on an island based on the hub, or on an SOV permanently stationed offshore. This hub and its surroundings have the most information available from previous NSE studies and are thus chosen to be researched more in-depth in this study.

Many stakeholders are involved in offshore logistic activities, but the report will be written from the perspective of an offshore logistic service provider. The analysis will be done on their general operation model, instead of daily operations. Lastly, the logistic problem will be reduced to fleet asset management.

1.5. Methodology

The research question introduced above will be answered in this study, which is divided into the following chapters as also depicted in Figure 1.1. Chapter 2 provides an extensive description of the offshore activities and contains additional information to help understand the problem. Chapter 3 dives into the previously studied models on the topic while Chapter ?? introduces the model developed for the problem described. The results of this model are presented in Chapter 5 and validated and varified in Chapter 6 with a base scenario, followed by a sensitivity analysis. These resutls and some insights gained are then given in Chapter 7, along with the final conclusions and recommendations regarding future research.

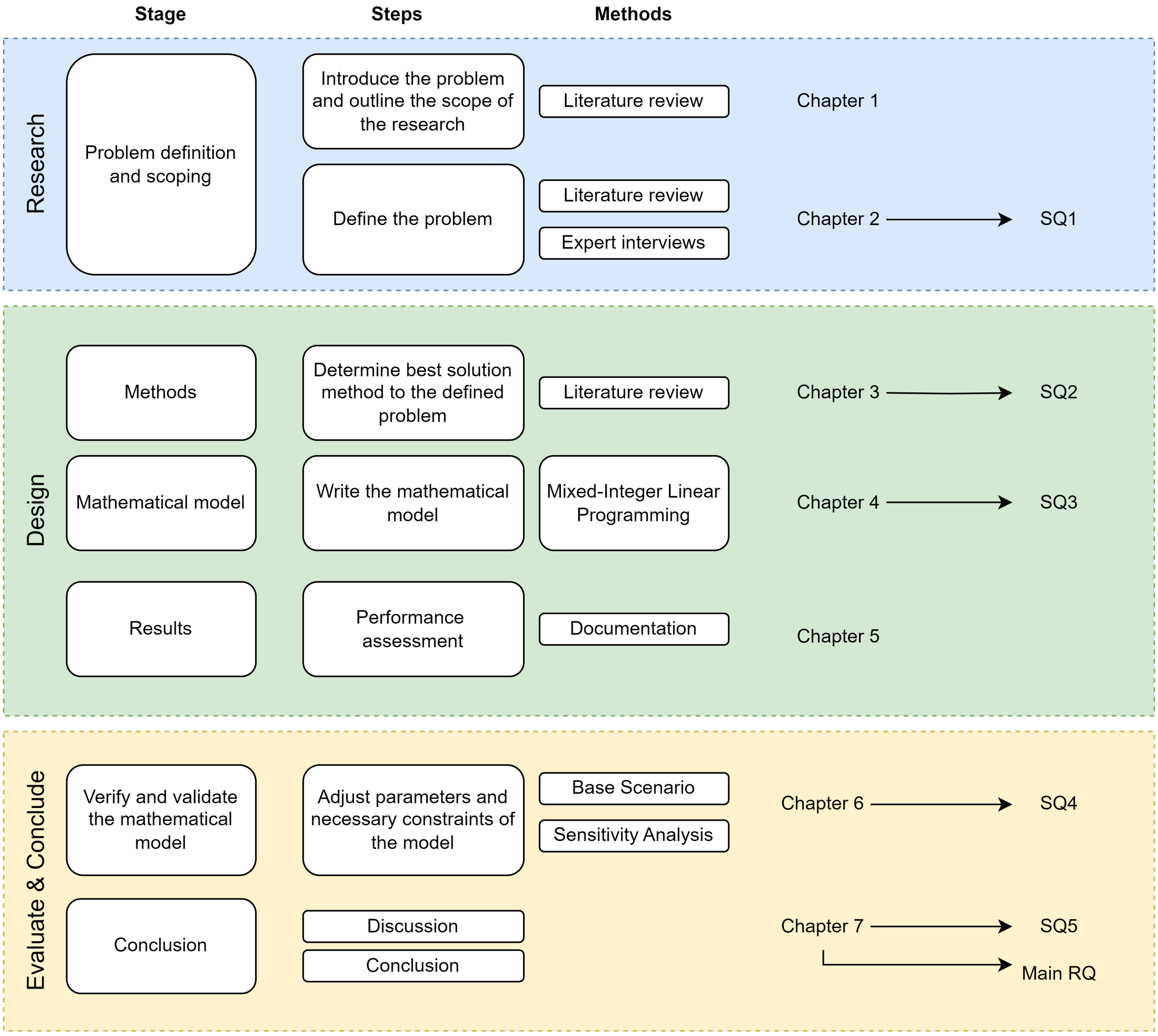

Figure 1.1: Methodology Flow Diagram

Table 1.1: Literature Review Table

	Energy Storage	LCA	Logistics	Failure Prediction	Spatial Planning	Mathematical Optimization	Fleet Management	P2X Conversion	Energy Islands	Wind Turbines	O&M
North Sea Energy (n.d.)		X									
Jay (2010)					X						
Dalgic et al. (2015)			X				X				X
Gea-Bermúdez et al. (2023)	X										
Zhang et al. (2022)									X		
Li et al. (2016)						X	X				
Zhang et al. (2021)						X	X				
Jansen et al. (2022)					X				X		
Singlitico, Østergaard, and Chatzivasileiadis (2021)	X							X			
Prokop (2022)						X	X				
Bittencourt et al. (2021)			X				X				
Sarker and Faiz (2017)						X				X	
Crivellari, Cozzani, and Dincer (2019)	X										
Kumar et al. (2023a)	X				X						
Kumar et al. (2023b)	X										
Giampieri, Ling-Chin, and Roskilly (2023)	X									X	
Seo et al. (2023)	X		X					X			
Li et al. (2016)				X						X	X
Li and Guedes Soares (2022)				X						X	
Saleh et al. (2023)										X	X
Gustavsson et al. (2014)							X			X	X
Louise Peet (2021)		X	X	X			X			X	X
Pejman Shoeibi Omrani et al. (2022)			X	X			X		X	X	X

2 Problem Description

The goal of the vessel fleet problem is to establish an optimal fleet mix consisting of heterogeneous vessels, which satisfy the requirements of offshore activities. As mentioned in Section 1.4, the activities considered in this research will be related to the operation & maintenance phase of Offshore Wind Farms (OWFs), Hydrogen Power Plants (HPP), and Carbon Capture Storage (CCS). This chapter aims to focus on the required maintenance activities on and around offshore energy hubs. First, a deeper understanding of offshore facilities is presented regarding their operational activities and corresponding maintenance activities. Then, an analysis will be done on the vessel fleet which can be or is currently used to perform the mentioned or related maintenance tasks. Finally, some assumptions are stated regarding the problem after which the first research question can be answered: *what are the logistic activities and requirements of the consolidated facilities on the offshore energy hubs?*

2.1. Offshore Activities

Compared to the installation & decommissioning phase of offshore facilities, the operation & maintenance phase consists of similar and recurrent tasks. The O&M phase involves servicing offshore locations, conducting repairs, and replacing components and equipment that have failed or degraded over the operational period. The daily activities generated during this phase can be grouped into three main types: scheduled maintenance, maintenance due to unforeseen failures, and regular servicing tasks. Corrective maintenance is carried out when parts or components have failed and need to be repaired or replaced for the facility to operate again. Preventive and scheduled maintenance activities are executed in order to decrease the chance of failure and prolong the lifetime of the commodities (Stålhane et al., 2019). Each type of maintenance activity requires varying vessel sizes, technician team sizes and skills. One vessel can execute one task at a time or multiple tasks can be grouped into a larger set of maintenance tasks. In the case of the latter, experts speak of an activity bundle - where one vessel executes a task parallel to related maintenance tasks (Tusar and Sarker, 2023). Activity bundles are mostly performed on multiple offshore wind turbines as part of one OWF, as these turbines are relatively close to each other in distance.

The decision-making for offshore fleet activities can be divided into three large, general sections as listed in Figure 2.1: strategic, tactical, and operational decisions (Tusar and Sarker, 2023). Strategic decisions are made for the long term and typically do not change over time. Tactical decisions are medium-term and are generally focused on organizational and management decision-making. Operational decisions are short-term decisions that are usually related to the planning and scheduling of the vessels. The planning and scheduling of the vessels is difficult to decide on a long-term basis as there are many uncertainties in weather changes and demand.

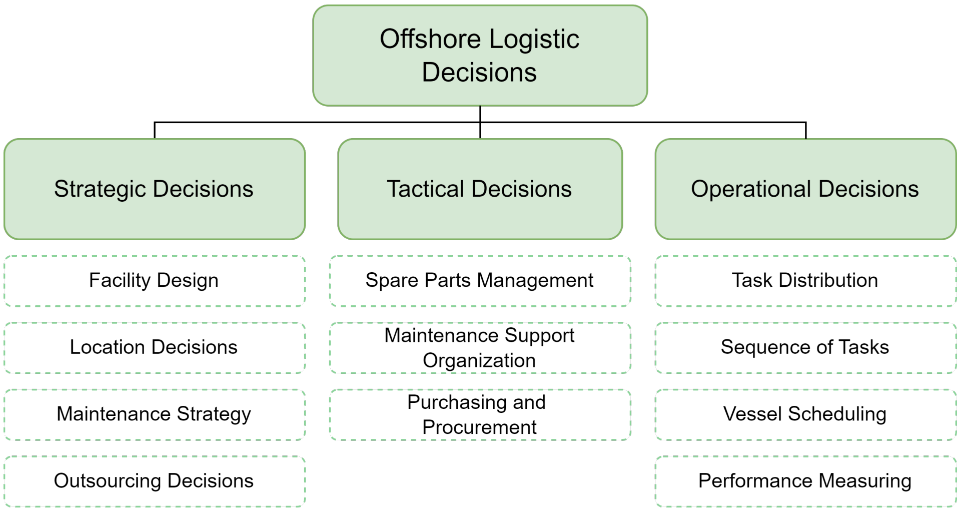

Figure 2.1: Classification of Offshore Logistic Decisions (Tusar and Sarker, 2023)

The strategic decisions related to maintenance strategy affect the decisions made on the maintenance organization's support. The maintenance strategy determines what equipment will run to fail and what parts have to be maintained regularly to prevent failure, which results in high downtime costs. The maintenance strategy will then be used to develop a plan for the maintenance organization's support. These include decisions related to the vessels needed to support the maintenance tasks and how they can be employed to efficiently facilitate them. This section looks at the various facilities included in this research and what type of maintenance strategy is used to facilitate the activities happening offshore.

The costs considered in the decision-making of offshore logistic decisions typically include vessel purchasing costs, daily vessel chartering costs, cost per mile, and base operation costs. The fuel costs and daily vessel chartering costs are volatile and change daily. Because the considered costs for the decision-making of offshore logistics are unpredictable for the future scenario of 2030 - 2050, the costs will not be considered for this research. However, costs are affected by elements like the number of vessels, their fuel consumption, and their distance travelled. These factors can be determined in the operational phase of the decision-making process.

Currently, the tasks as part of the operational decisions are done manually at the interviewed logistic service operator. For example, the vessel chartering schedules are determined per quarter of the year based on the logistic requirements of the offshore operators in O&G and wind. Any changes and deviations from this fixed schedule are monitored and based on the discrepancies, the KPI of successful sailings as a percentage of the total number of sailings can be measured. To take into account the uncertainties in failure rates of the offshore facilities, certain vessels need to be flexible for additional requests done at the last minute.

2.1.1. Offshore Wind Farms

Currently, there are seven operational wind farms in the Dutch North Sea Region with a combined capacity of 2,45 GW, most of which are within a distance of around 20 km from the shore. The installation of new wind turbines keeps increasing in distance to the shore, making them more difficult to reach. A tactical planning schedule needs to be established to carry out the maintenance tasks as efficiently as possible, as it is desired to prevent any downtime of the turbines. Preventive maintenance needs to be carried out regularly to avoid unforeseen failures, but doing it too frequently would be a waste of money and resources. These types of tasks can be part of the yearly maintenance or it can be a major overhaul, each consisting of their own subset of tasks.

Scheduled maintenance can be divided into several maintenance strategies. Some equipment is monitored to detect certain faults in the system, after which maintenance will be performed. In other cases, engineers will predict when the failure will occur and schedule maintenance before the system fails. Even though reactive maintenance dominated in the recent past, the latest wind turbines with a capacity of more than 5MW have lower failure rates. Now, less than 25% of the work undertaken on modern wind farms consists of unscheduled maintenance (Pejman Shoeibi Omrani et al., 2022). Based on the activities done on currently operating OWFs, scheduled maintenance is anticipated to be between once and twice a year.

In the case that offshore wind turbines fail, corrective or reactive maintenance needs to be performed. These types of activities include minor repair, major repair, minor replacement, and major replacement (Dinwoodie et al., 2015). Some parts of the equipment run to fail, meaning that they will operate until the part fails. Only after the part fails, resources are sent out to repair the part. This strategy is usually employed for non-critical equipment where the cost of maintenance and downtime is lower than the cost of preventive or proactive maintenance.

To determine the frequency and duration needed for the repair and replacement of components of wind turbines, their failure rates need to be analyzed in more detail. The literature provides multiple models on the failure rates of wind turbines, but finding and using the actual failure rates of wind turbines is impracticable. First, the actual data on failure rates are hard to acquire due to the competitiveness of the wind farm operators in the industry. Second, the wind farms scheduled for 2030 and onwards consist of innovative wind turbines appropriate for deeper waters in the North Sea. To use the failure rates of the current turbines on or near the shore would be inadequate.

Commonly used methods to model the failure rates of wind turbines are a Weibull distribution or a Poisson distribution. A Weibull distribution provides the necessary theory for comprehending the assumption of a constant failure rate. The parameters used in a Weibull distribution can be modified such that a variety of features can be evaluated, which is frequently done in reliability engineering (Tusar and Sarker, 2023). The Weibull model is used to model the time until failure occurs, while a Poisson distribution is used to count the number of failures within a predetermined time interval. From a logistics point of view, it is useful to identify the frequency of voyages needed to visit a certain platform. For this purpose, a Poisson distribution would be more appropriate. Louise Peet (2021) modelled the failure rates of wind farms stochastically, using a Poisson distribution with deterministically assumed repair times. The three vessel types used in their classification of required vessels for the O&M activities of offshore wind farms are Crew Transfer Vessels (CTVs), Field Support Vessels (FSVs), and Heavy Lift Vessels (HLVs). An overview of the required tasks during the O&M phase of offshore wind turbines is given in Table 2.2 on page 15.

Completing all maintenance tasks for an offshore wind farm (OWF) within a single day is not feasible, especially for larger wind farms. As a result, technicians need transportation between onshore facilities and the offshore site, or among on-site facilities like a vessel that also functions as a housing platform that is stationed near the OWF. Currently, most OWFs are located within 20 km of the coastline. This proximity enables small workboats to reach the shore in less than half an hour. The wind farms built before or around 2030 will be relatively close to the shore and will require CTVs for daily maintenance, with the spare use of helicopters in transferring personnel (Pejman Shoeibi Omrani et al., 2022). Smaller wind farms entail less maintenance compared to the larger ones in the North Sea, resulting in a lower daily average of technicians required for on-site tasks. In the case of smaller wind farms, an optimized approach involves multiple technicians travelling together, each assigned distinct tasks upon arrival. This strategy allows the vessels to operate at maximum capacity as much as possible during transit to the wind farm, ensuring a minimized number of vessels required to fulfil the demand.

The Dutch government has released a concrete roadmap to install 11.5 GW of offshore wind farms by 2030, with the ambition to increase this amount even further to 22 GW in the same time frame. A few search areas have been established as potential sites for offshore wind farms. A 2021 report from the Dutch National Water Program (NWP) estimates the development of an additional 27 GW of offshore wind in 8 search areas by 2040 (Pejman Shoeibi Omrani et al., 2022). With the construction of more OWFs in deeper waters, the demands on the maintenance fleet increase, necessitating either an expansion of resources or the establishment of a permanent offshore base (Tusar and Sarker, 2023). Of these future wind farms, a total of 14 GW is expected to be installed closest to Hub West: 6 GW is expected to be installed by 2030, with an additional 8 GW between 2030 and 2040.

2.1.2. Hydrogen Power Plants

Hydrogen production can be divided into multiple categories depending on the in and outputs of the production process. The three main categories in which hydrogen can be produced are green, blue, and grey hydrogen. The most common form of hydrogen produced is grey hydrogen, created from fossil fuels. The fuels undergo a process named Steam Methane Reforming (SMR), producing hydrogen, carbon monoxide and a relatively small amount of carbon dioxide. The carbon dioxide produced by SMR is not captured and released into the atmosphere, making grey hydrogen the least environmentally friendly form of hydrogen. Another form of hydrogen that is also produced from natural gases and undergoes the same process as grey hydrogen is blue hydrogen. The difference between blue hydrogen compared to grey hydrogen is the capture and storage of the emitted carbon dioxide, making this more ecologically friendly than grey hydrogen. The most ecological form of hydrogen is green hydrogen. Green hydrogen is produced in a process called electrolysis, where water is split into hydrogen and oxygen using renewable energy sources. This type of hydrogen is expected to have a lot of potential to realize the future of a net-zero world where all electricity and fuel are produced by emission-free sources. However, many challenges need to be faced to drive the development and adoption of green hydrogen (Oliver Hague, 2021). The literature mostly discusses the potential of green hydrogen, but for concrete plans for the future of hydrogen, information is acquired through expert interviews with involved organisations within NSE5.

To achieve the goal of 2050 to have zero net emissions of greenhouse gases, only blue or green hydrogen production can be considered for the offshore scenario. Fernández-Guillamón et al. (2019) discusses and reviews trends and perspectives of offshore wind power plants for the integration of future systems. The offshore trends considered in their review include turbine capacity, windfarm capacity, water depth and distance from the shore. They conclude that energy storage in the form of hydrogen and compressed air energy seems to have the potential to become an alternative to conventional storage technologies. Gea-Bermúdez et al. (2023) investigated the role of generating hydrogen offshore in a future integrated system. They reviewed the benefits of hydrogen generation for both onshore as well as offshore from a socio-economic perspective for the future European North Sea energy system towards 2050. The two research fields considered in this analysis are (1) generating hydrogen onshore after transmitting power from offshore wind farms and (2) generating hydrogen offshore and transporting it in gas form to shore with pipeline infrastructures. With their research, they argue that, socio-economically, it would be most beneficial to generate hydrogen onshore for future scenarios towards 2050. Hydrogen generation will have a limited role offshore, as its flexibility can be better handled at the shore. Hou et al. (2017) found that the best configuration would be to generate hydrogen complementary to the electricity generation from the wind farms. In this case, it would be best to sell the hydrogen directly to the end user instead of storing it and re-generating electricity in times of high electricity prices. Gea-Bermúdez et al. (2023) claims that forcing all hydrogen offshore would lead to increased energy system costs, while Singlitico, Østergaard, and Chatzivasileiadis (2021) claims that the process of electrolysis can be better done offshore, as this would result in the lowest cost of hydrogen. However, this process of performing electrolysis offshore is not mature yet as there is a lack of necessary infrastructure or integration with the offshore power systems. Kumar et al. (2023b) suggests that the offshore industry can benefit from the proliferation opportunities that green hydrogen synergy provides after having done a critical analysis reviewing the benefits and limitations of integrating offshore renewable energy systems.

NSE5 and their partners are considering several scenarios for offshore hydrogen production on Hub West. While most parties are analyzing the possibilities of producing hydrogen offshore by electrolysis and transporting this to the shore under high pressure, there are differences in the capacities of the amount of hydrogen that will be produced offshore. Transmission System Operator TenneT is looking at a total of 8 GW of offshore hydrogen, while Gasunie is aiming for 1 GW hydrogen per 1 GW of wind energy and TNO considers a total of 4 - 8 GW of offshore hydrogen for Hub West. In any case, the hydrogen power plants will be unmanned, meaning that they will not be equipped with living quarters.

Investigations into the possibilities of large-scale production of green hydrogen at the Maasvlakte area in Rotterdam are done by Uniper and the Port of Rotterdam Authority (Port of Rotterdam, 2024). They are looking at producing 100 MW of hydrogen by 2025 with the opportunity to expand this to 500 MW. Hydrogen plants consist of building blocks, of which each is a stack of electrolytic cells, each providing up to 5 MW of electricity per cell. Each stack of cells needs to be replaced and/or refurbished every 6 to 10 years. The process of replacement takes approximately a week for onshore hydrogen plants, but 2 weeks can be approximated for the same process offshore. Two general strategies can be considered for the replacement of the stacks, where (1) all stacks are replaced at the same time or (2) the stacks are replaced one by one at different time periods. The first strategy would need more transportation assets to serve all the units, but this would be the most efficient for centralized platforms to get them running as soon as possible after maintenance. This also means that a load of 5 MW stack of electrolytes needs to be available for all units. For the second alternative, the units can be served at different time periods and the replacement of the cells can be aligned with other tasks that need to be done around the same time period. When the stack of electrolytes in one unit is replaced, the old stack can be refurbished and used as the replacement in the second unit. For this strategy, the replacement of all units is more time-consuming but more cost-saving. In both scenarios, a specific vessel with lifting capabilities is needed to perform the replacement task.

According to expert interviews (see Appendix B), the operators are in the process of preparing an overview of all the expected planned activities for the offshore hydrogen plants, their frequencies, duration, and expected transportation assets alongside a master equipment list. Unfortunately, this specific list can not be shared with outside parties due to the competitiveness of the industry and uncertainties in the current development and research of offshore power plants. However, the expectation is that Service Operation Vessels (SOVs) are used to sail around Hub West, especially in the first few months, to monitor the power plants and their potential inaccuracies or defects. There is a high probability that this will result in daily check-ups, where SOVs stay offshore for one week at a time and will return to their base to switch technicians and the necessary equipment.

The number of vessels depends on the number of platforms used and the number of platforms used depends on the size of the hydrogen plant. For this problem, a capacity of 1 GW per platform is considered, consisting of 200 cells of 5 MW per platform, but this can be increased to a higher capacity depending on future innovations. Different scenarios can be considered to consider multiple potential innovations and what their impact would be on the required number of vessels as an increase in the capacity of electrolysis units is expected to result in a lower number of required vessels.

2.1.3. Carbon Capture Storage

A method to move towards a carbon-free future is to capture the CO_2 that is emitted in the air, transport it and store it deep under the ground. This process is called Carbon Capture Storage (CCS). The CO_2 is captured and transported through pipelines to a location where CO_2 from several locations is compressed and transported to be stored underground. Several Oil & Gas platforms are looked into to be transformed into CCS platforms. The soil under the former Oil & Gas platforms consists of empty gas fields that were once filled with natural gases. The soil below the caprock decreased in pressure due to the extraction of gas, but this pressure can be restored with the storage of CO_2 in these areas.

The goal for 2050 is to be able to store up to 27 MT per annum in total - all of which is planned to be stored around Hub West. Here, five key platforms have been selected to play a big role in the North Sea Region due to their potential for CO_2 storage (Kawale et al., 2020). Similar to offshore hydrogen power plants, the capture of carbon emissions is not yet realized in the North Sea Region. This means that the literature on the logistic activities around CCS platforms is still relatively scarce, as companies are reluctant to share their data and expectations. Something that has been shared by experts, however, is that they have yearly planned maintenance. For this activity, the platform has an outage for 3 weeks. Additionally, they are considering 20 days a year for unplanned maintenance, where a vessel would need to be available. For each activity, around 20 technicians are needed along with a larger walk-to-work vessel. Finally, once every 5 years, a jack-up vessel is required for painting activities of the CCS platforms. The painting job requires ± 40 technicians and takes 2 - 3 months to finish.

2.2. Vessel Fleet System Analysis

To perform the required tasks introduced in Section 2.1, a fleet of different vessel types is needed due to the difference in characteristics and purposes of these maintenance tasks. Operating in shifts, the schedule of each vessel begins when it leaves its base and ends upon its return to the same base. As the vessels operate in shifts and have varying operational requirements as well as varying activity bundles to complete, some smaller vessels have to return to their base after finishing a smaller bundle of activities, as they have to return to base at the end of their shift, which lasts up to ± 12 hours. Other, bigger, vessels can stay offshore for multiple shifts, as they provide accommodation facilities on board (Gundegjerde et al., 2015). This section dives more into the details of a vessel fleet system, the types of assets, how they can be utilized, and what the constraints are.

To be able to maintain their operations and meet specific task demands, vessels must return to their base periodically. Regular base returns allow for essential activities such as refuelling, resupplying of equipment, and performing minor maintenance that ensures vessels remain in working condition. Smaller vessels typically require more frequent returns due to limited on-board resources, lack of accommodation facilities, and shorter operational ranges, which make daily or shift-based returns practical. However, larger service vessels, equipped with accommodation and support facilities, can remain offshore for extended periods. By staying offshore, these larger vessels can reduce transit time and increase their operational efficiency, as they can serve as mobile offshore bases for crew and equipment, thus minimizing the number of required base returns.

Port activities and their durations differ significantly based on vessel size, with smaller vessels requiring shorter base returns compared to larger vessels. For instance, smaller vessels have shorter trip durations and therefore have a refuelling process lasting up to 30 minutes, while refuelling larger vessels can extend to nearly half a day. Crew changes similarly vary: CTVs typically board only up to three crew members, whereas larger vessels accommodate more personnel due to onboard living facilities. Loading and discharge procedures further highlight these differences. CTVs primarily handle the boarding and disembarking of technicians, often requiring around 30 minutes. In contrast, larger vessels also load and discharge equipment and materials, with times varying widely depending on the cargo. Beyond personnel and cargo handling, all vessels are required to return to base annually for inspections, ensuring their compliance and operational readiness.

The bases, which can be onshore ports, offshore stations or hubs, or mother vessels have designated capacities for vessels and technicians (Stålhane et al., 2019). The mother vessel is located close to, or within the wind farm and is a specialized concept developed for the wind industry. It functions as a base for smaller daughter vessels, provides accommodation for maintenance technicians, and is, in some cases, equipped with a crane for heavy lift operations; hence the mother vessel itself can be used to support maintenance activities. Other potential vessel bases are characterized by their distance to the wind farm(s), investment cost and their capacity to accommodate for vessel types (Gundegjerde et al., 2015).

Currently, the vessels in the North Sea Region use the Den Helder shore as their base. From here, they are chartered to their offshore locations. To model the difference in the future, different scenarios can be taken into consideration. For the logistic activities in the future, the activities can be considered to be either of three: shore-based, SOV-based, or island-based. In the shore-based scenario, the vessels are chartered like they are now - they leave from a location onshore and return to the same point after each voyage. In the SOV-based scenario, a designated offshore point will serve as the return hub for each Service Operation Vessel (SOV). From this offshore location, technicians, equipment, and materials will be transferred vessel-to-vessel to a secondary vessel. Following this exchange, the secondary vessel will transport these resources back to shore, ensuring efficient logistical flow between the offshore site and onshore facilities. In theory, the offshore SOVs do not return to the shore. For the island-based scenario, the energy hubs are facilitated with a (sandy) island which can be used as a base for the vessels. In any case, adding additional bases to the current single-base situation causes the need for a modification of the corresponding single-base operations.

2.2.1. Vessel Types and Characteristics

To support maintenance activities, various types of vessels and helicopters can be utilized. The vessel fleet consists of the main logistics vessels and additional transport alternatives. The logistics strategy is built around the primary vessel, which is determined based on the distance between the technician base and the offshore facility and the type of activity that needs to be performed. The options considered for the vessel fleet consist of Crew Transfer Vessels (CTVs), Service Operation Vessels (SOVs), Surface Effect Ships (SESs), Heavy-Lift Vessels (HLVs), supply vessels and walk-to-work vessels. The characteristics of the primary vessel which are relevant to determining the logistics strategy include their (technician) capacity, their speed, and specifics like their towing abilities (Pejman Shoeibi Omrani et al., 2022).

The primary vessel also determines what type of supporting transportation options are needed. The additional vessels can be chartered to support activities like providing additional supplies, emergency transport or the transportation of a smaller scale of people. This can be done by so-called daughter crafts, large-scale supply ferries, and helicopters. Helicopters are not considered for this research, as they consider a different set of constraints and characteristics compared to the other types of transportation.

The distance between the technician base and the offshore facility, along with the assets required for certain activities, affects the choice of the primary vessel. Larger vessels like SOVs can stay longer offshore compared to smaller vessels like CTVs, which means that SOVs are generally used to serve facilities that are further from the shore instead of CTVs. Currently, a system of vessel sharing is already in place for the O&G industry, where the activities of multiple platforms owned by different operators are consolidated and performed by one fleet of vessels. These activities can be extrapolated for the activities of offshore hydrogen, carbon capture storage, and offshore wind. The sharing concepts can be divided into (1) the sharing of the crew, where the technicians are skilled to perform multiple sets of maintenance tasks and (2) the shared use of transport options for transferring crew to or between offshore structures.

For this research, all main vessels will be generalized and referred to as SOVs. The SOVs can be used as a technician base and as the mother vessel of daughter vessels. The daughter vessels are CTVs and are solely used for the purpose of transporting a smaller group of technicians to their destination for one working day. The capacity of the used SOVs can vary depending on the type of vessel that is used but can be estimated to be suitable for approximately 50 technicians. The CTVs are used to transport technicians in smaller groups, with a capacity of 12 technicians. This type of smaller vessel travels with a higher speed of 25 knots compared to SOVs which can travel with a speed of up to 15 knots. Another vessel type that is used for specific activities like CCS painting jobs and HPP cell replacement is a Heavy-Lift Vessel (HLV) also known as a Jack-Up Vessel (JUV). In addition to the operational activities conducted at offshore locations, ancillary tasks such as vessel preparation, including loading and unloading, as well as administrative functions, are excluded given the uncertainties surrounding CCS and HPP implementations. This exclusion is necessitated by the lack of definitive information or requirements pertaining to the requisite equipment for the offshore activities.

2.2.2. Accessibility and Constraints

Accessibility is used to measure the percentage of time in which a certain type of service fleet can support offshore facilities. For instance, smaller workboats can visit an OWF for slightly more than half of the year, while larger vessels can access it over 90% of the time. This discrepancy arises from variations in the maximum allowable wave height for different vessels, as well as restrictions imposed by wind speeds and reduced visibility due to fog. Certain areas may become inaccessible for months during adverse weather seasons, regardless of the mode of transportation (Tusar and Sarker, 2023).

Accessibility in the North Sea Region can also be improved by installing energy islands in the future. The energy islands are sandy islands that can be located within an energy hub and provide a central hub location, where offshore activities in O&G and OWFs can be coordinated. The island will also act as a centerpoint for the energy collection from surrounding wind farms. Additionally, they can facilitate the production of sustainable fuels such as green hydrogen using electrolysers powered by the energy collected from offshore wind farms. The warehousing of spare parts of wind turbines, accommodation services for personnel, and marshalling port for large component replacement or installation vessels can also be supported by the energy islands, as well as options for the refuelling and sheltering of offshore vessels (Pejman Shoeibi Omrani et al., 2022).

Each base where vessels can be stationed also has a capacity for the number of vessels that can be stationed at the same time. This capacity is not only related to a spatial capacity but also the human resources needed to serve the vessels. It is not certain yet what additional island uses will be deployed, hence why the vessel capacity of the base is not researched yet. Aside from serving as a technician base, activities like hydrogen production, warehousing, data centres, and tourism are considered additional island uses (Pejman Shoeibi Omrani et al., 2022). Because this aspect of the energy islands is not determined yet, this model assumes an unlimited capacity of vessels for the islands.

The accessibility of bases is subject to variability, particularly when a base undergoes maintenance.

During such periods, the base becomes temporarily inaccessible, necessitating the relocation of vessels to alternative bases or rendering the vessels stationed at the affected base inoperative for the duration of the maintenance. This operational constraint requires strategic planning to ensure continuity of fleet deployment and mitigate the impact on overall logistical operations.

For the activities at wind farms, CTVs travel according to a drop-off and pick-up system at each wind farm. Currently, it is not customary for technicians to perform maintenance activities on wind farms of different operators. To save on costs and maintain the turbines more efficiently, it would be possible for multiple operators to share their technicians and share the costs of vessel use. SOVs on the other hand, only operate according to a drop-off and pick-up structure for O&G platforms. Operators of CCS and HPP platforms plan to adopt a similar structure for the upcoming offshore facilities on the North Sea. An SOV will be used to visit CCS and HPP platforms on the same trip as a so-called walk-to-work vessel, but the operators have no intentions yet to retrain their technicians such that they are qualified to perform maintenance activities for both facilities.

2.3. Assumptions

Many offshore operators and organisations of NSE5 are still heavily researching the future scenarios on and around the energy hubs. To simplify this model and to be able to solve this model, a number of assumptions need to be made.

1. A vessel can only be stationed at one base and does not change throughout the planning horizon.
2. The maintenance activities for the vessels themselves are not taken into account for this model.
3. The technicians are multi-skilled and are not distinguished for each offshore facility. In this model, the technicians are regarded as individuals who can be sent out to all destinations.
4. Newer offshore wind turbines in deeper water demand the same type of operation and maintenance as the current wind turbines as found in the literature.
5. The bases considered in this research are equipped with all necessary machinery and materials during the considered time horizon. There is no need to ship additional equipment to the offshore bases for maintenance activities.
6. CTVs must return to their base after concluding their tasks.
7. No opening hours are considered for either the bases or the offshore units.
8. Per year, there are 20 days ”reserved” for unplanned maintenance of CCS platforms. For simplicity, it is assumed that these 20 days are spread over the year and for every time unplanned maintenance is required, its maintenance takes 1 working day.
9. An SOV can stay offshore for a longer period of time, this can vary from one to two weeks at a time.

2.4. Combined Logistic Activities and Requirements

Three types of facilities need maintenance in the future: Offshore Wind Farms, Hydrogen Power Plants, and Carbon Capture Storage platforms. The frequency at which the wind farms need to be visited linearly increases with the size of the wind farms in terms of the number of turbines. The more turbines one wind farm has, the more visits it requires. The Hydrogen Power Plants that will be linked to Hub West are scheduled to have a capacity of 4 - 8 GW, consisting of several platforms of 500 MW each. Professionals from the hydrogen operators suggest that current research allows for 5 MW capacity per cell, adding up to 100 cells per platform. Each platform will require daily maintenance and check-ups with one large maintenance task every 6 to 10 years, which has a duration of 2 weeks per cell. However, future research could result in a larger capacity per cell and thus fewer cells per platform. The daily maintenance of the HPPs are assumed to be platform-based, where a vessel will visit one or more platforms every day for daily check-ups. The platforms that are used for Carbon Capture Storage, however, have a set amount of scheduled activities for the future, with little to no uncertainties. There will be one yearly scheduled activity, which will have a duration of 3 weeks in total.

The available set of vessels that will be used to fulfil all the required activities of the offshore facilities can be associated with the tasks of each location. Wind farms, for example, will mostly require CTVs for frequent tasks while CCS and HPP platforms will predominantly be served by SOVs and HLVs. The CTVs considered in this research can transport up to 12 technicians and travel with an average speed of 25 knots, this type of vessel has to be back at their base at the end of their shift. SOVs, on the other hand, can stay offshore for longer periods of time as they provide lodging facilities. This type of vessel is bigger than a CTV, as it can carry up to 50 technicians. However, an SOV can only travel with speeds up to 15 knots and will typically be used as a walk-to-work vessel for HPP/CCS platforms or as a mother vessel to smaller vessels servicing offshore wind farms. The available vessels and their characteristics are given in Table 2.1.

Tables 2.2 - 2.4 show the visiting demands of each offshore location type. Tables 2.2 and 2.3 are given on the lowest level - per wind turbine and hydrogen cell, respectively - meaning that the given frequencies are higher for a whole wind farm or hydrogen platform, depending on their total size and capacity. The demands given for the CCS platforms in Table 2.4 are given for a whole CCS platform and are thus fixed for each platform.

Table 2.1: Available vessel types

Vessel Type	Technician Capacity	Max. speed [knots]	Max. Duration of Use [h]
CTV	12	25	12
SOV	50	15	168
HLV	50	15	168

Table 2.2: Operation & Maintenance Tasks of an Offshore Wind Turbine

Task name	Occurence Rate [per year]	Required Asset	Technicians	Task Duration [h]
Manual reset	7.5	CTV	2	3
Minor repair	6.81	CTV	2	7.5
Medium repair	3.35	CTV	3	22
Major repair	1.17	SOV	4	26
Major replacement	0.29	HLV	5	52
Yearly servicing	1	CTV	3	60

Table 2.3: Operation & Maintenance Tasks of Offshore Hydrogen Platforms

Task name	Occurence Rate [per year]	Required Asset	Technicians	Task Duration [days]
Cell replacement	0.125	HLV	20	14
Daily maintenance	365	SOV	20	1

Table 2.4: Operation & Maintenance Tasks of a CCS platform

Task name	Occurence Rate [per year]	Required Asset	Technicians	Task Duration [days]
Yearly maintenance	1	SOV	20	21
Unplanned maintenance	20	SOV	20	1
Painting	0.167	HLV	40	70

3 Methods

The problem described in Chapter 2 contains information and data regarding the logistic activities and requirements for offshore facilities in the future. The facilities considered in this study are offshore wind turbines, hydrogen production plants, and carbon capture storage platforms. There are two types of hydrogen production that are considered: green hydrogen is produced by electrolysis, which is generated using renewable sources from wind farms, and blue hydrogen for which carbon capture storage platforms are needed to make the blue hydrogen low-carbon. In this chapter, the method to model and solve the system is presented. First, a literature review is given of similar problem descriptions and their solution approaches previously used in comparable vessel fleet problems. This part will answer the sub-question *How can the pool and sharing system of the mixture of fleet assets be modelled and what are the Key Performance Indicators?* Then, the problem described in Chapter 2 is given as a deterministic model. This model is then solved by mathematical optimisation using Gurobi, answering sub-question *How to develop a model that represents the mixture of fleet assets in a future scenario, incorporating the offshore energy hubs and their corresponding facilities?* The model looks at the vessel fleet size and mix model and determines what combination of vessels is required to perform the necessary Operation & Maintenance tasks while allocating the vessels to the different bases to minimize the travel distance from the base to the offshore facility.

3.1. Literature Review

A fleet size and mix problem can be described for multiple situations. The maritime vessel fleet size and mix problem in the literature primarily has looked into the maintenance activities of offshore wind farms. With the upcoming developments in the North Sea Region, the problems previously described in the literature will have to be adjusted to future scenarios. Bittencourt et al. (2021) proposes a framework which selects the supply set each vessel should provide. This framework is used to compare a number of different fleet management policies and analyze the impacts of these strategies in a discrete-event simulator that realistically represents the offshore operation scenario. In this study, the fleet is heterogeneous with multiple compartments; therefore, each vehicle has its own storage capacity for each commodity. The objective of their research is to maximize the service level defined by the percentage of requests that are delivered on time and this is computed by implementing it in Python and solved using Gurobi 8.0. The outputs of different scenarios are compared to each other to analyze the effects their elements have on the output. The main difference between the scenarios is whether an aggregated or disaggregated fleet is used - in the aggregated fleet, one vessel can carry a combined set of goods while the vessels in the disaggregated fleet carry only one type of good. Eskandari and Mahmoodi (2016) includes routing in their study and compares two alternatives for vessel routing, one based on a fixed schedule and another based on the demand of offshore platforms. The routing policy determines the sequence of locations a vessel will visit. With a fixed schedule, the route for a vessel is predetermined and each location will be visited 2,3 or 4 times a week according to expert knowledge. For the second policy, routing and planning are based on the demand pattern of the locations. The assignment of vessels will be based on a set of general rules where (1) the platform demand is assigned to the smallest possible vessel, (2) the platform demand is assigned to a long-term vessel if one is available, and (3) more than one platform request is assigned to a vessel if possible. This study uses a simulator to generate near-optimal solutions, minimizing costs while satisfying the minimum platform service level. The research consists of two separate experimental phases, where the first phase determines the optimal decision variable values. The second phase uses these optimal values, after which it will run the model multiple times. The results of the second phase of each routing policy will be statically compared against each other. Similar to Eskandari and Mahmoodi (2016), Vieira et al. (2021) looks at a periodic supply vessel planning problem (PSVPP) while considering vessel routes. To solve this problem, Vieira et al. (2021) introduces a branch-and-cut algorithm and an Adaptive Large Neighbourhood Search (ALNS) heuristic. The problem consists of a periodic vehicle routing problem while determining an optimal fleet size and mix of heterogeneous offshore supply vessels, their weekly routes and schedules for servicing the offshore oil and gas installations, and the berth allocations at the supply base. The problems described for these three models are centered around the demand and supply activities of Oil & Gas installations, but parts of their general model can still be applied to the problem described for this research.

Du, Brunner, and Kolisch (2016) proposes a model that addresses the problem of a cost-minimal fleet composition. This model introduces a 4-step approach to aggregate demand. The demand for this problem is related to tractors used to tow airplanes when leaving the gate and is derived from flight schedule information acquired from a collaborating airport in a case study. The 4-step model to aggregate the demand starts with selecting a representative peak day in the established time period. Then, the time window of vehicle occupancy for each task of this selected day needs to be calculated. Finally, the aggregated demand of job types needs to be satisfied for overlapping vehicle compatibilities. There are additional constraints that need to be added to the model if one vehicle is compatible with carrying out more than one type of task. The problem described in this paper has a different character than the offshore vessel fleet problem, as these vehicles do not have the same characteristics as offshore vessels and are used for completely different purposes. However, the 4-step approach to aggregate demand can be used in modelling the demand to eventually shape the vessel fleet size and mix.

Studies performed by Tusar and Sarker (2023), Stålhane et al. (2019), and Gundegjerde et al. (2015) consider the vessel fleet problem in the context of OWF maintenance activities. Tusar and Sarker (2023) looks at a vessel fleet size and mix problem that arises while maintaining offshore wind farms using a fleet of maintenance vessels. They focus on establishing the best vessel assignments while minimizing the costs by formulating an Integer Programming model. In the research done by Stålhane et al. (2019), the problem is divided into two stages and solved by formulating the problem as a stochastic programming (SP) model. First, decisions are made on what vessels to charter, subject to uncertainty in the demand of maintenance tasks and weather conditions. The second stage of the model can be used to decide how to support maintenance tasks using the chartered vessels determined from the first stage of the model. Gundegjerde et al. (2015) studies the vessel fleet size and mix problem that arises for the maintenance operations at offshore wind farms and proposes a stochastic three-stage programming model. The fixed costs of acquired or chartered vessels and their bases are minimized in the first stage, followed by the minimization of the expected cost of the vessels chartered. Finally, in the third stage, the expected costs of using the vessels, downtime costs of delayed maintenance tasks, penalty costs and transportation costs are considered. This study considers a stochastic model and builds on the deterministic version of the problem studied by Halvorsen-Weare et al. (2013). The problems described by Stålhane et al. (2019) and Gundegjerde et al. (2015) consider a number of different maintenance activities and analyze them specifically by their type in their methods, whereas Tusar and Sarker (2023) generally considers the transport to and from wind farms.

A comparative overview of the analysed studies is given in Table 3.1. The developed model for the problem described in Chapter 2 adds to the literature of the previously studied models by finding synergy in the use of the vessel fleet of multiple offshore facilities. The literature mainly focuses on the vessel fleet of wind turbine (maintenance) activities and does not consider the potential to combine the fleet with the maintenance of other facilities. This model aims to help decision-makers in the offshore industry develop a logistic strategy for assigning vessels to certain offshore activities and consolidate tasks where possible. The results of the model can be used to compare different scenarios related to scheduling decisions and future developments. The problem described can be composed as a deterministic model, as the input in terms of platform demand and available resources is given beforehand.

Table 3.1: Literature Review on Vessel Fleet Size & Mix Problems with Heterogeneous Fleet

Reference	**Model Formulation**	**Deterministic/ Stochasticity**	**Objective**	**Solution Approach**
Bittencourt et al. (2021)	MIP	Product handling Demand Fleet management External influences	Maximize service level	Simulation
Vieira et al. (2021)	Voyage-based	Deterministic	Minimize costs	Exact and heuristic algorithms
Eskandari and Mahmoodi (2016)	Simulation	Weather conditions	Minimize costs	Simulation
Tusar and Sarker (2023)	IP	Deterministic	Minimize costs	Algorithm, Commercial solver
Du, Brunner, and Kolisch (2016)	Extended formulation	Deterministic	Minimize costs	Column Generation Heuristic (CGH)
Stålhane et al. (2019)	SP	Weather conditions Occurrence of failures	Minimize costs	Matheuristic solution approach based on apriori column generation
Gundegjerde et al. (2015)	SP	Prices Weather Failures	Minimize costs	Commercial solver
Gutierrez-Alcoba et al. (2017)	MILP	Deterministic	Minimize costs	OPLEX solver

To understand the concept of maintenance planning and scheduling, a brief analysis is done on a number of articles related to offshore maintenance planning. A lot of research has been done on optimizing the maintenance planning of offshore wind farms to minimize both operational costs as well as downtime costs. Zhang et al. (2024) provides an optimization model robust to uncertain maintenance demand in scenarios with limited data, which can be used as a template to schedule the maintenance tasks of offshore wind farms. They take into account the uncertainty in maintenance demand due to corrective maintenance activities. This method can be especially beneficial for scheduling the maintenance tasks of more modern wind turbines for which limited data is available due to the competitiveness of the industry. Another study done on maintenance strategies incorporating uncertainties in demand develops a closed-loop decision-making approach (Li et al., 2023). This decision-making process divides the entire maintenance optimization problem into sub-problems and is regularly updated with new operational data, gradually diminishing uncertainties in model parameters over time. Their application of feedback from the offshore wind farm system proved to reduce about 3.4% of revenue losses compared to existing open-loop strategies. Table 3.2 shows the consulted literature on optimized maintenance schedules of offshore wind farms.

Table 3.2: Literature Review on Maintenance Schedules of Offshore Wind Farms

Reference	**Model Formulation**	**Stochasticity**	**Objective**	**Solution Approach**	**Time Horizon**
Zhang et al. (2024)	DRO-based	Uncertain maintenance demand	Minimize overall maintenance costs	Commercial solver	30 days
Li et al. (2023)	X	Offshore wind farm states and inaccuracies in model parameters	Minimize the annual revenue loss in the horizon	PSO algorithm	Wind farm life span
Schrotenboer, Ursavas, and Vis (2020)	MISP	Weather conditions and maintenance tasks	Minimize costs (transportation & technician hours)	Sample Average Approximation	One lease term
Gutierrez-Alcoba et al. (2019)	MILP	Deterministic	Minimize costs (tactical and operational)	CPLEX Solver	One year (730 periods)
Zhang and Zhang (2021)	adaptive robust optimization problem	Deterministic	Optimize wind turbine maintenance schedules	CCG algorithm	30 days

3.2. Solution Method

An optimization problem can be solved using various methods, which can broadly be categorized into exact optimization methods or heuristic optimization methods. Aside from these two methods, simulations are also often used for problems subjected to random variables. In the case of offshore maintenance, the random variables used in optimization models are related to uncertainty in maintenance demand or weather conditions. However, simulations are not guaranteed to result in the global optimum, as the goal of simulations is often to understand the system behaviour, assess performance, or make decisions under uncertainty rather than finding an exact optimal solution. Similarly, heuristic optimization methods cannot guarantee an optimal solution as they generally use algorithms that are specific to the model conditions, making them less robust to changes in system conditions (Tusar and Sarker, 2023).

The optimization for he problem description in Chapter 2 can be formulated using Mixed-Integer Linear Programming (MILP) and solved through an exact optimization approach, specifically with the commercial solver Gurobi. MILP is widely recognized modelling method in the optimization of Vehicle Routing and Scheduling problems, as appears in the literature review in Tables 3.1 and 3.2. This method is especially valuable for the logistics of offshore facilities expected to operate by 2050, providing a structured way to handle decision-making for long-term, complex scenarios.

The exact optimization method implemented by Gurobi relies on branch-and-cut, a powerful algorithm designed to guarantee an optimal solution. This approach enables Gurobi to efficiently manage the binary, integer, and continuous variables present in the MILP model, making it highly suitable for obtaining precise solutions in large-scale, complex logistics models. Despite the availability of limited data regarding future demand, MILP can generate strategic insights that are applicable over extended periods, thereby providing valuable guidance for long-term planning. The ability to perform scenario analysis and sensitivity testing within the MILP framework further enhances its suitability, allowing stakeholders to explore a range of future conditions and make informed decisions that will remain robust over the span of several decades.

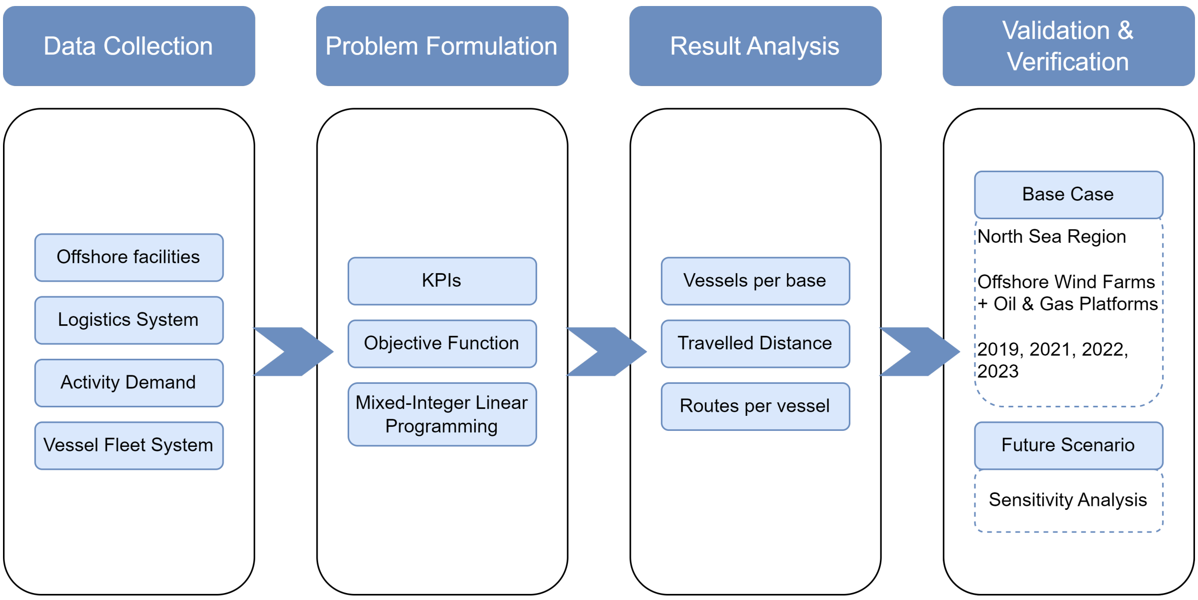

Figure 3.1: Methodology Synopsis

4 Model

The most important requirement for a logistic service provider is that they have the assets required to facilitate the demand generated. This can be achieved using several methods, and the performance of each method can be evaluated using a number of Key Performance Indicators (KPIs). Pejman Shoeibi Omrani et al. (2022) discussed a number of KPIs that can be monitored and optimized to achieve the most optimal method possible. Their suggested KPIs include transport costs, availability of uptime for the vessels, distance travelled by the vessels and transport options, and emissions from transport and the technician base operation. Some of these performance indicators can also be used for the vessel fleet problem. The performance indicators can be translated into the following corresponding goals of the resulting model and thereby linked to the main objectives of the system:

- **Minimize the number of vessels in the fleet mix.** Many of the future platforms will be unmanned, thus changing offshore logistic activities. A plausible scenario is that the frequency of voyages will be reduced compared to the current situation while increasing the load capacity. This means that the number of operating vessels is expected to be reduced in the future scenario.
- **Minimize the total distance travelled.** The travel distance can be used as a measure which indicates the efficiency of the tactical and operational vessel management. Moreover, the total distance travelled can be directly linked to the emissions and costs.

To solve the problem described in Chapter 2, the problem can be written as a mathematical problem. The objective functions of the model are based on the KPIs and are defined to minimize (1) the number of vehicles used and (2) the total distance travelled. Figure 4.1 shows a general overview of the in- and output variables of the model.

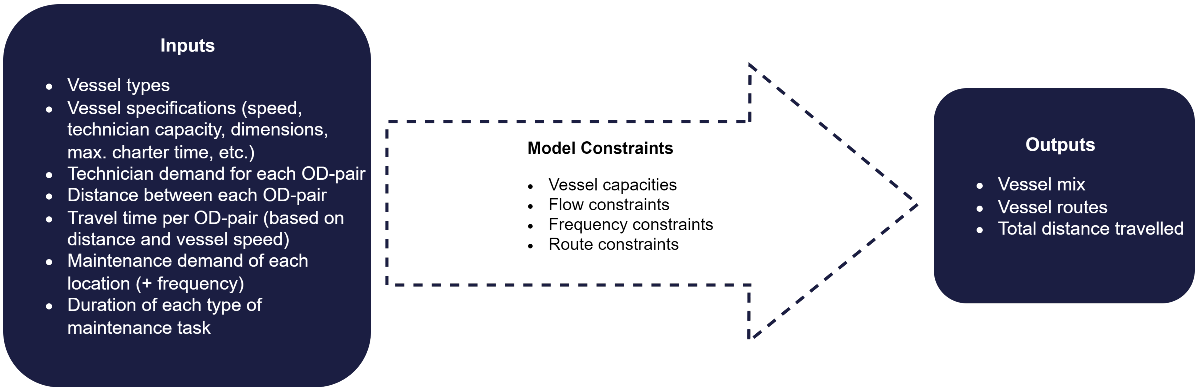

Figure 4.1: Model Data Flow

4.1. Model Formulation

Let B be the set of both onshore and offshore bases, from where the vessels can be departed. Each vessel leaving a base can be used to serve a location $i \in N$ to perform maintenance activity $a \in A$. Each vessel can stay offshore for its Maximum Duration of Use (MDU) before it has to return to base for fuel, exchange of technicians, pick-up of supply, etc. The MDU of a vessel depends on the vessel type, whether the vessel is a Crew Transfer Vessel or a Service Vessel.

The model consists mostly of deterministic parameters, where the set of locations consists of a total of 4 bases, 7 wind farms, 5 CCS platforms and 1 Hydrogen platform, consecutively defined as $B = \{0, 1, 2, 3\}$ for the bases and $N = \{4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16\}$ for the offshore locations. The solution will be described as a number of routes $r \in R$, where each route lasts at most the MDU hours. There are a total of >10.000 tasks that need to be completed within one year. Depending on the availability of the bases, each vessel can be assigned to a maximum number of routes per year. This maximum depends on the MDU of the vessels, as CTVs have an MDU of one working day (12h) while SOVs and HLVs have an MDU of one week (168h). A maximum of 365 routes can be assigned to a CTV per vessel for a fully operational base whereas a maximum of 52 routes can be assigned to SOVs and HLVs in the same scenario. In a scenario where bases have limited accessibility due to maintenance, fewer routes can be assigned to the vessels linked to that base.

Each location can be served from any of the 4 bases. A route originates from one base, visits exactly one location and then returns to the same base. Each vessel is assigned to one base only and can only be assigned to routes that originate from its assigned base. Every time a location is visited, a combination of activities needs to be completed at that location.

In this model, the constraints have been deliberately simplified to focus solely on the demand and the duration of each visit. Specifically, each activity must be completed, and the duration of each visit cannot exceed the maximum duration of time. A key aspect not incorporated into the model is the capacity of the vessel in terms of the number of technicians it can transport. In practice, technicians are typically deployed to different wind turbines within a wind farm to carry out various tasks simultaneously. However, this model prioritizes compliance with the MDU constraint, thereby offering a lower bound on the number of activities that can feasibly be completed on each route. This approach allows for a more conservative estimation of operational capacity while ensuring that time constraints are respected.

- d_{ij} are the distances between locations i and j. The maximum speed of the vessel type affects the time it takes to travel from one location to another.
- u_a the duration of each maintenance task $a \in A$
- f_{ai} the frequency of maintenance activity $a \in A$ at location i
- vs_v the vessel speed.
- MDU the time limit in hours of how long vessels can stay offshore before they have to return to their base.
- M a large number equal to the number of total activities of demand.
- R_{max} the maximum number of routes a vessel can be assigned to per time period.

The decision variables for this part of the optimization problem are:

- $x_{bir} = 1$ if route r travels from base b and includes node i and $= 0$ if otherwise.
- $y_{air} \geq 0$ is a non-negative integer variable, counting the number of activities at node i that are completed during route r.
- $T_r \geq 0$ is a continuous variable counting the duration of each route r.
- δ_b is a non-negative integer variable, counting the number of vessels allocated to base b.

4.2. Mathematical Model

Based on the KPIs, the parameters and the variables, the objective function of the model can be formulated along with the corresponding constraints. The constraints related to this problem can generally be divided into demand constraints, time constraints and resource constraints. The demand constraints ensure that the required visiting frequency for each location is met. The time constraints enable effective decision-making regarding the maintenance schedule while adhering to limits on vessel operating hours. The resource constraints address the limitations related to the vessels.

Sets

B	Set of bases
N	Set of nodes
A	Set of maintenance activities

Parameters

d_{ij}	Distance between nodes i and j, with travel time tt_{bi}
f_{ai}	Required frequency of maintenance activity a at location i
vs_v	Maximum speed of vessel v in nautical miles per hour
m_a	The activity type of maintenace task $a \in A$
u_a	The duration of each maintenance task $a \in A$.
R_{max}	The maximum number of routes a vessel can be assigned to per time period
MDU	The time limit in hours of how long vessels can stay offshore before they have to return to their base.
M	Large number equal to the number of total activities of demand.

Decision Variables

x_{bir}	$\in 0, 1$, indicating whether route r travels from base b and includes node i.
y_{air}	$\in \mathbb{Z}_{\geq 0}$, counting the number of completed activities at node i during route r.
T_r	$\in \mathbb{R}_{\geq 0}$, is a continuous non-negative variable counting the duration of each route r in hours.
δ_{bv}	$\in \mathbb{Z}_{\geq 0}$, is an integer non-negative variable stating the number of required at base b.

Objective Function

$$min \sum_{b \in B} \sum_{i \in N} \sum_{r \in R} x_{bir}$$

Subject to:

$$\sum_{b \in B} \sum_{i \in N} x_{bir} \leq 1 \qquad \forall r \in R \quad (4.1)$$

$$\sum_{a \in A} y_{air} \leq M \sum_{b \in B} x_{bir} \qquad \forall i \in N, r \in R \quad (4.2)$$

$$\sum_{a \in A} \sum_{i \in N} y_{air} u_a + 2tt_{bi} \sum_{b \in B} \sum_{i \in N} x_{bir} \leq MDU \qquad \forall r \in R \quad (4.3)$$

$$\sum_{r \in R} y_{air} \geq f_{ai} \qquad \forall a \in A, i \in N \quad (4.4)$$

$$\frac{\sum_{i \in N} \sum_{r \in R} x_{bir}}{R_{max}} \leq \delta_b \qquad \forall b \in B \quad (4.5)$$

Constraint 4.1 makes sure that each route leaves from one base and visits one location only while constraint 4.2 assures that that location is only visited if and only if that location has activities that need to be completed. Constraint 4.3 is a time constraints respecting the Maximum Duration of Use of the vessels during each route. The demand of the locations is met by enforcing Constraint 4.4, while 4.5 determines the number of vessels per base, while counting the number of routes per base.

5 Results

This section presents the data used to test the model and the outcomes of the results analysis. First, the dataset is presented. Due to computational constraints, the initial computations are done with a subset of the data shown in Section 5.1. This subset is then used as the input data for the mathematical model presented in Section 4.2. The results of this model are then analyzed in Section 5.2.

5.1. Input Data

The geographic scope of this study encompasses the region surrounding Hub West in the North Sea. Within this area, four potential base locations are considered, along with seven wind farm sites, five carbon capture and storage facilities, and one hydrogen power plant. The precise coordinates of these locations, along with the Euclidean distances between each base and facility, are detailed in Appendix C.

The maintenance demand for the wind farms surrounding Hub West is directly influenced by their respective sizes and capacities per wind turbine. While Table 2.2 in Chapter 2 provides maintenance demand estimates for individual wind turbines, Table 5.1 outlines the seven wind farms under consideration, including their capacities and sizes (*Windenergie op zee - Noordzeeloket* n.d.). Although *Windenergie op zee - Noordzeeloket* (n.d.) does not explicitly specify the size of the IJmuiden Ver wind farm, this value can be inferred from its given capacity of 4000 MW. By comparing this capacity to the typical size of wind turbines, such as those used in HKW, it is estimated that IJmuiden Ver would require approximately 286 turbines to achieve its rated power.

Table 2.2 in Chapter 2 states that Offshore Wind Farms mainly require the use of CTVs. However, due to the large distance of the IJmuiden Ver wind farm from any of the considered bases, activities intended to be serviced by a CTV will instead be conducted by an SOV. This adjustment is necessitated by the otherwise long travel times, which would take about 2.5 hours to reach the nearest base from the IJmuiden Ver wind farm. Given that crew members can only remain on board for approximately 30 minutes to a maximum of one hour, utilizing an SOV ensures that operational needs are met effectively while accommodating the constraints imposed by travel time.

Table 5.1: Windfarms in the Dutch North Sea Linked to Hub West

Wind farm	**Power Capacity** [MW]	**No. of turbines**	**Year of first operation**
Egmond aan Zee	108	36	2007
Prinses Amalia	120	60	2008
Luchterduinen	129	43	2015
HKW	840	60	2025
HKN	759	69	2008
HKZ	1529	139	2023
IJmuiden Ver	4000	286	2027

As for the maintenance activities for carbon capture & storage, their demands are the same for every facility as the assumption is that they are of the same size. Table 2.4 shows that a painting job for a CCS can last from 8 - 12 weeks, but for the initial computations, a duration of 10 weeks thus 70 days is considered. Table 2.3 shows the Operation & Maintenance Tasks of both a single hydrogen cell for replacement and daily maintenance check-ups on platform level. The Hydrogen Power Plant on the North Sea is predicted to consist of several hydrogen platforms, which in turn, consist of multiple hydrogen cells. The nominal capacity of one platform is assumed to be 1 GW, this implies that each platform houses 200 cells of 5 MW. It is important to note that there exists an inherent uncertainty regarding the future capacities of these cells. There is a potential for individual cells to achieve capacities exceeding the nominal value, which could lead to a reduction in the number of cells required per platform to attain the same capacity of 1 GW. The cells have to be replaced every 6 to 10 years, but in the initial calculations, an average of once every 8 years is considered. The exact dimensions of these platforms and the total capacity of the power plant remain subject to uncertainty, given the potential for unforeseen technological advancements. These types of scenarios based on external factors are later discussed in Section 6.3

Due to computational constraints, it is necessary to reduce the dataset to a manageable subset. Given that the activities follow a repetitive pattern, their frequency can be effectively analyzed over both short and long time periods. Although the data is provided on an annual basis, this repetition allows for extrapolation over extended periods or examination within shorter time frames. Since the maximum operational duration of CTVs is limited to a single working day, the activity frequency can be analyzed on a daily basis. For SOVs and HLVs, which can remain offshore for up to a week, a monthly analysis is more appropriate.

The activities listed in Tables 2.2 to 2.4 combined with the reduced time frames result in the set of activities as given in Tables 5.2 and 5.3, with node specifications detailed in Table 5.4. The observed discrepancies in activity types between the initial tables in Chapter 2.4 and this chapter are primarily due to the implementation of maximum duration constraints on vessel utilization. Tables 2.2 to 2.4 include activity durations that surpass the maximum duration of use for specific vessels, consequently making the initial schedules infeasible as they demand vessels to operate beyond their capacity. To rectify the infeasibility, Tables 5.2 and 5.3 employ a strategy of dividing activity durations into more manageable segments, taking into account a vessel's MDU, travel times and transfer times. The transfer times for a CTV are counted before and after the completion of each activity within a route, whereas the transfer times for SOVs and HLVs are taken into account for every shift of 12 hours within a route. This distinction arises because SOVs and HLVs, which provide onboard accommodation, operate on a walk-to-work basis, eliminating the need for frequent return trips between shifts. This adjustment guarantees that vessels can return to base within the time limits. As a result of the shorter activity durations, vessels must be scheduled to visit each activity with greater frequency to complete the overall task. This increased frequency is a direct consequence of adhering to the maximum duration constraints.

Table 5.2: Activitity Types with Daily Frequencies CTV

Activity Type	Node	Duration [h]	Frequency	Activity Type	Node	Duration [h]	Frequency
0	0	3.00	1	12	3	3.00	3
1	0	6.39	1	13	3	7.03	3
2	0	6.39	1	14	3	7.03	1
3	0	6.39	1	15	3	7.03	1
4	1	3.00	2	16	4	3.00	2
5	1	6.43	2	17	4	6.63	2
6	1	6.43	1	18	4	6.63	1
7	1	6.43	1	19	4	6.63	1
8	2	3.00	1	20	5	3.00	3
9	2	5.64	1	21	5	5.31	3
10	2	5.64	1	22	5	5.31	2
11	2	5.64	1	23	5	5.31	1

Table 5.3: Activitity Types with Monthly Frequencies SOV (left) and HLV (right)

SOV				HLV			
Activity Type	**Node**	**Duration [h]**	**Frequency**	**Activity Type**	**Node**	**Duration [h]**	**Frequency**
0	0	26.00	4	0	0	52	1
1	1	26.00	6	1	1	52	2
2	2	26.00	5	2	2	52	2
3	3	26.00	11	3	3	52	3
4	4	26.00	7	4	4	52	2
5	5	26.00	14	5	5	52	4
6	6	26.00	56	6	6	52	6
7	6	3.00	6	7	7	156.85	10
8	6	7.50	6	8	7	111.53	1
9	6	22.00	3	9	8	159.26	10
10	6	60.00	1	10	8	87.38	1
11	7	12.00	2	11	9	159.06	10
12	7	157.71	3	12	9	89.40	1
13	7	30.86	1	13	10	155.46	10
14	8	12.00	2	14	10	125.43	1
15	8	160.13	3	15	11	160.10	10
16	8	23.61	1	16	11	78.99	1
17	9	12.00	2	17	12	156.50	34
18	9	159.93	3	18	12	23.01	17
19	9	24.22	1				
20	10	12.00	2				
21	10	156.32	3				
22	10	35.03	1				
23	11	12.00	2				
24	11	160.97	3				
25	11	21.10	1				
26	12	12.00	244				

Table 5.4: Node Specifications from Activity Types

Node	Location	Name	Size
0	OWF	Egmond aan Zee	108 MW
1	OWF	Prinses Amalia	120 MW
2	OWF	Luchterduinen	129 MW
3	OWF	HKW	840 MW
4	OWF	HKN	759 MW
5	OWF	HKZ	1529 MW
6	OWF	IJmuiden Ver	4000 MW
7	CCS	CCS 1	-
8	CCS	CCS 2	-
9	CCS	CCS 3	-
10	CCS	CCS 4	-
11	CCS	CCS 5	-
12	HPP	HPP	8 GW

5.2. Computational Results

The Objective Function presented in Section 4.2 is designed to minimize the number of routes generated by the model. The number of routes essentially influences the number of vessels required and the total distance travelled. When the objective shifts to minimizing the total distance as described in relation to the KPIs mentioned in Section 4, the objective function can be reformulated to prioritize distance minimization. In this case, the function becomes $min \sum_{b \in B} \sum_{i \in N} \sum_{r \in R} 2d_{bi}x_{bir}$. Another objective based on the KPIs discussed in Section 4 focuses on minimizing the size of the vessel fleet. This objective is closely tied to the minimization of routes, as fewer routes naturally translate to fewer vessels, a relationship captured by Equation 4.5 in Section 4.2. The relations between the different objective functions can be reflected in the results presented in this section. These results are acquired by solving the Mixed Integer Linear Problem (MILP) model using Gurobi Optimizer version 11.0.3 build v11.0.3rc0 (linux64 - "Red Hat Enterprise Linux 8.10 (Ootpa)"). A 32-thread solver was used on a system with an Intel(R) Xeon(R) Gold 6248R CPU @ 3.00GHz, featuring 48 physical cores and 48 logical processors (DHPC, 2024).

Tables 5.5 to 5.13 present the computational outcomes of minimizing the number of routes, the total distance travelled, and the number of vessels required for CTVs, SOVs, and HLVs, respectively. The results for the minimization of distance travelled and the minimization of routes might look almost identical to each other at first, but a closer analysis of the results indicates that the assigned routes are different in both cases. This discrepancy is caused by the prioritization of fewer routes over the distance covered by each route in the minimization of routes, whereas the minimization of distance creates more but shorter routes.

Table 5.5: Results CTV: minimizing number of routes

	Minimize Routes			
Base	**No. of activities**	**No. of routes**	**No. of vessels**	**Total distance**
Den Helder	0	0	0	0
IJmuiden	38	27	27	1112.45
SOV	0	0	0	0
Island	0	0	0	0
Total	38	**27**	27	1112.45

Table 5.6: Results CTV: minimizing distance

	Minimize Routes			
Base	**No. of activities**	**No. of routes**	**No. of vessels**	**Total distance**
Den Helder	0	0	0	0
IJmuiden	38	27	27	1112.45
SOV	0	0	0	0
Island	0	0	0	0
Total	38	27	27	**1112.45**

Table 5.7: Results CTV: minimizing vessels

	Minimize Routes			
Base	**No. of activities**	**No. of routes**	**No. of vessels**	**Total distance**
Den Helder	0	0	0	0
IJmuiden	38	27	27	1112.45
SOV	0	0	0	0
Island	0	0	0	0
Total	38	27	**27**	1112.45

The results for CTVs in Tables 5.5 to 5.7 show that all routes, despite the different objective functions, are assigned to the IJmuiden base. This route assignment is plausible given that the CTVs in this scenario are exclusively used for servicing the OWFs, with the IJmuiden base being considerably closer to the OWFs compared to the other bases. A closer analysis of the detailed results as presented in Appendix E shows that the assigned routes in Tables 5.5 and 5.7 are identical while the routes in the minimization of distance in Table 5.6 slightly vary.

Table 5.8: Results SOV: minimizing number of routes

	Minimize Routes			
Base	**No. of activities**	**No. of routes**	**No. of vessels**	**Total distance**
Den Helder	6	4	1	172.06
IJmuiden	91	16	4	1005.1
SOV	24	16	4	442.72
Island	244	18	5	0
Total	365	**54**	14	1619.9

Table 5.9: Results SOV: minimizing total distance

	Minimize Distance			
Base	**No. of activities**	**No. of routes**	**No. of vessels**	**Total distance**
Den Helder	6	4	1	172.06
IJmuiden	91	16	4	1005.96
SOV	24	17	5	442.72
Island	244	18	5	0
Total	365	55	15	**1619.9**

Table 5.10: Results SOV: minimizing vessels

	Minimize Vessels			
Base	**No. of activities**	**No. of routes**	**No. of vessels**	**Total distance**
Den Helder	0	0	0	0
IJmuiden	0	0	0	0
SOV	0	0	0	0
Island	365	54	14	3192
Total	365	54	**14**	3192

For the results of SOVs and HLVs in Tables 5.8 to 5.10 and Tables 5.11 to 5.13, respectively, the distances for the minimization of routes and the minimization of distance are identical. However, the allocation of routes to bases is significantly altered when minimizing the number of SOVs in Table 5.10, with all SOVs forced to the Island base. This outcome can be explained by the activities shown in Table 5.3, which shows that a substantial portion of the activities for SOVs are performed at an HPP platform. The full and detailed results of the routes, what nodes they visit, and how many activities are performed per route, can be found in Appendix E. Here, the results show that all 18 routes leaving from the Island base are sent to perform activities at the hydrogen plant when minimizing the routes and the distance. This is logical given that the island base is assumed to be located in the same area as the hydrogen plant, as there is effectively no travel distance between the Island and the HPP. This also explains how the distance is equal to zero for the 18 routes allocated to the Island base in Tables 5.8 and 5.9. A comparison of the results across the three objectives reveals that the minimization of routes and the minimization of distance results in the same number of vessels as well as the same amount of distance travelled, whereas the minimization of vessels saves the use of one vessel, but results in an increase in the distance by almost 80%.

Table 5.11: Results HLV: minimizing number of routes

	Minimize Routes			
Base	**No. of activities**	**No. of routes**	**No. of vessels**	**Total distance**
Den Helder	11	11	3	473.17
IJmuiden	8	7	2	323.28
SOV	44	44	11	1217.47
Island	51	37	10	0
Total	114	**99**	26	2013.92

Table 5.12: Results HLV: minimizing distance

	Minimize Distance			
Base	**No. of activities**	**No. of routes**	**No. of vessels**	**Total distance**
Den Helder	11	11	3	473.17
IJmuiden	8	7	2	323.28
SOV	44	44	11	1217.47
Island	51	37	10	0
Total	114	99	26	**2013.92**

Table 5.13: Results HLV: minimizing vessels

	Minimize Vessels			
Base	**No. of activities**	**No. of routes**	**No. of vessels**	**Total distance**
Den Helder	44	32	8	2490.90
IJmuiden	24	24	6	3003.73
SOV	21	20	5	994.78
Island	25	23	6	725.95
Total	114	99	**25**	7215.36

Similar to the results of the SOVs, Tables 5.11 and 5.12 show that the total distances for the minimization of routes and the minimization of distance are identical to each other for every base. Moreover, the other variables related to the activities, routes, and vessels appear to show identical values as well. However, the specific routes allocated to each base and node generated by the model exhibit notable differences when the objective is shifted - with comparable overall results. As for the minimization of vessels, almost all activities seem to be allocated to a different set of routes compared to the results for the other two objectives. With a total distance of more than triple the distance travelled in Tables 5.11 and 5.12, the minimization of vessels results in one vessel less than the total vessels required for the other objectives.

A closer analysis of the detailed results - particularly in the minimization of distance - reveals that the model allows for the generation of routes that do not perform any activities, which can be referred to as ”empty routes”. When an excessive number of empty routes emerges from solving one of the objective functions, it may be more reliable to filter out the empty routes in the results and establish the number of required vessels from this new value. Another method would be to focus on minimizing the number of routes, after which the minimum number of vessels required can be determined using Equation 4.5 in the mathematical model in Section 4.2. The latter method, however, does not guarantee the same results.

6

Model Validation & Verification

The objective of the model given in Section 4 is to ultimately minimize the number of vessels used to complete the demand of the offshore sites in the North Sea, as stated in Section 2.4. The constraints imposed on the problem description presented in Chapter 2 are multifaceted, encompassing the need to satisfy demand within specified timeframes and adhere to limitations pertaining to vessel capacity, base availability, and location restrictions. The method is then solved using Mixed-Integer Linear Programming. To assess the model's predictive capabilities and ensure its reliability for future applications, this chapter will focus on its validation and verification. A base case centered on the North Sea and its current activities are employed and used to analyze the results of the model. While the model is designed to consider future conditions, its accuracy can be evaluated by comparing the outputs of the base case to historical data from the North Sea. Finally, a sensitivity analysis is performed on the model to analyze the effect of different inputs and scrutinize the robustness of the model.

6.1. Base Case: North Sea Region

As mentioned in the Problem Description in Chapter 2, the facilities of Carbon Capture & Storage are not implemented yet in the North Sea. Consequently, this base case will be centered around the current logistical activities of the North Sea region, exclusively consisting of the servicing of existing Wind Turbines and Oil & Gas Platforms. The collected data for this analysis has been acquired from Peterson Energy Logistics, spanning the recent years of 2019 (pre-covid) and 2021 to 2023. It is important to note that (1) the collected dataset does not contain all activities of 2023 as it was collected before the end of the year, (2) it is not reported by the logistic service operator how many technicians are transported during each trip, and that (3) this dataset is exclusively confined to Service Vessels, thereby excluding information pertaining to CTVs (Crew Transfer Vessels). This limitation arises from the ad hoc nature of CTV requests, which are typically initiated by external parties.

The data includes four bases[1], multiple offshore ports, and platforms. The available data is from the perspective of the logistic service operator, meaning the specific activities carried out at the offshore locations are neither specified nor detailed. The recorded activities predominantly concern vessel operations, such as loading and discharge, passage (travel time), and idle time. Certain activities within the dataset indicate specific offshore operations. For instance, "Handling Offshore" (HO) denotes that a vessel is actively engaged with a platform within a 500-meter radius. "Waiting for Dayshift Offshore" (WODAYO) and "Waiting on Handling Offshore" (WOHO) imply that a vessel is in a standby mode, either positioned outside the 500-meter zone during the daytime shift of a production platform or waiting at a platform without being allowed within the 500-meter boundary, respectively. The activities relevant to offshore operations, along with their corresponding descriptions, are presented below. The full list of activities performed by the vessels of the logistic service operator is presented in Appendix D.

[1] Four bases: Aberdeen, Den Helder, Great Yarmouth, IJmuiden

Abbrev.	**Activity name**	**Explanation**
DHO	Dedicated Handling Offshore	Dedicated vessel working a platform/rig within the 500 mtr. zone.
DITO	Dedicated Idle Time Offshore	Idle time offshore of a dedicated Vessel (including W.O.W.). Also used for Economic Speed Sailing (ESS) with a dedicated Vessel.
DPASSO	Dedicated Passage Offshore	Dedicated vessel sailing to offshore location
DPASSP	Dedicated Passage to Port	Dedicated vessel sailing to port
DWODAYO	Dedicated Waiting on Dayshift Offshore	Dedicated vessel waiting outside 500 mtr zone on dayshift of a production platform. Applicable during night hours from 19:00 till 7:00.
DWODAYP	Dedicated Waiting on Dayshift in Port	Dedicated vessel is waiting in port for the dayshift of a production platform.
ESSO	Economic Speed Sailing Offshore	When a Vessel is sailing longer than regular, the extra hours are registered as economic speed sailing. Regular sailing time is based on 10 nautical miles per hour.
ESSP	Economic Speed Sailing to Port	When a Vessel is sailing longer than regular, the extra hours are registered as economic speed sailing. Regular sailing time is based on 10 nautical miles per hour.
FLEXO	Flexible Time Offshore	Vessel consuming Flex time offshore compared to Sailing Schedule
HO	Handling Offshore	Working a platform/rig within the 500 mtr. zone.
INTF	Interfield Passage	Sailing between several platforms of one operator in a defined cluster until arrival 500 mtr. zone.
PASS	Passage	Sailing until/from 500 mtr. zone.
PINTB	Interbase Passage	Sailing from port to port on Pool planning request.
WODAYO	Waiting on Dayshift Offshore	Vessel waiting outside 500 mtr zone on dayshift of a production platform. Applicable during night hours from 19:00 till 7:00.
WODAYP	Waiting on Dayshift in Port	Vessel is waiting in port for the dayshift of a production platform.
WOHO	Waiting on Handling Offshore	Vessel is waiting at a platform and not allowed to enter the 500 mtr. zone.

The full list of activities is completed within the span of one year and for each year, 20 - 30 different vessels were used to fulfill all activities. In 2019, 22 vessels were required to fulfill all activities, whereas 2021, 2022 and 2023 required a total of 29, 30, and 24 vessels, respectively. Figure 6.1 shows that the ratio of offshore activities compared to the other activities is approximately 54-59% for each year. It can be concisely stated that just the same percentages of the vessels are sufficient for offshore operations, resulting in the number presented in Table 6.1 for each year.

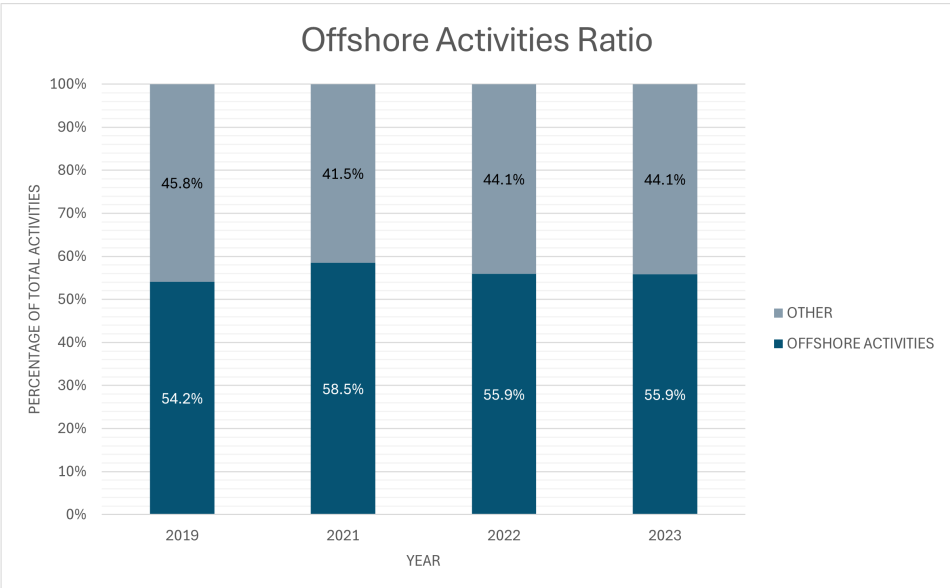

Figure 6.1: Offshore activities as a Percentage of Total Activities

Table 6.1: Vessels in Relation to the Ratio of Offshore Activities on a Yearly Basis

	Number of Offshore Activities	Number of OTHER Activities	% Off-shore Activities	Vessels All Activities	% Vessels Offshore Activities
2019	14.745	27.224	54,16%	22	12
2021	12.604	21.529	58,54%	29	17
2022	13.911	24.869	55,94%	30	17
2023	8.663	15.509	55,86%	24	14

The data presented in Table 6.2 reflects the number of vessels deployed on a monthly basis, which consistently hovers around 12 vessels per month, ranging between a minimum of 8 and a maximum of 16 vessels. By comparing these figures with the percentages provided in Table 6.1, it is possible to estimate the number of vessels required for offshore maintenance activities on a monthly scale. These percentages serve as a useful guideline for understanding the proportion of offshore activities conducted throughout the year. When combining these percentages with the vessel numbers in Table 6.2, a reasonable estimate can be made that approximately 4 to 10 vessels, with an average of seven, per month are utilized for offshore operations in the North Sea region. A more detailed overview of the monthly numbers is given in Table D.2 in Appendix D.

Table 6.2: Distinct Number of Vessels used on a Monthly Basis

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2019	11	10	10	11	12	12	11	13	13	12	12	11
2021	9	10	10	8	8	8	10	13	11	16	16	12
2022	11	12	12	13	14	16	12	12	11	10	12	11
2023	12	12	11	13	14	13	13	12	9	-	-	-

Aside from the number of vessels assigned to offshore activities, as presented in Table 6.1, it is also interesting to examine their allocation across the different bases. Figure 6.2 illustrates the distinct count of vessels fulfilling activities from each of the four bases: Aberdeen, Den Helder, Great Yarmouth, and IJmuiden. It is important to note that, while the figure shows the number of distinct vessels per base, a single vessel may operate from multiple bases. Consequently, the sum of vessels per year in Figure 6.2 does not equate to the total number of vessels used annually, as the values shown in Table 6.1. Nonetheless, these figures offer a useful benchmark for understanding the typical distribution of vessels assigned to offshore activities at each base. By applying the offshore activity percentages from Table 6.1, the estimated number of vessels assigned to offshore tasks per base is derived and displayed in Figure 6.3.

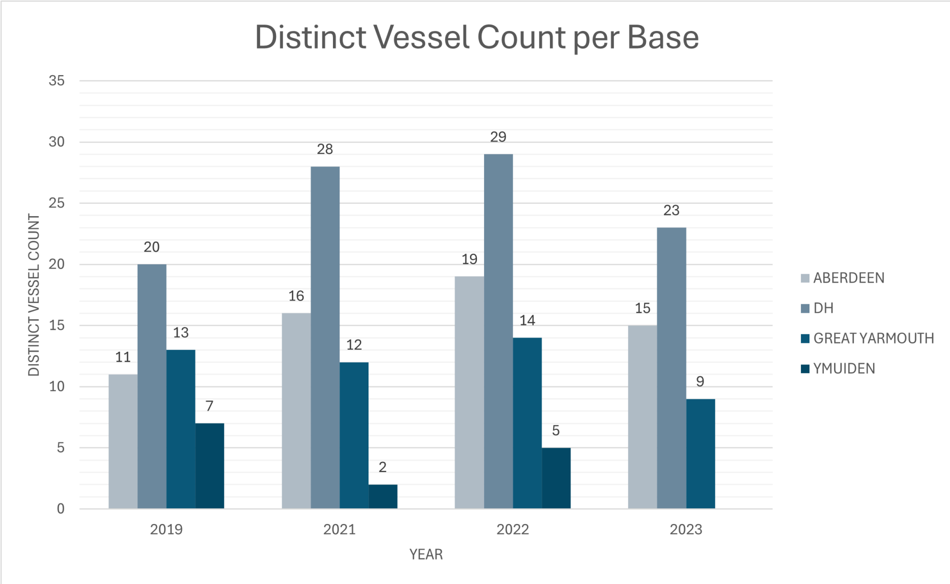

Figure 6.2: Vessel Allocation per Base

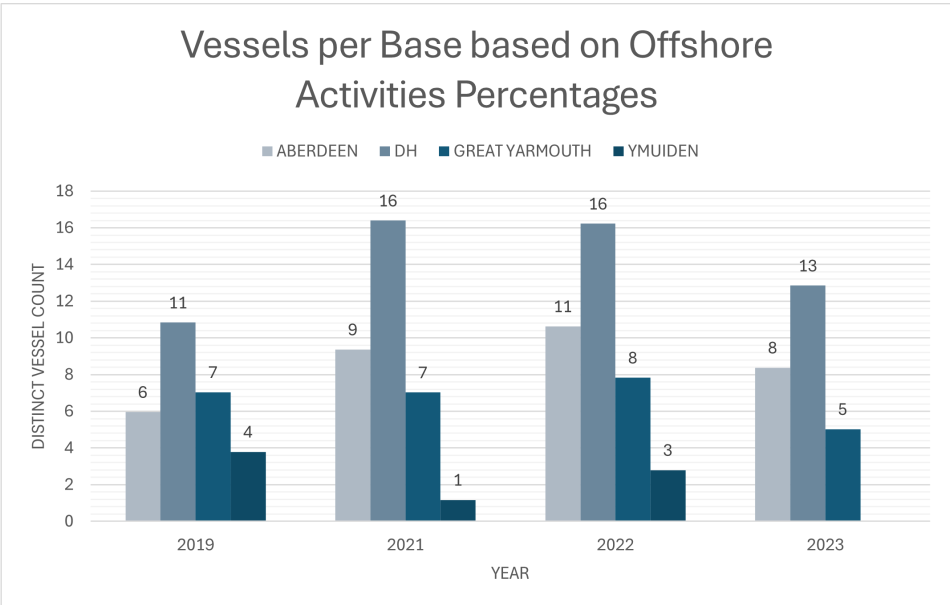

Figure 6.3: Vessel Allocation per Base, based on Percentages of Offshore Activities

This data on vessel usage, distribution, and allocation pertains specifically to Service Vessels and does not include any information about the CTVs involved in North Sea activities. CTVs are chartered by offshore logistics operators and are provided to clients upon request, which is generally submitted one to two weeks in advance. These vessels primarily facilitate the maintenance of offshore wind farms (OWFs) by transporting technicians between turbines to carry out designated tasks. Due to the sensitivity of CTVs to seasonal changes and weather conditions, the transfer schedules are usually established at the start of each day, assigning specific maintenance activities to designated technician teams.

6.2. Model Validation

The results of the model in Section 5.2 are compared to the outcomes of the base case presented in Section 6.1 to evaluate the model's reliability and validity. While the activities in the two cases are not directly comparable due to their different natures regarding their facility demands, the number of vessels can still be assessed across both cases. Validating the model against the current base serves as an essential benchmark to assess the model's reliability and operational soundness. Comparing the model results with this base case enables a consistency check, ensuring that the model does not produce outcomes that deviate drastically from realistic operations; if significant discrepancies arise due to differences in activities, it may indicate that the future scenario requires adjustments, such as an increased or decreased number of vessels, to adequately meet its operational demands.

While the model considers the three vessel types CTV, SOV, and HLV, the validation of the model is conducted using only SOV data due to limited data availability. Even though the outcomes can not be validated for all three vessel types, validating the results for only the SOVs can provide valuable insights into the model's core functions. The shared operational constraints and principles across vessel types mean that validating one type can effectively test the model's underlying structure and its ability to generalize across different vessel demands. While an ideal validation would include all vessel types, focusing on SOVs serves as a logical starting point, as these vessels are consistently deployed across all offshore facilities, both in the base case and in the future scenario.

The base scenario for SOVs shows that the offshore facilities that are currently active in the North Sea Region require approximately four to ten vessels with an average of seven per month and around 10 to 15 vessels a year to fulfill their offshore activities, assuming that vessels are used multiple times a year and can be chartered from multiple bases. Comparing the numbers from the base case to the computational results in Section 5.2, it becomes evident that the computational outcomes yield vessel requirements is almost double the average number of seven vessels in the base case. This discrepancy can be attributed to the fact that all activities originally planned for completion once per year - or even once every few years - are now scheduled to be fulfilled (once) within a single month. Other plausible explanations could be that the vessels can be allocated to multiple bases in the base case, whereas the model considers a scenario where the vessels do not travel from one base to another, or the number of HPP platforms and its high demand.

The activities related to the hydrogen platform as presented in Table 2.3 in Section 2.4, show that SOVs are used only for the daily maintenance activities of the HPP. This is again reflected in Table 5.3 in Section 5.1, showing that the hydrogen platform in node 12 requires a much higher visiting frequency compared to the other activities done at OWFs and CCS facilities. However, due to the shorter duration of activities at the hydrogen platform, multiple activities can be completed within a single route. In contrast, activities at the CCS platforms require more time, allowing only one activity per route for some of the activities. Consequently, the number of routes, and therefore the number of vessels needed, is comparable for both the CCS and hydrogen platforms. The results in Tables 5.8 to 5.10 show that most of the activities are performed from the IJmuiden and the Island base - resulting in the most vessels required at these bases. The full results for SOVs in Appendix E Tables E.4 to E.6 verify that a large portion of the routes is travelled to visit the hydrogen platforms and that the routes allocated to the IJmuiden and the Island bases are used to perform activities at the CCS platforms and the hydrogen plant. In short, the discrepancies in the number of vessels in the base case compared to the results of the model can be associated with the activities related to CCS platforms and the hydrogen plant.

Though the outcomes are not necessarily comparable, they may suggest important differences in activity demands rather than a direct one-to-one confirmation. Since the future scenario encompasses expanded activities related to the larger OWFs and other offshore facilities such as the hydrogen plant and CCS platforms, the increase in projected requirements can reasonably be expected due to the greater complexity, frequency, or duration of operations needed in the future. This does not necessarily indicate an issue with model accuracy but rather reflects the operational intensity anticipated in the future case relative to the current baseline. Therefore, even if model results exceed current figures, the discrepancy can be justified as a logical extension of the more extensive future demands. There remains considerable research to be conducted regarding hydrogen platforms, particularly in determining the feasible capacity of such plants. The current assumptions, including the daily maintenance activities — where a vessel is sent to each platform every day throughout the year — are still subject to further evaluation and debate.

6.3. Sensitivity Analysis

A sensitivity analysis is conducted to assess how variations in input parameters affect the model's results, with the goal of understanding the robustness of the solution and identifying the most influential parameters. By systematically adjusting key variables, the stability of the model's outcomes can be evaluated and its behaviour under different conditions can be explored. Additionally, scenario and uncertainty analyses are used to investigate how the model responds to various operational situations or the impact of external factors, respectively. The scenarios included in the sensitivity analysis are (1) the MDU of SOVs and HLVs, (2) two different scenarios for both the Hydrogen Power Plant and (3) the IJmuiden Ver Offshore Wind Farm, respectively.

One of the key parameters for the vessels includes their Maximum Duration of Use (MDU) and specific activity durations. For instance, the charter period of an SOV or an HLV can be extended from one week to two weeks, affecting multiple elements of the model described in Section 4.2. A higher MDU not only allows more activities to be completed within a single route but also reduces the number of routes that can be assigned to a vessel within a given month. For instance, with a one-week MDU, a vessel could complete up to four routes per month, while a two-week MDU reduces this quantity to only two routes per month. Additionally, extending the MDU impacts the scheduling of longer activities, such as the painting of CCS, which requires at least eight weeks, or the replacement of HPP cells, which takes two weeks. These activities, previously divided into shorter tasks to align with the MDU, can now be split into fewer, but longer, tasks as the MDU increases. Consequently, this reduces the total number of routes, further affecting vessel assignments. Note that this scenario can only be applied to SOVs and HLVs, as the MDU for CTVs is only one working day and can not be extended to last longer.

Table 6.3: Sensitivity Analysis - SOV Maximum Duration of Use

Objective	No. of Activities		No. of Routes		No. of Vessels		Total Distance	
	BASE	MDU	BASE	MDU	BASE	MDU	BASE	MDU
Min. Routes	365	-2.7%	54	-46.3%	14	+7.1%	1619.9	-46.1%
Min. Dist	365	-2.7%	55	-45.5%	15	+6.7%	1619.9	-46.1%
Min. Ves	365	-2.7%	54	-46.3%	14	+7.1%	3192	-40.6%

Table 6.4: Sensitivity Analysis - HLV Maximum Duration of Use

Objective	No. of Activities		No. of Routes		No. of Vessels		Total Distance	
	BASE	MDU	BASE	MDU	BASE	MDU	BASE	MDU
Min. Routes	114	-36.8%	99	-45.5%	26	+7.1%	1619.9	-38.1%
Min. Dist	114	-36.8%	99	-45.5%	26	+6.7%	1619.9	-38.1%
Min. Ves	114	-36.8%	99	-45.5%	25	+7.1%	3192	-67.0%

Tables 6.3 and 6.4 show the effects of an extended Maximum Duration of Use for both SOVs and HLVs, respectively. Across all three objective functions, a reduction can be observed in the number of activities. This can be attributed to the fact that activities with a duration longer than the MDU are now being divided into fewer segments to comply with the extended MDU. For instance, the yearly maintenance of CCS platforms that originally lasted three weeks can now be divided into two smaller tasks, rather than three, leading to a decrease in the overall number of activities. Consequently, the number of required routes also decreases. The considerable difference between the reduction in the number of activities and the reduction in the number of routes can be explained by the fact that fewer activities are divided solely due to longer tasks being split into fewer portions, whereas the significant decrease in routes is a result of the extended MDU allowing more activities to be accommodated within a single route, given that each route can now fulfill a greater number of tasks.

Although the total number of routes decreases when the MDU is extended, the number of required vessels increases. The full results in Appendix F reveal that the number of routes per base is reduced by half, except for those assigned to the IJmuiden Base. Under the original MDU of one week, a single vessel could be allocated to four routes per month. With the extension of the MDU to two weeks, however, each vessel can now only be assigned to two routes per month. As a result, even though the number of routes is halved, the same number of vessels is still required on a monthly basis for most bases for all other bases except the IJmuiden Base, as fewer routes are being serviced by the same number of vessels. The number of routes assigned to IJmuiden, however, remains unchanged despite the reduction in routes, leading to a doubling of vessels required to service the same number of routes. This explains the overall increase in vessel demand following the extension of the MDU. A detailed analysis of the results reveals that the routes departing from IJmuiden exclusively serve wind farms, which are unaffected by the extended MDU, as they must be visited once per month regardless of the maximum duration of use limit. Overall, despite the increase in the number of vessels, the reduction in the number of activities and the number of vessels also leads to a reduction in the total distance travelled.

Another key factor in the model involves the activities, their durations, and their respective quantities. Ongoing research is still exploring the full potentials and capacities of both Offshore Wind Farms (OWFs) and Hydrogen Power Plants (HPPs). This study includes wind farms that are planned but not yet operational, such as Hollandse Kust West (expected by 2025) and IJmuiden Ver (expected by 2027). Current wind farms in the North Sea Region generally consist of turbines with capacities ranging from 11 to 14 MW (*Windenergie op zee - Noordzeeloket* n.d.). While the capacities for Hollandse Kust West have been established for their implementation in 2025, the capacities for IJmuiden Ver remain undetermined. Given the uncertainty surrounding the size of the IJmuiden Ver wind farm, multiple scenarios are explored in this analysis. Here, two scenarios are considered to address this uncertainty.

The size of the IJmuiden Ver (IJMV) wind farm was initially estimated based on the size and capacities of Hollandse Kust West (HKW), with a corresponding ratio suggesting that IJMV would require approximately 286 turbines to reach its projected capacity with a 14 MW capacity per turbine. However, given recent innovations in wind turbine technology, with turbines now reaching capacities of up to 26 MW in Fujian Province, China (Adnan Memija, 2024), several scenarios are considered based on varying turbine capacities. The larger capacities considered for the turbines are 16 and 18 MW, resulting in a wind farm size of 250 and 223 turbines, respectively, to meet the desired capacity of 4000 MW total. These modifications will influence only the operational outcomes for SOVs and HLVs, as CTVs are not involved in servicing these wind farms.

Table 6.5: Sensitivity Analysis - SOV IJmuiden Ver 223 Windturbines

Objective	No. of Activities		No. of Routes		No. of Vessels		Total Distance	
	BASE	223 WTB	BASE	223 WTB	BASE	223 WTB	BASE	223 WTB
Min. Routes	365	-2.2%	54	-1.9%	14	0.0%	1619.9	-6.2%
Min. Dist	365	-2.2%	55	-3.6%	15	-6.7%	1619.9	-6.2%
Min. Ves	365	-2.2%	54	-1.9%	14	0.0%	3192	-4.3%

Table 6.6: Sensitivity Analysis - HLV IJmuiden Ver 223 Windturbines

Objective	No. of Activities		No. of Routes		No. of Vessels		Total Distance	
	BASE	223 WTB	BASE	223 WTB	BASE	223 WTB	BASE	223 WTB
Min. Routes	114	0.0%	99	0.0%	26	0.0%	1619.9	0.0%
Min. Dist	114	0.0%	99	0.0%	26	0.0%	1619.9	0.0%
Min. Ves	114	0.0%	99	0.0%	25	0.0%	3192	0.0%

Table 6.7: Sensitivity Analysis - SOV IJmuiden Ver 250 Windturbines

Objective	No. of Activities		No. of Routes		No. of Vessels		Total Distance	
	BASE	250 WTB	BASE	250 WTB	BASE	250 WTB	BASE	250 WTB
Min. Routes	365	-1.1%	54	0.0%	14	0.0%	1619.9	0.0%
Min. Dist	365	-1.1%	55	0.0%	15	0.0%	1619.9	0.0%
Min. Ves	365	-1.1%	54	0.0%	14	0.0%	3192	+15.2%

Table 6.8: Sensitivity Analysis - HLV IJmuiden Ver 250 Windturbines

Objective	No. of Activities		No. of Routes		No. of Vessels		Total Distance	
	BASE	250 WTB	BASE	250 WTB	BASE	250 WTB	BASE	250 WTB
Min. Routes	114	0.0%	99	0.0%	26	0.0%	1619.9	0.0%
Min. Dist	114	0.0%	99	0.0%	26	0.0%	1619.9	0.0%
Min. Ves	114	0.0%	99	0.0%	25	0.0%	3192	0.0%

Tables 6.5 and 6.6 represent the changes in results when the IJmuiden Ver wind farm has 223 wind turbines instead of 286 as presented in the base scenario. At first glance, the smaller scale of the

IJmuiden Ver wind farm appears to reduce the number of activities, routes, and vessels by less than 5%, and decreases the total distance travelled by less than 10% in the across all three objectives for the SOV-related results in Table 6.5. This reduction is primarily due to the activities at IJmuiden Ver being fully supported by SOVs, making the wind farm's size a key factor in the sensitivity analysis of SOV usage. For other wind farms, the low frequency of major repairs per turbine, as shown in Table 2.2, ensures that the monthly visitation schedule remains relatively unaffected. The reduction to 250 turbines represents a roughly 12.5% decrease in wind farm size, while a reduction to 223 turbines marks a decrease of about 20%. The latter introduces a more significant impact, as it results in fewer visits to IJmuiden Ver. These changes in wind farm size do not produce a linear effect on the number of activities, routes, vessels, or total distance travelled.

The results for the sensitivity analysis of Heavy Lift Vessels in Tables 6.6 and 6.8 show a 0% difference in the different sizes for the IJmuiden Ver windfarm. The activities in Table 2.2 in Section 2.4 show that an HLV is used on offshore windfarms with an occurrence rate of 0.29 times a year, meaning that its required frequency for wind farms is even lower on a monthly basis. As a result, reducing the number of turbines in a wind farm has little impact on the outcomes across the various objective functions.

In addition to the uncertainty surrounding the total capacity of IJmuiden Ver, there is also a lack of consensus among stakeholders regarding the total capacity of the offshore hydrogen plant. Various stakeholders are evaluating hydrogen capacities ranging from 4 to 8 GW, with some, like Gasunie, considering even higher capacities. If the capacity of individual electrolysis cells increases by the time of implementation, fewer platforms and cells would be required to achieve the same overall capacity, which would consequently impact the associated maintenance activities. Conversely, if the total plant capacity increases without a corresponding change in the number of cells or platforms, the maintenance requirements are anticipated to remain consistent. The data input used for the initial calculations assumes a total capacity of 8 GW, comprised of 8 platforms, each equipped with 200 electrolysis cells. Given the uncertainties around this due to ongoing research and pilot programmes, this analysis will incorporate a range of potential capacities, with scenarios considering total capacities of 4 GW and 12 GW. These variations directly affect the demand for preventive maintenance, as an increase in the capacity of Hydrogen Power Plant (HPP) facilities would lead to a larger number of platforms, ultimately resulting in a higher demand for daily maintenance at HPP platforms. This analysis will assess how such uncertainties could influence the operational needs and strategic planning for future offshore maintenance activities regarding the requirements for SOVs and HLVs, as CTVs are not involved in the O&M activities of the offshore hydrogen plant.

Table 6.9: Sensitivity Analysis - SOV HPP Capacity of 4 GW

Objective	No. of Activities		No. of Routes		No. of Vessels		Total Distance	
	BASE	4 GW	BASE	4 GW	BASE	4 GW	BASE	4 GW
Min. Routes	365	-33.4%	54	-16.7%	14	-14.3%	1619.9	-0.0%
Min. Dist	365	-33.4%	55	-16.4%	15	-13.3%	1619.9	-0.0%
Min. Ves	365	-33.4%	54	-16.7%	14	-14.3%	3192	-0.0%

Table 6.10: Sensitivity Analysis - HLV HPP Capacity of 4 GW

Objective	No. of Activities		No. of Routes		No. of Vessels		Total Distance	
	BASE	4 GW	BASE	4 GW	BASE	4 GW	BASE	4 GW
Min. Routes	114	-21.1%	99	-17.2%	26	-19.2%	1619.9	0.0%
Min. Dist	114	-21.1%	99	-17.2%	26	-19.2%	1619.9	0.0%
Min. Ves	114	-21.1%	99	-17.2%	25	-16.0%	3192	-57.6%

Table 6.11: Sensitivity Analysis - SOV HPP Capacity of 12 GW

Objective	No. of Activities		No. of Routes		No. of Vessels		Total Distance	
	BASE	12 GW	BASE	12 GW	BASE	12 GW	BASE	12 GW
Min. Routes	365	+33.2%	54	+16.7%	14	+14.3%	1619.9	-0.0%
Min. Dist	365	+33.2%	55	+16.4%	15	+13.3%	1619.9	-0.0%
Min. Ves	365	+33.2%	54	+16.7%	14	+14.3%	3192	-0.0%

Table 6.12: Sensitivity Analysis - HLV HPP Capacity of 12 GW

Objective	**No. of Activities**		**No. of Routes**		**No. of Vessels**		**Total Distance**	
	BASE	12 GW	BASE	12 GW	BASE	12 GW	BASE	12 GW
Min. Routes	114	+21.1%	99	+17.2%	26	+15.4%	1619.9	0.0%
Min. Dist	114	+21.1%	99	+17.2%	26	+15.4%	1619.9	0.0%
Min. Ves	114	+21.1%	99	+17.2%	25	+16.0%	3192	+29.2%

The scenarios addressing uncertainties in HPP capacity reveal fewer activities, routes, and vessels for a lower capacity of 4 GW compared to the base value of 8 GW, while a larger capacity results in higher values relative to the base scenario as depicted in Tables 6.9 and 6.10. Since SOVs are utilized exclusively for the daily maintenance of HPPs, and this maintenance is performed per hydrogen platform, the number of activities is directly proportional to the number of platforms when comparing Table 6.9 to Table 6.11. This linear relationship explains the mirrored values in the number of activities of a 4GW plant compared to a 12GW plant.

For the Operations & Maintenance activities of offshore hydrogen plants, HLVs are exclusively used for cell replacement. Each platform contains 200 cells, meaning that changes in plant capacity directly and linearly affect the number of activities requiring HLVs. This linear relationship is evident in the corresponding columns for 4GW and 12 GW capacities in Tables 6.10 and 6.12, where the percentage values for a 4 GW and 12 GW plant mirror each other in terms of the number of activities and routes. Although the percentage change in the number of vessels does not follow the same mirrored pattern across the different objective functions, the results remain consistent and logical when aligned with other values. The results for the 4 GW capacity are almost equal in magnitude but opposite in sign to the values for the 12GW capacity for both vessel types, except when the distance is minimized - specifically in the total distance travelled of HLVs. Although the actual values for both 4GW and 12GW are linearly related, this discrepancy in percentage differences stem from the reallocation of routes to the bases when minimizing the number of vessels. This reallocation leads to a total distance travelled that deviates from the base value.

6.4. Model Verification

The scenarios included in the sensitivity analysis are (1) the MDU of SOVs and HLVs, (2) two different scenarios for both the Hydrogen Power Plant and (3) the IJmuiden Ver Offshore Wind Farm, respectively. The full results of the sensitivity analyses can be found in Appendices F to G. Tables 6.3 to 6.12 show a general overview of the scenario results compared to the base results. The values in the grey-coloured base columns here yield the total values of the results as given in Section 5.2. The other columns indicate the variations from the base values for the scenarios mentioned. The "MDU" column represents the difference from the base values if the maximum duration of use of an SOV and HLV is extended from one week to two weeks, the columns "4 GW" and "12 GW" reflect the potential impacts of varying capacities of offshore hydrogen plants on the operational activities of SOVs and HLVs. Finally, "223 WTB" and "250 WTB" denote the respective sizes of the IJmuiden Ver wind farms, indicating either 223 or 250 wind turbines.

The sensitivity analyses primarily focus on SOVs and HLVs, as none of the scenarios impact activities related to CTVs. This approach adequately tests the model's sensitivity, as analyzing these vessel types captures the effects that different scenarios have on the overall results. By concentrating on SOVs and HLVs, the model remains robust and responsive to potential operational changes across scenarios.

The sensitivity analysis reveals that the model is particularly sensitive to changes in the Maximum Duration of Use (MDU) for vessels and the size of the hydrogen power plant. Although the total number of vessels appears to increase when the MDU is extended, the general concept for the extension of the MDU actually shows that the number of vessels remains equal for routes with activities that had to be divided into multiple segments based on the MDU limits. However, when activity durations are not limited by the MDU, the vessel requirement rises due to the constant number of activities and routes. In these cases, fewer routes can be assigned to each vessel with an extended MDU, necessitating more vessels to cover the same workload. In conclusion, the MDU appears to be a critical parameter for routes with activities independent from the MDU but does not have a significant influence on the number of vessels used for activity segments divided according to the MDU limits.

The activities associated with the Hydrogen Power Plants are directly proportional to the capacity of the HPP. This capacity is assumed to depend entirely on the number of platforms and, consequently, the number of cells within the entire plant. As a result, the outcomes are expected to vary linearly with the size of the hydrogen plant, which is consistent with the results presented in Tables 6.9 to 6.12. As anticipated, the number of activities, routes, and vessels decreases with a reduction in the HPP size and increases with a larger capacity of the HPP. In the minimization of routes and distance, the results for the different HPP size scenarios remain consistent with the base values. Since the allocation of activities to the bases mirrors that of the base scenario, the distances do not vary. This is because the distance from the HPP to the island base is zero, and all HPP activities are allocated to the island base. However, when minimizing the number of HLV vessels, the results differ from the base scenario due to a reallocation of activities across the bases.

Regarding the effect of varying sizes of the IJmuiden Ver wind farm, the differences in wind turbine capacities - and consequently the overall size of the wind farm — do not appear to significantly impact the results compared to other scenarios. This outcome can be attributed to the low annual frequency of activities required per wind turbine for both SOVs and HLVs, resulting in an even lower monthly frequency. Consequently, variations in the wind farm's size have a negligible effect on the overall results for SOVs and HLVs.

Overall, the sensitivity analysis highlights that the model is particularly sensitive to changes in the Maximum Duration of Use (MDU) for vessels and the size of the hydrogen power plant (HPP). Extending the MDU increases the vessel requirement for activities independent of MDU limits, as fewer routes can be assigned per vessel, but does not affect vessels used for segmented activities. The HPP size directly impacts activities, routes, and vessels, varying linearly with capacity due to proportional relationships with the number of platforms. While HPP size influences vessel allocation in the minimization of vessels, scenarios minimizing routes and distances remain unchanged as activities are allocated entirely to the island base. In contrast, changes in the size of the IJmuiden Ver wind farm have minimal impact on results due to the low frequency of activities related to the turbines, resulting in negligible effects compared to other scenarios.

7 Discussion & Conclusions

This chapter provides a comprehensive discussion of the methodologies, results, analyses, and key findings presented in previous chapters, with an emphasis on the most significant outcomes. These findings are further interpreted in the context of the research questions, with an examination of their implications. Additionally, the goal of this research is evaluated according to the model, its results and its limitations. Finally, some final conclusions and further research recommendations are provided.

7.1. Comparison to Existing Literature

The findings of this study offer preliminary insights regarding vessel fleet requirements for the anticipated demands of offshore energy hubs and their corresponding facilities. Existing literature on vessel fleet size and mix spans various industries, including aviation and shipping, typically focusing on demand or the impact of different policies. Notable studies, such as those by Tusar and Sarker (2023), Stålhane et al. (2019), and Gundegjerde et al. (2015), examine the vessel fleet problem specifically within the context of Offshore Wind Farm (OWF) maintenance activities. These studies employ in-depth stochastic analyses of necessary activities before developing models to determine optimal fleet sizes. In contrast to most models in the literature, which often focus on the maintenance of a single facility, this research uniquely addresses the logistics of multi-platform demand. It thus adds to the literature in the following ways:

- This research integrates the operational and maintenance needs of various facilities that have not been implemented yet, each with distinct requirements, thereby providing a foundational basis that may incentivize operators to consider more integrated policies for vessel fleet management in offshore environments.
- Previous research has been done on offshore hydrogen. However, the literature lacks studies focusing on the potential maintenance activities that need to be performed once the offshore hydrogen platforms are implemented. This study fills that gap by providing a general overview of anticipated maintenance activities based on expert interviews, then building a model to address these activities. The model's sensitivity to changes in input parameters was also tested, confirming that its behaviour aligns well with expected operational demands. This flexibility in the model ensures it can be readily adjusted to accommodate any potential changes in activity types or frequencies, offering a robust tool for planning and adaptation as the developments of offshore hydrogen evolve.
- The findings of this study indicate that the operational phase of HPPs will likely require more intensive maintenance activities, especially regarding daily maintenance within the first few operational years. The activities corresponding to the maintenance of HPP may alter standard vessel allocation strategies compared to the current operations where SOVs are primarily used for offshore wind farms and oil and gas platforms.

7.2. Results, Validation and Verification

The computational results in Section 5.2 indicate a vessel fleet comprising up to 27 CTVs, 14 SOVs, and 26 HLVs. Compared to the numbers of the base scenario, these results are notably higher, primarily due to the model's assumptions regarding technician scheduling and vessel utilization. In practice, CTVs operate on a drop-off and pick-up system, enabling technicians to conduct activities across multiple turbines simultaneously within a single route. However, in this model, activities are scheduled sequentially, assuming a set list of tasks that must be completed in order during each route. This simplification overlooks the potential for simultaneous task completion, a capability that significantly increases operational efficiency. The detailed results for CTVs in Appendix E illustrate that some activities, such as manual resets for OWFs, are performed multiple times within a single route, typically up to three times. While the model assumes only two technicians are required per route to achieve this, a fully loaded CTV could, in reality, carry up to 12 technicians, theoretically allowing for at least six manual resets per route to be completed simultaneously. This capacity increase implies a potential threefold reduction in the number of routes needed to complete the same tasks, underscoring the efficiency gains achievable by optimizing technician allocation. Accounting for an MDU of 12 hours and disregarding travel time, this could even be increased to 24 manual resets per route.

For the Service Operation Vessels (SOVs), the model estimates a fleet of 15 - 16 vessels, substantially higher than the base scenario of an average of seven vessels per month. This discrepancy may be explained by the model's approach of scheduling all maintenance activities within a single month, including those typically planned for once a year or even less frequently. Additional contributing factors include the size of the hydrogen power plant (HPP) platforms and its high operational demands, which require more SOVs, as well as the model's restriction of vessels to single bases rather than allowing inter-base allocation, as does occur in the base case. Additionally, some activities at IJmuiden Ver technically require only a CTV. However, due to the considerable distance from any of the bases considered, an SOV is assigned to this location instead. The results indicate that three SOVs are necessary to cover the activities at the IJmuiden Ver wind farm. Nevertheless, assigning a single SOV with daughter vessels to support these tasks could also suffice, as the presence of the SOV itself is not strictly required for all activities.

The model's behaviour as analyzed in the sensitivity analysis in Section 6.3, shows the differences when extending the MDU or adjusting the wind turbine and HPP capacities. The key findings in this sensitivity analysis indicate an increase in the required number of vessels when extending the MDU of an SOV from one week to two weeks. Additionally, when evaluating different capacities for wind turbines at the IJmuiden Ver wind farm, the analysis reveals a reduction in the number of activities, routes, vessels, and distance as fewer visits are required on a smaller wind farm. Even though all activities of IJmuiden Ver are supported by SOVs, the size of this wind farm does not significantly affect the monthly vessel requirement. The model's behaviour thus only shows clear sensitivity to the scenarios regarding the extension of the MDU and the HPP capacities.

The model results indicate a need for 25 to 26 HLVs to complete all activities listed in Table 5.3 within a one-month timeframe. This high estimate may appear excessive, particularly given the high chartering costs associated with these vessels. This requirement likely stems from the model's deterministic scheduling, which seeks to ensure all major activities are fulfilled within a single month. CCS and HPP facilities, in particular, have notably high visitation frequencies within this period, thereby increasing the demand for HLVs. However, in practical operations, it is unlikely that all scheduled tasks would be condensed into such a short timeframe, especially for long-duration tasks. The model assumes that tasks like CCS painting, which generally require an HLV and take approximately 10 weeks to complete, would be carried out within a month. Because the model's Maximum Duration of Use (MDU) for HLVs is capped at one week, it splits this extended task among multiple vessels to ensure completion within the given month. In practice, however, chartering multiple HLVs to complete a 10-week activity within one month would be impractical and cost-prohibitive. A more realistic scheduling approach would distribute these tasks across an extended timeframe, better aligning with resource availability and cost constraints, suggesting the model's outputs reflect a highly conservative scenario that could be adjusted for operational feasibility.

In a scenario where CCS platforms are painted over a six-year cycle—meaning only one platform is painted each year—the required number of HLVs would be substantially reduced. Appendix E shows that nearly half of all routes are allocated to CCS facilities, which strongly impacts the total vessel count. Limiting operations to just one CCS painting job in a given month, with a cap of four routes to complete the task, would reduce the total routes by approximately 45%. Consequently, a reasonable estimate would be to decrease the required vessel fleet by 45%, lowering the monthly requirement from 26 vessels to around 13. For the remaining routes, over 60% are designated for hydrogen power plants (HPPs), which still require a relatively high vessel count due to their ongoing maintenance needs. This distribution indicates that even with a reduction in CCS-related demand, the substantial maintenance activities required at HPPs continue to necessitate a significant HLV fleet.

7.3. Project Goal Reflection

Based on the results, validation, and verification of the model, one can conclude that this model provides preliminary insights for decision-makers in offshore logistics to optimize their vessel fleet strategies effectively. The model's insights reveal key dynamics in fleet composition, fleet size, and allocation, offering a flexible approach that can adapt as offshore energy hubs expand and demands evolve. By examining critical factors such as maintenance schedules and fleet composition, logistics operators can use this model to make informed decisions on optimal vessel numbers, routes, and maintenance strategies. As real-time data becomes available from emerging offshore activities, decision-makers can refine the model's inputs to align fleet allocation closely with actual demand, ensuring that vessel resources are available as needed. With this, the main goal of this research can be addressed:

The goal of this research is to identify an optimal vessel fleet strategy for offshore activities in a future scenario with energy hubs and their corresponding facilities

To determine an optimal vessel fleet mix, it is essential that logistics service providers stay well-informed about the decisions and developments made by other stakeholders involved in the maintenance activities of offshore facilities. These stakeholders play a critical role in defining facility capacities and operational needs, which directly impact vessel requirements. In an assumed scenario where offshore wind farms will have a maximum turbine capacity of 14 MW each and the hydrogen plant will operate with eight platforms of 1 GW each, logistics service providers can consider an initial upper bound of 27 CTVs, 14 SOVs, and 26 HLVs to meet operational demands. However, these estimates represent a conservative upper limit; the actual number of vessels required could be reduced when accounting for (1) the capacity constraints of technicians on each vessel, keeping in mind a drop-off and pick-up system and (2) the consideration of vessel overlap, where two vessel types can be used simultaneously. These elements are also discussed in Section 7.4.

7.4. Limitations and Challenges

Certain simplifications and limitations were made in the model due to practical constraints on data and computational resources, as well as inherent uncertainties in future offshore operations. For instance, the model does not account for technicians' capacity on vessels or the logistical aspects of technicians' pick-up and drop-off on CTVs, which are simplified to assume sequential completion of tasks without simultaneous operations. This simplification implies an upper bound on the vessel requirements, as in reality, simultaneous technician deployments would allow for more efficient use of each vessel, potentially enabling several activities to be completed multiple times within a single route by the same set of technicians. CTVs are often capable of transferring multiple technicians and, depending on logistical arrangements, visiting multiple locations owned by the same company in a single trip. These simultaneous multi-location visitations could theoretically increase operational efficiency but are not captured in the current model.

Furthermore, the model solely considers technician transfer times while neglecting the loading and unloading times of equipment. Including these equipment handling times would require treating them as independent activities, potentially adding time constraints (time windows) that synchronize vessel arrivals with loading or unloading requirements at each location. Such adjustments would add complexity to the model by introducing additional time-based constraints, which could impact the feasibility of certain routes within the model's framework.

A critical limitation of this study is the absence of data on the current operations of CTVs and HLVs, which precluded the validation of the model results against existing data of a base case. While the available data made the validation for SOVs possible, the nature of this data is fundamentally different from the model's input. The existing data reflects operations primarily associated with Oil & Gas platforms, whereas the model's inputs are related to assumed activities of future offshore facilities that differ substantially in both structure and activity requirements, and which are yet to be implemented. Although an alternative approach could involve running the collected data through the model to assess for convergence with empirical results, the lack of detail in the dataset prevented such comparative validation.

7.5. Theoretical and Practical Implementations

The main focus of this computational study is to identify an optimal vessel fleet strategy for offshore activities in a future scenario with energy hubs and their corresponding facilities. In order to find this optimal vessel fleet strategy, a more detailed analysis was done of the future implementation of CCS and HPP facilities, as well as the activities linked to these facilities. The model developed in this research uses a deterministic approach and solves for a given input of an initial set of maintenance activities across multiple facility types. The vessel scheduling outcome of this model is made possible by formulating the problem into a multi-depot vessel fleet size & mix problem, which can be used as a decision support tool not only to determine the vessel fleet size and mix but may also be used for a number of analyses in other directions, not explored in this paper.

- Examine the various scenarios and their impact on vessel fleet size and mix, especially in light of the uncertainties surrounding the capacities of future facilities. By analyzing different capacity scenarios, insights into potential cost savings for the vessel fleet can be gained, as adjustments in facility capacities directly influence the fleet composition and required resources.
- Analyze the impact of different objective functions on the model's results, considering the diverse interests of stakeholders involved in vessel chartering. Beyond the logistics provider, energy operators also play a significant role in deciding cost-saving priorities. They may choose to focus on reducing time and distance travelled to lower operational costs or prioritize minimizing the total number of vessels required, each approach reflecting a different cost-saving strategy aligned with their operational goals.
- While this model was designed specifically for offshore facilities, a vessel fleet size and mix problem has broad applications across multiple industries and types of fleets. Although the model is structured to permit only one location visit per route, modifying the constraints to allow multiple location visits within a single route opens possibilities for applying this model to other sectors. This flexibility enables adaptation to diverse logistical scenarios, enhancing its relevance and utility across various industries provided that a fixed set of activities is established beforehand.

7.6. Further Research Directions

While this research addresses the questions asked in Section 1.3, it also uncovers new opportunities and generates additional questions that may serve as valuable directions for future investigation.

- The mathematical model developed in this research could be further refined to incorporate a more realistic representation of technician and time capacities. Currently, the model primarily emphasizes the time capacity regarding the Maximum Duration of Use (MDU) for vessels, with limited consideration of technician allocation constraints. Expanding the model to account for a designated technician capacity for each vessel, alongside additional time windows for technician transfer and task completion, would allow for a more accurate and dynamic scheduling outcome. Integrating technician-specific scheduling parameters, such as skill requirements or availability could enhance the model's capability to represent real-world scenarios where technician resources are as critical as vessel availability. Moreover, this extended approach would provide a clearer understanding of the interplay between technician deployment and vessel usage, offering deeper insights into optimizing offshore logistical operations. This enhancement could prove invaluable for planning and resource allocation, particularly as future offshore facilities become increasingly complex.
- The current model relies on deterministic input data and constraints, assuming that all conditions and variables remain constant over time. However, in real-world offshore logistics, many factors

are inherently unpredictable. Introducing stochastic elements could enhance the model's robustness and make it more reflective of operational conditions. By integrating variables like weather uncertainties, variable costs, and potential delays, the model could account for the impact of these factors on vessel scheduling and resource allocation. This would allow for the exploration of risk-mitigation strategies and enable planners to anticipate and adjust for disruptions. Moreover, a stochastic approach could consider cost fluctuations, especially for ad-hoc or emergency maintenance, providing a clearer picture of budget requirements under various scenarios. Such modifications could significantly enhance the model's applicability for strategic decision-making in complex offshore operations.

- This study does not account for the potential overlap in vessel usage, though incorporating such considerations could enhance the model's practicality and efficiency. In particular, SOVs are used in the model for daily crew transport to hydrogen platforms as part of regular maintenance. However, a more cost-effective and operationally feasible setup could involve an SOV being used as a mother vessel and adding daughter vessels to the configuration, where CTVs operate as daughter vessels and are deployed for crew transport. Such an extension could reveal new insights into optimizing vessel assignments, minimizing operational expenses, and providing a more adaptable logistical framework for offshore activities. Integrating vessel overlap would also introduce an additional layer of decision-making complexity, but its potential to improve resource efficiency in offshore logistics makes it worth investigating in further studies.

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A
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B Expert Interviews

B.1. TNO - Business Director Gas Energy, Strategy Consultant, Offshore Wind Researcher [August 2023]

In interviews conducted with experts at TNO, who are also involved in the NSE5 research, insights were shared into the logistic aspects of the emerging North Sea energy hubs. The logistics focus of the NSE research is primarily managed by Peterson Energy Logistics and TNO, as they explore the best ways to service these hubs efficiently.

The concept of an energy hub on the North Sea is designed to bring multiple energy functions together in one strategic location. Hub West, for instance, will focus on energy storage, Carbon Capture & Storage, hydrogen production, and establishing infrastructural resources to Den Helder. Located near the German border, Hub East is envisioned to combine wind energy and hydrogen conversion, as well as support the electrification of gas extraction; it will also connect with German wind farms to reinforce cross-border energy cooperation. Hub North will be primarily dedicated to converting wind energy into hydrogen, with additional energy storage capabilities, possibly serving as a buffer for fluctuating energy needs. This hub may also interconnect with neighbouring countries, unlike the other two hubs.

In planning for these hubs, key logistical questions arise: Can the hubs be supported by technicians, each handling multiple functions? Could training for technicians be adapted to accommodate the unique maintenance demands of hydrogen platforms? And what specialized maintenance can be expected for these hydrogen facilities?

Pilot programs are scheduled for Hollandse Kust Noord, Zuid, and West, though the exact locations remain under consideration. It's likely, however, that a pilot will be linked to the Hollandse Kust West wind farm. Stakeholders in the North Sea hydrogen industry bring varied expectations for hydrogen capacity: TenneT anticipates a demand of 8 GW, GasUnie explores a 1:1 ratio of hydrogen to wind energy, and TNO itself projects take a range of 4–8 GW into account. To simulate logistical requirements, TNO relies on blueprints from other operators, using them to model vessel deployments and routes. Before data is incorporated into these simulations, however, it undergoes rigorous testing to ensure accuracy and reliability, drawing insights from real offshore activity patterns.

B.2. Shell - Head of Pre-Commissioning and Commissioning [September 2023]

Shell is one of the stakeholders in implementing the hydrogen platforms in the North Sea Region and takes part in the NSE5 research, mainly for their role in the implementation of CCS platforms. Aside from their focus on CCS, they are also involved with projects surrounding developments in offshore hydrogen. They are making efforts to create a model in an Excel spreadsheet to forecast and align required maintenance and operational activities for offshore hydrogen facilities. This model aims to synchronize various planned activities over a common timeline, ensuring that essential tasks happen within an optimal schedule. However, this specific information could not be shared due to the competitive nature of the industry and uncertainties surrounding offshore hydrogen production and maintenance.

One of Shell's core maintenance considerations is the electrolysis system. Every 6–10 years, offshore electrolysers will have to be replaced by either new cells or refurbished ones. Offshore, this process is more complex than onshore due to the need for specialized equipment, such as lifting cranes, and the logistical challenge of handling multiple cells. Shell faces a strategic decision on whether to carry out these replacements in batches or one at a time to optimize efficiency. They highlighted the importance of strategic planning for these "battery" changes. Depending on vendor strategy, either the stacks could be replaced simultaneously to minimize the downtime, or individual cells could be refurbished one by one. This approach would dictate the number of SOVs required and the type of towing and lifting equipment necessary to facilitate these operations.

In addition to long-term maintenance, Shell emphasizes the importance of regular preventive maintenance. Offshore hydrogen facilities will require a Service Operation Vessel (SOV) to stay on-site for a month annually, equipped with small cranes, operators, and maintenance teams to handle tasks ranging from minor checks to significant interventions. These tasks may need to be performed as often as every few weeks or months, depending on the equipment's maintenance schedule. For instance, a standalone 5 MW unit or a centralized 400 MW platform would need preventive SOV support, with monthly checks to ensure smooth operations and proactive monitoring to detect potential issues early. Shell also stresses the importance of a reliable SOV on standby for unplanned maintenance. This vessel, staffed with the necessary crew and equipped with essential tools, can return to the site as needed for unexpected repairs or adjustments. However, the frequency of these activities also depends on understanding the specific equipment in place and the level of care required.

The scale of hydrogen production offshore brings additional complexity. For example, a 1 GW hydrogen facility would be an ambitious undertaking, especially when compared to current facilities like the 0.2 GW pilot plant in the Port of Rotterdam. Offshore facilities would require hundreds of electrolyzers, each needing refurbishment every 6–10 years. Shell estimates that offshore maintenance for these units could extend to about two weeks per stack, compared to a one-week timeframe onshore, due to the need for towing and lifting equipment.

The frequency of checks varies across different systems—some checks are needed every 3–5 weeks, while others are required less frequently, every 1–2 years. As a result, Shell anticipates a constant rotation of SOVs - with daily visits per platform in the first few years of operations - and specialized technicians handling these diverse tasks, underscoring the need for a robust logistical framework.

C

Location Specifications

Table C.1: Coordinates for the Locations Surrounding Hub West

Location	Location Type	Longitude	Latitude
Den Helder	Base	53.4	4.8
IJmuiden	Base	52.459	4.594
Service Operation Vessel	Base	53.499	3.369
Island	Base	53.701	3.852
Luchterduinen	OWF	53.4	4.8
Egmond aan Zee	OWF	52.600	4.420
Prinses Amalia	OWF	52.580	4.236
Luchterduinen	OWF	52.405	4.162
Hollandse Kust West	OWF	52.680	3.804
Hollandse Kust Noord	OWF	52.617	4.200
Hollandse Kust Zuid	OWF	52.330	4.072
IJmuiden Ver	OWF	52.617	3.251
CCS 1	CCS	53.499	3.369
CCS 2	CCS	53.404	4.201
CCS 3	CCS	53.269	3.626
CCS 4	CCS	53.696	3.339
CCS 5	CCS	53.247	3.986
HPP	HPP	53.701	3.852

Table C.2: Location Distances in Nautical Miles

	Den Helder	Ijmuiden	SOV	Island	Egmond aan Zee	Prinses Amalia	Luchterduinen	HKW
Den Helder	0	57.02262	51.6609	38.44214	49.99361	53.33392	64.10621	56.3121
Ijmuiden	57.02262	0	76.64843	79.28352	10.60035	14.99674	16.18888	31.81484
SOV	51.6609	76.64843	0	21.08252	66.05533	63.50229	71.73397	51.64911
Island	38.44214	79.28352	21.08252	0	69.24009	68.74539	78.64629	61.34547
Egmond aan Zee	49.99361	10.60035	66.05533	69.24009	0	6.837575	15.05419	23.01578
Prinses Amalia	53.33392	14.99674	63.50229	68.74539	6.837575	0	10.85594	16.89261
Luchterduinen	64.10621	16.18888	71.73397	78.64629	15.05419	10.85594	0	21.08812
HKW	56.3121	31.81484	51.64911	61.34547	23.01578	16.89261	21.08812	0
HKN	51.83634	17.261	60.93726	66.32983	8.106859	2.56604	12.78993	14.95866
HKZ	69.51074	20.68695	74.71264	82.73037	20.63986	16.17714	5.589488	23.20386
IJmuiden Ver	73.23649	50.08933	53.17052	68.63945	42.75625	36.09177	35.72305	20.55665
CCS1	51.6609	76.64843	0	21.08252	66.05533	63.50229	71.73397	51.64911
CCS2	21.50758	58.53233	30.3753	21.77533	48.94511	49.51442	60.02607	45.80359
CCS3	42.94274	60.04628	16.61571	27.17216	49.44978	46.93814	55.43878	35.96342
CCS4	55.21344	87.07434	11.88268	18.27883	76.53935	74.4559	83.07146	63.29353
CCS5	30.68757	52.24328	26.84133	27.68508	41.93723	41.08149	50.98086	34.69232
HPP	38.44214	79.28352	21.08252	0	69.24009	68.74539	78.64629	61.34547

	HKN	HKZ	IJmuiden Ver	CCS 1	CCS 2	CCS 3	CCS 4	CCS 5	HPP
Den Helder	51.83634	69.51074	73.23649	51.6609	21.50758	42.94274	55.21344	30.68757	38.44214
Ijmuiden	17.261	20.68695	50.08933	76.64843	58.53233	60.04628	87.07434	52.24328	79.28352
SOV	60.93726	74.71264	53.17052	0	30.3753	16.61571	11.88268	26.84133	21.08252
Island	66.32983	82.73037	68.63945	21.08252	21.77533	27.17216	18.27883	27.68508	0
Egmond aan Zee	8.106859	20.63986	42.75625	66.05533	48.94511	49.44978	76.53935	41.93723	69.24009
Prinses Amalia	2.56604	16.17714	36.09177	63.50229	49.51442	46.93814	74.4559	41.08149	68.74539
Luchterduinen	12.78993	5.589488	35.72305	71.73397	60.02607	55.43878	83.07146	50.98086	78.64629
HKW	14.95866	23.20386	20.55665	51.64911	45.80359	35.96342	63.29353	34.69232	61.34547
HKN	0	17.84717	34.69335	60.93726	47.2956	44.37569	71.90172	38.65195	66.32983
HKZ	17.84717	0	34.68659	74.71264	64.68395	58.69247	86.24109	55.17052	82.73037
IJmuiden Ver	34.69335	34.68659	0	53.17052	58.49027	41.47813	64.91075	46.3153	68.63945
CCS1	60.93726	74.71264	53.17052	0	30.3753	16.61571	11.88268	26.84133	21.08252
CCS2	47.2956	64.68395	58.49027	30.3753	0	22.20828	35.47824	12.19616	21.77533
CCS3	44.37569	58.69247	41.47813	16.61571	22.20828	0	27.63513	13.03494	27.17216
CCS4	71.90172	86.24109	64.91075	11.88268	35.47824	27.63513	0	35.57023	18.27883
CCS5	38.65195	55.17052	46.3153	26.84133	12.19616	13.03494	35.57023	0	27.68508
HPP	66.32983	82.73037	68.63945	21.08252	21.77533	27.17216	18.27883	27.68508	0

D
Base Case

Table D.1: Base Case: Total List of Vessel Activities with Offshore Activities highlighted Green.

Abbrev.	Activity name	Explanation
BULK	Bulk Handling in Port	Vessel loading or discharging bulk in port.
CIT	Chargeable Idle Time	Vessel is waiting a second night after a two days production run. Only applicable if there is no waiting on weather registered.
CLEAN	Cleaning Bulk Tanks	Cleaning bulk tanks - costs are for last user of the tank.
DBO	Delayed By Operator	Operator is delaying the departure time after Vessel is (partly) loaded, because offshore is not ready to handle the Vessel.
DBULK	Dedicated Bulk Handling in Port	Dedicated vessel loading or discharging bulk in port.
DCLEAN	Dedicated Cleaning Bulktanks	Cleaning bulk tanks of dedicated vessel
DHIP	Dedicated Handling in Port	Load or Discharge special" cargo and/or load or discharge cargo from a dedicated Vessel.
DHO	Dedicated Handling Offshore	Dedicated vessel working a platform/rig within the 500 mtr. zone.
DIP	Discharge in Port	Discharge deck cargo (in port).
DITO	Dedicated Idle Time Offshore	Idle time offshore of a dedicated Vessel (including W.O.W.). Also used for Economic Speed Sailing (ESS) with a dedicated Vessel.
DITP	Dedicated Idle Time in Port	Idle time in port of a dedicated Vessel.
DLC	Delay Late Cargo	Time from loading planned cargo until loading additional cargo. And time after loading last lift until departure.
DPASSO	Dedicated Passage Offshore	Dedicated vessel sailing to offshore location

Continued on next page

Table D.1: Base Case: Total List of Vessel Activities with Offshore Activities highlighted Green. (Continued)

DPASSP	Dedicated Passage to Port	Dedicated vessel sailing to port
DWOWO	Dedicated Waiting on Weather Offshore	Dedicated vessel is not able to work due weather conditions (captain's decision) and is waiting for better weather offshore.
DWOWP	Dedicated Waiting on Weather in Port	Dedicated vessel is not able to work due weather conditions (captain's decision) and is waiting for better weather in port.
DWODAYO	Dedicated Waiting on Dayshift Offshore	Dedicated vessel waiting outside 500 mtr zone on dayshift of a production platform. Applicable during night hours from 19:00 till 7:00.
DWODAYP	Dedicated Waiting on Dayshift in Port	Dedicated vessel is waiting in port for the dayshift of a production platform.
ESSO	Economic Speed Sailing Offshore	When a Vessel is sailing longer than regular, the extra hours are registered as economic speed sailing. Regular sailing time is based on 10 nautical miles per hour.
ESSP	Economic Speed Sailing to Port	When a Vessel is sailing longer than regular, the extra hours are registered as economic speed sailing. Regular sailing time is based on 10 nautical miles per hour.
FLEXO	Flexible Time Offshore	Vessel consuming Flex time offshore compared to Sailing Schedule
FLEXP	Flexible Time in Port	Vessel consuming Flex time in port compared to Sailing Schedule
HO	Handling Offshore	Working a platform/rig within the 500 mtr. zone.
INTF	Interfield Passage	Sailing between several platforms of one operator in a defined cluster until arrival 500 mtr. zone.
LDS	Long Distance Sailing	Used for Cleeton/Perenco sailing.
LFP	Loading Fuel/Potwater	Loading fuel or portable water (in port).
LIP	Loading in Port	Loading deck cargo (in port).
MAINT	Maintenance	Vessel maintenance time (12 hrs per month)
NCCH	Non-Chargeable Cargo Handling	Transfer deck cargo from one Vessel to another because of bad weather, technical problems on the Vessel or in request of the Pool planning.
NH	Night Hours	Idle Time of a Vessel in port
PASS	Passage	Sailing until/from 500 mtr. zone.
PINTB	Interbase Passage	Sailing from port to port on Pool planning request.
PM	Port Management	Miscellaneous activities on Vessel in port. Mention port activity in comments (e.g. TOFS, Audits etc.)
PTC	Potwater Tank Cleaning	Cleaning potable water tanks.

Continued on next page

Table D.1: Base Case: Total List of Vessel Activities with Offshore Activities highlighted Green. (Continued)

SHIFT	Shifting in Port	Shifting between berths (in port).
WOD	Waiting on Departure	Vessel is waiting in port to sail to a drilling rig, accommodation unit or another port.
WODAYO	Waiting on Dayshift Offshore	Vessel waiting outside 500 mtr zone on dayshift of a production platform. Applicable during night hours from 19:00 till 7:00.
WODAYP	Waiting on Dayshift in Port	Vessel is waiting in port for the dayshift of a production platform.
WOHO	Waiting on Handling Offshore	Vessel is waiting at a platform and not allowed to enter the 500 mtr. zone.
WOHP	Waiting on Handling in Port	Vessel waiting for cargo or bulk handling in port during working hours (not at night) (12 hrs reason required).
WOOP	Waiting on Orders in Port	Vessel waiting for orders (plans).
WOWO	Waiting on Weather Offshore	Vessel is not able to work due weather conditions (captain's decision) and is waiting for better weather offshore.
WOWP	Waiting on Weather in Port	Vessel is not able to work due weather conditions (captain's decision) and is waiting for better weather in port.

Table D.2: Base Case: Monthly Percentages of Offshore Activities compared to the Total Number of Activities

	Jan			Feb			Mar			Apr		
	Offshore	Total	Percentage	Offshore	Total	Percentage	Offshore	Total	Percentage	Offshore	Total	Percentage
2019	1036	1901	54.50%	943	1776	53.10%	1035	1829	56.59%	1155	1955	59.08%
2021	795	1497	53.11%	819	1381	59.30%	847	1543	54.89%	953	1594	59.79%
2022	988	1802	54.83%	820	1580	51.90%	1355	2366	57.27%	1355	2341	57.88%
2023	855	1678	50.95%	979	1629	60.10%	1033	1911	54.06%	1183	1994	59.33%

	May			Jun			Jul			Aug		
	Offshore	Total	Percentage	Offshore	Total	Percentage	Offshore	Total	Percentage	Offshore	Total	Percentage
2019	1287	2294	56.10%	1336	2573	51.92%	1524	2696	56.53%	1493	2578	57.91%
2021	1046	1833	57.06%	1000	1751	57.11%	1167	1867	62.51%	1219	2051	59.43%
2022	1385	2306	60.06%	1358	2355	57.66%	1326	2306	57.50%	1168	2315	50.45%
2023	1198	2137	56.06%	1046	1972	53.04%	1092	1907	57.26%	1172	2103	55.73%

	Sep			Oct			Nov			Dec		
	Offshore	Total	Percentage	Offshore	Total	Percentage	Offshore	Total	Percentage	Offshore	Total	Percentage
2019	1399	2635	53.09%	1303	2522	51.67%	1227	2407	50.98%	1007	2058	48.93%
2021	1151	2067	55.68%	1346	2162	62.26%	1103	1836	60.08%	1158	1947	59.48%
2022	1141	2127	53.64%	1093	1991	54.90%	1030	1712	60.16%	892	1668	53.48%
2023	105	178	58.99%	-	-	-	-	-	-	-	-	-

E

Detailed Results

Table E.1: CTV Detailed Results for Minimizing of Routes

Route	Activities	Distance	Duration	Base	Node
1	1	41.37	7.04	1	5
4	1	41.37	7.04	1	5
5	2	41.37	10.04	1	5
7	1	32.38	7.00	1	2
8	1	32.38	7.00	1	2
9	1	29.99	7.70	1	1
10	2	34.52	11.07	1	4
11	1	21.20	7.31	1	0
12	2	29.99	10.70	1	1
13	1	34.52	8.07	1	4
14	1	29.99	7.70	1	1
15	2	32.38	10.00	1	2
16	1	63.63	9.64	1	3
17	1	63.63	9.64	1	3
18	1	41.37	7.04	1	5
19	3	63.63	11.55	1	3
20	1	63.63	9.64	1	3
22	1	63.63	9.64	1	3
23	1	21.20	7.31	1	0
24	2	21.20	10.31	1	0
27	2	41.37	10.04	1	5
28	2	41.37	10.04	1	5
30	1	63.63	9.64	1	3
31	1	34.52	8.07	1	4
33	1	63.63	9.64	1	3
34	2	34.52	11.07	1	4
36	2	29.99	10.70	1	1

Table E.2: CTV Detailed Results for Minimizing of Distance

Route	Activities	Distance	Duration	Base	Node
0	2	32.38	10.00	1	2
1	3	63.63	11.55	1	3
2	1	29.99	7.70	1	1
3	1	63.63	9.64	1	3
5	1	41.37	7.04	1	5
6	1	41.37	7.04	1	5
7	1	41.37	7.04	1	5
8	1	63.63	9.64	1	3
9	2	29.99	10.70	1	1
11	1	63.63	9.64	1	3
14	2	41.37	10.04	1	5
15	1	21.20	7.31	1	0
16	1	63.63	9.64	1	3
17	1	32.38	7.00	1	2
19	2	21.20	10.31	1	0
20	2	29.99	10.70	1	1
21	1	29.99	7.70	1	1
22	1	34.52	8.07	1	4
25	1	34.52	8.07	1	4
26	2	41.37	10.04	1	5
27	1	21.20	7.31	1	0
28	2	41.37	10.04	1	5
29	2	34.52	11.07	1	4
30	1	63.63	9.64	1	3
32	1	32.38	7.00	1	2
35	1	63.63	9.64	1	3
37	2	34.52	11.07	1	4

Table E.3: CTV Detailed Results for Minimizing of Vessels

Route	Activities	Distance	Duration	Base	Node	Route	Activities	Distance	Duration	Base	Node
1	1	41.37	7.04	1	5	18	1	41.37	7.04	1	5
4	1	41.37	7.04	1	5	19	3	63.63	11.55	1	3
5	2	41.37	10.04	1	5	20	1	63.63	9.64	1	3
7	1	32.38	7.00	1	2	22	1	63.63	9.64	1	3
8	1	32.38	7.00	1	2	23	1	21.20	7.31	1	0
9	1	29.99	7.70	1	1	24	2	21.20	10.31	1	0
10	2	34.52	11.07	1	4	27	2	41.37	10.04	1	5
11	1	21.20	7.31	1	0	28	2	41.37	10.04	1	5
12	2	29.99	10.70	1	1	30	1	63.63	9.64	1	3
13	1	34.52	8.07	1	4	31	1	34.52	8.07	1	4
14	1	29.99	7.70	1	1	33	1	63.63	9.64	1	3
15	2	32.38	10.00	1	2	34	2	34.52	11.07	1	4
16	1	63.63	9.64	1	3	36	2	29.99	10.70	1	1
17	1	63.63	9.64	1	3						

Table E.4: SOV Detailed Results for Minimization of Routes

Route	Activities	Distance	Duration	Base	Node	Route	Activities	Distance	Duration	Base	Node
0	14	0	168	3	12	30	1	43.02	163.00	0	8
1	14	0	168	3	12	31	1	43.02	163.00	0	8
2	14	0	168	3	12	32	1	43.02	163.00	0	8
3	14	0	168	3	12	33	3	0.00	54.86	2	7
4	14	0	168	3	12	34	1	0.00	157.71	2	7
5	14	0	168	3	12	35	1	0.00	157.71	2	7
6	14	0	168	3	12	36	1	0.00	157.71	2	7
7	14	0	168	3	12	37	9	100.18	165.68	1	6
8	14	0	168	3	12	38	12	100.18	166.68	1	6
9	14	0	168	3	12	39	6	100.18	162.68	1	6
10	14	0	168	3	12	40	6	100.18	162.68	1	6
11	14	0	168	3	12	41	6	100.18	162.68	1	6
12	14	0	168	3	12	42	6	100.18	162.68	1	6
13	14	0	168	3	12	43	6	100.18	162.68	1	6
14	14	0	168	3	12	44	6	100.18	162.68	1	6
15	14	0	168	3	12	45	6	100.18	162.68	1	6
16	6	0	72	3	12	46	6	100.18	162.68	1	6
17	3	53.68	48.68	2	11	47	3	100.18	84.68	1	6
18	1	53.68	164.55	2	11	48	6	41.37	158.76	1	5
19	1	53.68	164.55	2	11	49	6	41.37	158.76	1	5
20	1	53.68	164.55	2	11	50	2	41.37	54.76	1	5
21	3	23.77	60.61	2	10	51	6	34.52	158.30	1	4
22	1	23.77	157.91	2	10	52	1	34.52	28.30	1	4
23	1	23.77	157.91	2	10	53	6	63.63	160.24	1	3
24	1	23.77	157.91	2	10	54	5	63.63	134.24	1	3
25	3	33.23	50.43	2	9	55	5	32.38	132.16	1	2
26	1	33.23	162.14	2	9	56	6	29.99	158.00	1	1
27	1	33.23	162.14	2	9	57	4	21.20	105.41	1	0
28	1	33.23	162.14	2	9	392	14	0.00	168.00	3	12
29	3	43.02	50.48	0	8						

Table E.5: SOV Detailed Results for Minimization of Distance

Route	Activities	Distance	Duration	Base	Node	Route	Activities	Distance	Duration	Base	Node
1	2	41.37	54.76	1	5	167	14	0.00	168.00	3	12
16	6	34.52	158.30	1	4	173	14	0.00	168.00	3	12
20	1	53.68	164.55	2	11	204	14	0.00	168.00	3	12
21	3	23.77	60.61	2	10	205	14	0.00	168.00	3	12
24	1	23.77	157.91	2	10	231	1	23.77	157.91	2	10
25	3	33.23	50.43	2	9	252	6	100.18	162.68	1	6
26	1	0.00	30.86	2	7	254	1	43.02	163.00	0	8
32	6	100.18	162.68	1	6	276	14	0.00	168.00	3	12
33	1	0.00	157.71	2	7	280	14	0.00	168.00	3	12
34	2	0.00	24.00	2	7	294	14	0.00	168.00	3	12
35	1	0.00	157.71	2	7	306	8	100.18	159.18	1	6
40	6	100.18	162.68	1	6	308	1	53.68	164.55	2	11
41	8	100.18	159.18	1	6	320	1	23.77	157.91	2	10
42	6	100.18	162.68	1	6	322	3	43.02	50.48	0	8
43	8	100.18	167.68	1	6	323	5	32.38	132.16	1	2
44	7	100.18	165.68	1	6	324	14	0.00	168.00	3	12
45	7	100.18	165.68	1	6	327	14	0.00	168.00	3	12
48	6	41.37	158.76	1	5	336	14	0.00	168.00	3	12
57	4	21.20	105.41	1	0	344	14	0.00	168.00	3	12
72	6	63.63	160.24	1	3	354	14	0.00	168.00	3	12
74	1	53.68	164.55	2	11	355	14	0.00	168.00	3	12
77	1	43.02	163.00	0	8	358	1	34.52	28.30	1	4
87	1	33.23	162.14	2	9	361	3	53.68	48.68	2	11
89	1	33.23	162.14	2	9	363	14	0.00	168.00	3	12
111	14	0.00	168.00	3	12	370	5	63.63	134.24	1	3
133	7	100.18	165.68	1	6	376	14	0.00	168.00	3	12
138	3	100.18	84.68	1	6	380	14	0.00	168.00	3	12
141	1	33.23	162.14	2	9	382	6	29.99	158.00	1	1
146	6	0.00	72.00	3	12	388	6	41.37	158.76	1	5
151	1	43.02	163.00	0	8	389	1	0.00	157.71	2	7

Table E.6: SOV Detailed Results for Minimization of Vessels

Route	Activities	Distance	Duration	Base	Node	Route	Activities	Distance	Duration	Base	Node
0	6	0	72	3	12	186	1	54.34	163.55	3	9
1	14	0	168	3	12	190	6	127.00	164.47	2	1
2	14	0	168	3	12	200	1	60.75	164.18	2	8
5	14	0	168	3	12	201	6	137.28	165.15	3	6
8	14	0	168	3	12	204	5	137.28	102.15	3	6
11	14	0	168	3	12	218	6	149.43	165.96	2	5
13	9	106.34	149.09	2	6	220	6	137.28	165.15	3	6
14	14	0.00	168.00	3	12	226	6	165.46	167.03	3	5
15	1	36.56	158.76	3	10	237	1	55.37	164.66	3	11
17	14	0.00	168.00	3	12	239	1	55.37	164.66	3	11
21	1	103.32	164.60	0	7	248	7	106.34	166.09	2	6
28	14	0.00	168.00	3	12	250	1	36.56	158.76	3	10
33	14	0.00	168.00	3	12	265	6	112.62	163.51	0	3
35	14	0.00	168.00	3	12	267	6	137.28	165.15	3	6
44	1	33.23	162.14	2	9	280	1	85.89	165.65	0	9
49	3	23.77	60.61	2	10	284	1	55.37	164.66	3	11
71	14	0.00	168.00	3	12	300	6	146.47	165.76	0	6
82	14	0.00	168.00	3	12	320	6	132.66	164.84	3	4
85	3	42.17	57.67	3	7	322	1	43.55	163.03	3	8
97	14	0.00	168.00	3	12	324	4	132.11	112.81	2	0
99	3	60.75	51.66	2	8	332	14	0.00	168.00	3	12
102	1	42.17	160.52	3	7	333	1	60.75	164.18	2	8
107	2	139.02	61.27	0	5	336	1	103.67	32.91	0	4
137	14	0.00	168.00	3	12	356	5	157.29	140.49	3	2
141	7	106.34	166.09	2	6	364	8	106.34	166.09	2	6
144	1	103.32	164.60	0	7	366	14	0.00	168.00	3	12
155	6	146.47	165.76	0	6	373	3	33.23	50.43	2	9
163	3	53.68	48.68	2	11	385	5	103.30	136.89	2	3
181	6	137.28	162.15	3	6	392	14	0.00	168.00	3	12
182	1	36.56	158.76	3	10						

Table E.7: HLV Detailed Results for Minimization of Routes

Route	Activities	Distance	Duration	Base	Node	Route	Activities	Distance	Duration	Base	Node
0	7	0.00	161.06	3	12	65	1	63.63	56.24	1	3
1	7	0.00	161.06	3	12	66	1	32.38	54.16	1	2
2	3	0.00	69.03	3	12	67	1	29.99	54.00	1	1
18	1	0.00	156.50	3	12	68	1	21.20	53.41	1	0
19	1	0.00	156.50	3	12	69	1	53.68	82.57	2	11
20	1	0.00	156.50	3	12	70	1	53.68	163.68	2	11
21	1	0.00	156.50	3	12	71	1	53.68	163.68	2	11
22	1	0.00	156.50	3	12	72	1	53.68	163.68	2	11
23	1	0.00	156.50	3	12	73	1	53.68	163.68	2	11
24	1	0.00	156.50	3	12	74	1	53.68	163.68	2	11
25	1	0.00	156.50	3	12	75	1	53.68	163.68	2	11
26	1	0.00	156.50	3	12	76	1	53.68	163.68	2	11
27	1	0.00	156.50	3	12	77	1	53.68	163.68	2	11
28	1	0.00	156.50	3	12	78	1	53.68	163.68	2	11
29	1	0.00	156.50	3	12	79	1	53.68	163.68	2	11
30	1	0.00	156.50	3	12	80	1	23.77	127.02	2	10
31	1	0.00	156.50	3	12	81	1	23.77	157.04	2	10
32	1	0.00	156.50	3	12	82	1	23.77	157.04	2	10
33	1	0.00	156.50	3	12	83	1	23.77	157.04	2	10
34	1	0.00	156.50	3	12	84	1	23.77	157.04	2	10
35	1	0.00	156.50	3	12	85	1	23.77	157.04	2	10
36	1	0.00	156.50	3	12	86	1	23.77	157.04	2	10
37	1	0.00	156.50	3	12	87	1	23.77	157.04	2	10
38	1	0.00	156.50	3	12	88	1	23.77	157.04	2	10
39	1	0.00	156.50	3	12	89	1	23.77	157.04	2	10
40	1	0.00	156.50	3	12	90	1	23.77	157.04	2	10
41	1	0.00	156.50	3	12	91	1	33.23	91.61	2	9
42	1	0.00	156.50	3	12	92	1	33.23	161.28	2	9
43	1	0.00	156.50	3	12	93	1	33.23	161.28	2	9
44	1	0.00	156.50	3	12	94	1	33.23	161.28	2	9
45	1	0.00	156.50	3	12	95	1	33.23	161.28	2	9
46	1	0.00	156.50	3	12	96	1	33.23	161.28	2	9
47	1	0.00	156.50	3	12	97	1	33.23	161.28	2	9
48	1	0.00	156.50	3	12	98	1	33.23	161.28	2	9
49	1	0.00	156.50	3	12	99	1	33.23	161.28	2	9
50	1	0.00	156.50	3	12	100	1	33.23	161.28	2	9
51	1	0.00	156.50	3	12	101	1	33.23	161.28	2	9
52	1	0.00	111.53	2	7	102	2	100.18	110.68	1	6
53	1	0.00	156.85	2	7	103	1	43.02	90.24	0	8
54	1	0.00	156.85	2	7	104	1	43.02	162.13	0	8
55	1	0.00	156.85	2	7	105	1	43.02	162.13	0	8
56	1	0.00	156.85	2	7	106	1	43.02	162.13	0	8
57	1	0.00	156.85	2	7	107	1	43.02	162.13	0	8
58	1	0.00	156.85	2	7	108	1	43.02	162.13	0	8
59	1	0.00	156.85	2	7	109	1	43.02	162.13	0	8
60	1	0.00	156.85	2	7	110	1	43.02	162.13	0	8
61	1	0.00	156.85	2	7	111	1	43.02	162.13	0	8
62	1	0.00	156.85	2	7	112	1	43.02	162.13	0	8
63	1	41.37	54.76	1	5	113	1	43.02	162.13	0	8
64	1	34.52	54.30	1	4						

Table E.8: HLV Detailed Results for Minimization of Distance

Route	Activities	Distance	Duration	Base	Node	Route	Activities	Distance	Duration	Base	Node
0	1	53.68	82.57	2	11	65	1	0.00	156.50	3	12
1	1	53.68	163.68	2	11	66	1	0.00	156.50	3	12
2	1	53.68	163.68	2	11	67	1	0.00	156.50	3	12
3	1	53.68	163.68	2	11	68	1	0.00	156.50	3	12
4	1	53.68	163.68	2	11	69	1	0.00	156.50	3	12
5	1	53.68	163.68	2	11	70	1	0.00	156.50	3	12
6	1	53.68	163.68	2	11	71	1	0.00	156.50	3	12
7	1	53.68	163.68	2	11	72	1	0.00	156.50	3	12
8	1	53.68	163.68	2	11	73	1	0.00	156.50	3	12
9	1	53.68	163.68	2	11	74	1	0.00	111.53	2	7
10	1	53.68	163.68	2	11	75	1	0.00	156.85	2	7
11	1	23.77	127.02	2	10	76	1	0.00	156.85	2	7
12	1	23.77	157.04	2	10	77	1	0.00	156.85	2	7
13	1	23.77	157.04	2	10	78	1	0.00	156.85	2	7
14	1	23.77	157.04	2	10	79	1	0.00	156.85	2	7
15	1	23.77	157.04	2	10	80	1	0.00	156.85	2	7
16	1	23.77	157.04	2	10	81	1	0.00	156.85	2	7
17	1	23.77	157.04	2	10	82	1	0.00	156.85	2	7
18	1	23.77	157.04	2	10	83	1	0.00	156.85	2	7
19	1	23.77	157.04	2	10	84	1	0.00	156.85	2	7
20	1	23.77	157.04	2	10	85	1	41.37	54.76	1	5
21	1	23.77	157.04	2	10	86	1	34.52	54.30	1	4
22	7	0.00	161.06	3	12	87	1	63.63	56.24	1	3
23	7	0.00	161.06	3	12	88	1	32.38	54.16	1	2
24	3	0.00	69.03	3	12	89	1	29.99	54.00	1	1
40	1	0.00	156.50	3	12	90	1	21.20	53.41	1	0
41	1	0.00	156.50	3	12	91	1	33.23	91.61	2	9
42	1	0.00	156.50	3	12	92	1	33.23	161.28	2	9
43	1	0.00	156.50	3	12	93	1	33.23	161.28	2	9
44	1	0.00	156.50	3	12	94	1	33.23	161.28	2	9
45	1	0.00	156.50	3	12	95	1	33.23	161.28	2	9
46	1	0.00	156.50	3	12	96	1	33.23	161.28	2	9
47	1	0.00	156.50	3	12	97	1	33.23	161.28	2	9
48	1	0.00	156.50	3	12	98	1	33.23	161.28	2	9
49	1	0.00	156.50	3	12	99	1	33.23	161.28	2	9
50	1	0.00	156.50	3	12	100	1	33.23	161.28	2	9
51	1	0.00	156.50	3	12	101	1	33.23	161.28	2	9
52	1	0.00	156.50	3	12	102	1	43.02	90.24	0	8
53	1	0.00	156.50	3	12	103	1	43.02	162.13	0	8
54	1	0.00	156.50	3	12	104	1	43.02	162.13	0	8
55	1	0.00	156.50	3	12	105	1	43.02	162.13	0	8
56	1	0.00	156.50	3	12	106	1	43.02	162.13	0	8
57	1	0.00	156.50	3	12	107	1	43.02	162.13	0	8
58	1	0.00	156.50	3	12	108	1	43.02	162.13	0	8
59	1	0.00	156.50	3	12	109	1	43.02	162.13	0	8
60	1	0.00	156.50	3	12	110	1	43.02	162.13	0	8
61	1	0.00	156.50	3	12	111	1	43.02	162.13	0	8
62	1	0.00	156.50	3	12	112	1	43.02	162.13	0	8
63	1	0.00	156.50	3	12	113	2	100.18	110.68	1	6
64	1	0.00	156.50	3	12						

Table E.9: HLV Detailed Results for Minimization of Vessels

Route	Activities	Distance	Duration	Base	Node	Route	Activities	Distance	Duration	Base	Node
0	1	158.57	167.07	1	12	58	1	42.17	159.66	3	7
1	1	117.06	167.07	1	8	59	1	85.89	164.79	0	9
2	1	76.88	161.62	0	12	60	1	42.17	159.66	3	7
3	1	42.17	159.31	2	12	61	1	0.00	156.50	3	12
4	1	42.17	159.31	2	12	62	1	0.00	156.50	3	12
5	1	0.00	156.50	3	12	63	1	43.55	162.17	3	8
6	1	76.88	161.62	0	12	64	1	110.43	162.82	0	10
8	1	76.88	161.62	0	12	65	1	103.32	163.73	0	7
9	1	63.63	56.24	1	3	66	1	174.15	167.07	1	10
11	1	76.88	161.62	0	12	67	1	99.99	58.67	0	0
13	1	23.77	157.04	2	10	69	1	41.37	54.76	1	5
14	1	53.68	163.68	2	11	70	1	121.87	60.12	2	4
15	1	53.68	163.68	2	11	71	1	110.43	162.82	0	10
16	1	42.17	159.66	3	7	72	1	104.49	167.07	1	11
17	1	158.57	167.07	1	12	73	1	43.02	162.13	0	8
18	1	42.17	159.31	2	12	74	1	55.37	163.79	3	11
19	1	120.09	167.07	1	9	75	1	42.17	159.31	2	12
20	1	76.88	161.62	0	12	78	1	36.56	157.89	3	10
21	1	43.02	162.13	0	8	79	1	120.09	167.07	1	9
23	1	53.68	163.68	2	11	80	1	76.88	161.62	0	12
24	1	43.55	162.17	3	8	81	2	106.34	111.09	2	6
25	1	158.57	167.07	1	12	82	1	33.23	91.61	2	9
27	1	55.37	163.79	3	11	83	1	153.30	167.07	1	7
28	1	23.77	157.04	2	10	84	1	153.30	167.07	1	7
30	1	36.56	157.89	3	10	85	1	76.88	161.62	0	12
31	1	85.89	164.79	0	9	86	1	153.30	167.07	1	7
32	1	43.02	162.13	0	8	87	1	54.34	162.68	3	9
33	1	85.89	164.79	0	9	88	3	0.00	69.03	3	12
34	1	0.00	156.50	3	12	89	1	76.88	161.62	0	12
35	1	110.43	162.82	0	10	90	1	76.88	161.62	0	12
36	1	42.17	159.31	2	12	91	1	120.09	167.07	1	9
37	1	0.00	156.50	3	12	93	1	158.57	167.07	1	12
38	1	43.55	162.17	3	8	94	1	61.38	164.19	0	11
39	1	103.32	118.42	0	7	95	7	76.88	166.19	0	12
40	1	42.17	159.66	3	7	97	1	36.56	157.89	3	10
41	1	60.75	163.31	2	8	98	1	117.06	167.07	1	8
42	1	158.57	167.07	1	12	99	1	158.57	167.07	1	12
43	1	29.99	54.00	1	1	100	1	76.88	161.62	0	12
44	1	174.15	137.04	1	10	101	1	54.34	162.68	3	9
45	1	85.89	164.79	0	9	102	1	42.17	159.31	2	12
46	1	42.17	159.66	3	7	103	1	55.37	163.79	3	11
47	1	76.88	161.62	0	12	104	7	76.88	166.19	0	12
48	1	61.38	164.19	0	11	105	1	120.09	167.07	1	9
49	1	32.38	54.16	1	2	107	1	0.00	156.50	3	12
50	1	42.17	159.31	2	12	108	1	61.38	83.08	0	11
51	1	23.77	157.04	2	10	109	1	60.75	163.31	2	8
53	1	76.88	161.62	0	12	111	1	42.17	159.31	2	12
54	1	76.88	161.62	0	12	112	1	104.49	167.07	1	11
55	1	42.17	159.31	2	12	113	1	43.02	90.24	0	8
56	1	153.30	167.07	1	7						

F

Sensitivity Analysis SOV

Table F.1: SOV Sensitivity Analysis for the Minimization of Routes

Min. Routes	**Number of Activities**						**Number of Routes**					
Base	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Den Helder	6	4	6	6	6	6	4	2	4	4	4	4
Ijmuiden	91	91	91	91	83	87	16	10	16	16	15	16
SOV	24	16	24	24	24	24	16	8	16	16	16	16
Island	244	244	122	365	244	244	18	9	9	27	18	18
Total	365	355	243	486	357	361	54	29	45	63	53	54
	Number of Vessels						**Total Distance Travelled**					
Base	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Den Helder	1	1	1	1	1	1	172.06	86.03	172.06	172.06	172.06	172.06
Ijmuiden	4	5	4	4	4	4	1005.07	565.01	1005.07	1005.07	904.89	1005.07
SOV	4	4	4	4	4	4	442.72	221.36	442.72	442.72	442.72	442.72
Island	5	5	3	7	5	5	0	0	0	0	0	0
Total	14	15	12	16	14	14	1619.85	872.4	1619.85	1619.85	1519.67	1619.85

Table F.2: SOV Sensitivity Analysis for the Minimization of Distance

Min. Dist	**Number of Activities**						**Number of Routes**					
Base	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Den Helder	6	4	6	6	6	6	4	2	4	4	4	4
Ijmuiden	91	91	91	91	83	87	16	10	16	16	15	16
SOV	24	16	24	24	24	24	17	9	17	17	16	17
Island	244	244	122	365	244	244	18	9	9	27	18	18
Total	365	355	243	486	357	361	55	30	46	64	53	55
	Number of Vessels						**Total Distance Travelled**					
Base	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Den Helder	1	1	1	1	1	1	172.06	86.03	172.06	172.06	172.06	172.06
Ijmuiden	4	5	4	4	4	4	1005.07	565.01	1005.07	1005.07	904.89	1005.07
SOV	5	5	5	5	4	5	442.72	221.36	442.72	442.72	442.72	442.72
Island	5	5	3	7	5	5	0	0	0	0	0	0
Total	15	16	13	17	14	15	1619.85	872.4	1619.85	1619.85	1519.67	1619.85

Table F.3: SOV Sensitivity Analysis for the Minimization of Vessels

Min. Ves	Number of Activities						Number of Routes					
Base	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Den Helder	0	0	0	0	0	21	0	0	0	0	0	10
Ijmuiden	0	0	0	0	0	0	0	0	0	0	0	0
SOV	0	0	0	0	0	164	0	0	0	0	0	24
Island	365	355	243	486	357	176	54	29	45	63	53	20
Total	365	355	243	486	357	361	54	29	45	63	53	54
	Number of Vessels						**Total Distance Travelled**					
Base	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Den Helder	0	0	0	0	0	3	0	0	0	0	0	959.29
Ijmuiden	0	0	0	0	0	0	0	0	0	0	0	0
SOV	0	0	0	0	0	6	0	0	0	0	0	1891.41
Island	14	15	12	16	14	5	3191.97	1895.35	3191.97	3191.97	3054.69	827.74
Total	14	15	12	16	14	14	3191.97	1895.35	3191.97	3191.97	3054.69	3678.44

G

Sensitivity Analysis HLV

Table G.1: HLV Sensitivity Analysis for Minimization of Routes

Min. Routes	**Number of Activities**						**Number of Routes**					
Base	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Den Helder	11	6	11	11	11	11	11	6	11	11	11	11
Ijmuiden	8	8	8	8	8	8	7	7	7	7	7	7
SOV	44	24	44	44	44	44	44	24	44	44	44	44
Island	51	34	27	75	51	51	37	17	20	54	37	37
Total	114	72	90	138	114	114	99	54	82	116	99	99
	Number of Vessels						**Total Distance Travelled**					
Base	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Den Helder	3	3	3	3	3	3	473.2	258.09	473.2	473.2	473.17	473.17
Ijmuiden	2	4	2	2	2	2	323.3	323.28	323.3	323.3	323.28	323.28
SOV	11	12	11	11	11	11	1217	664.08	1217	1217	1217.47	1217.47
Island	10	9	5	14	10	10	0	0	0	0	0	0
Total	26	28	21	30	26	26	2013.5	1245.45	2013.5	2013.5	2013.92	2013.92

Table G.2: HLV Sensitivity Analysis for Minimization of Distance

Min. Dist	**Number of Activities**						**Number of Routes**					
Base	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Den Helder	11	6	11	11	11	11	11	6	11	11	11	11
Ijmuiden	8	8	8	8	8	8	7	7	7	7	7	7
SOV	44	24	44	44	44	44	44	24	44	44	44	44
Island	51	34	27	75	51	51	37	17	20	54	37	37
Total	114	72	90	138	114	114	99	54	82	116	99	99
	Number of Vessels						**Total Distance Travelled**					
Base	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Den Helder	3	3	3	3	3	3	473.2	258.09	473.2	473.2	473.17	473.17
Ijmuiden	2	4	2	2	2	2	323.3	323.28	323.3	323.3	323.28	323.28
SOV	11	12	11	11	11	11	1217	664.08	1217	1217	1217.47	1217.47
Island	10	9	5	14	10	10	0	0	0	0	0	0
Total	26	28	21	30	26	26	2013.5	1245.45	2013.5	2013.5	2013.92	2013.92

Table G.3: HLV Sensitivity Analysis for Minimization of Vessels

Min. Ves	**Number of Activities**						**Number of Routes**					
Base	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Den Helder	44	0	0	58	44	44	32	0	0	40	32	32
Ijmuiden	24	0	0	31	24	24	24	0	0	28	24	24
SOV	21	0	22	24	21	21	20	0	22	24	20	20
Island	25	72	68	25	25	25	23	54	60	24	23	23
Total	114	72	90	138	114	114	99	54	82	116	99	99
	Number of Vessels						**Total Distance Travelled**					
Base	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Den Helder	8	0	0	10	8	8	2491	0	0	3240.28	2491	2490.9
Ijmuiden	6	0	0	7	6	6	3004	0	0	3879.69	3004	3003.73
SOV	5	0	6	6	5	5	994.8	0	590.51	1127.14	994.8	994.78
Island	6	27	15	6	6	6	726	2383.28	2470.33	1077.52	726	725.95
Total	25	27	21	29	25	25	7215.8	2383.28	3060.84	9324.63	7215.8	7215.36

H

Thesis Article

Identifying Logistical Fleet Strategies for Future Scenarios of Offshore Energy Innovations in the North Sea Region

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Abstract— **To support the deployment of future offshore facilities aimed at achieving net-zero greenhouse gas emissions by 2050, offshore logistics operators must adjust their fleet management and routing strategies to accommodate diverse facility types. Existing methods for determining optimal vessel fleet size and composition are primarily tailored to offshore wind farm activities, lacking integration across multiple offshore facility types. To address this gap, we propose a Mixed-Integer Linear Programming (MILP) approach to optimize vessel fleet configuration, leveraging traditional solution methods such as branch-and-cut with commercial solvers. This model presents a mixed fleet of crew transfer vessels, service operation vessels, and heavy lift vessels to meet the specific demands of future offshore operations. With a focus on hydrogen power plants and carbon capture and storage platforms in addition to offshore wind farms, it demonstrates how a strategically configured fleet can efficiently support the diverse activities involved in integrating these new facilities.**

I. Introduction

Global and regional climate targets have been established to reduce the worldwide carbon footprint. The European Commission aims to reduce the net greenhouse gas emissions by at least 55% by 2030, compared to the 1990 levels and reduce it even further to zero net emissions of greenhouse gases by 2050, according to the European Green Deal [1]. It is necessary that a transition takes place to a carbon-free energy supply, which can be enabled by offshore wind energy [2]. In combination with offshore wind energy, energy stakeholders in the North Sea region aim to implement offshore hydrogen platforms and facilities for carbon capture & storage. This research will explore the changes in maintenance demand in the North Sea as a result of these new facilities such that decision-makers in offshore logistics can facilitate these new demands. This research will therefore look into these logistic requirements and determine what offshore fleet services have to be provided, in terms of fleet size and mix.

Existing literature on offshore operations and maintenance often centers on single location types, such as wind farms. Due to limited asset sharing among offshore operators, few studies explore the potential for shared logistics between competitors, especially across different facility types. Additionally, the literature rarely addresses the concept of energy hubs, where a region is segmented into smaller zones, each serving as a hub with the potential of shared logistical services. This study examines potential adjustments in vessel requirements to support future activities in the North Sea Region. It builds on previous research into logistical challenges in future scenarios in the Dutch North Sea Region [3]. Furthermore, this research contributes to the NSE5 project, by achieving the goal of identifying an optimal vessel fleet strategy for offshore activities in a future scenario with energy hubs and their corresponding facilities. NSE5 is the fifth phase of a public-private initiative investigating the North Sea's potential for an integrated energy system.

This study focuses on the logistics of offshore energy hubs, specifically examining Hub West in the North Sea Region, which will include seven offshore wind farms, five carbon capture and storage facilities, and a hydrogen power plant consisting of eight platforms, all expected to be operational by 2050. Four potential service bases are considered: the onshore bases of Den Helder and IJmuiden, along with an offshore Service Operations Vessel (SOV) base and an offshore island base. Given the range of facilities, numerous stakeholders are involved in offshore logistics, though this report is written from the perspective of an offshore logistics service provider. The analysis will focus on a general operational model rather than day-to-day logistics, with the problem scoped down to fleet asset management.

To achieve this goal, an extensive description of the vessel fleet problem will be presented in Section II, containing an overview of the anticipated activities related to future offshore facilities. A review of the current literature on similar problems is given in Section III, along with the developed mathematical model. The produced results of the model are stated in Section V, followed by the validation and verification in Sections VI and VII, respectively. Finally, this paper is concluded with the discussion and conclusion in Sections VIII and IX, respectively.

II. Problem Description

Maintenance activities in offshore operations generally fall into two categories: corrective and preventive. Corrective maintenance is performed when components fail and require repair or replacement for operations to resume. Preventive maintenance, on the other hand, is scheduled to reduce the likelihood of failure and extend the operational life of the equipment or system by addressing potential issues before they become critical [4]. Each type of activity requires varying vessel sizes, technician team sizes and skills. One vessel can execute one task at a time or multiple tasks can be grouped into a larger set of maintenance tasks. In the latter case, experts speak of an activity bundle - where one vessel executes a task parallel to related maintenance

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tasks [5]. Activity bundles are mostly performed on multiple offshore wind turbines as part of one farm, as these turbines are relatively close to each other in distance. The problem, however, focuses on the activities themselves and works with the assumption that the activities are done sequentially rather than simultaneously.

In the case that turbines of an Offshore Wind Farm (OWF) fail, corrective or reactive maintenance needs to be performed. These types of activities include minor repair, major repair, minor replacement, and major replacement [6]. Certain equipment operates on a "run-to-failure" basis, meaning it is used until a part fails, after which resources are dispatched to perform repairs. This approach is typically applied to non-critical equipment, where the combined cost of maintenance and downtime is less than that of conducting preventive or proactive maintenance.

To determine the necessary frequency and duration for repair and replacement of wind turbine components, a detailed analysis of their failure rates is essential. While numerous models on wind turbine failure rates are available in the literature, obtaining actual failure rate data poses challenges. First, accessing such data is difficult due to competitive constraints within the wind farm industry. Second, the wind farms planned for 2030 and beyond will incorporate innovative turbine designs suited for deeper North Sea waters, making current failure rate data—based on existing near-shore turbines insufficient for predicting maintenance needs in these future settings, as well as for accurately assessing warranty liabilities on newly installed wind farms.

Commonly used methods to model the failure rates of wind turbines are a Weibull distribution or a Poisson distribution. The Weibull model is used to model the time until failure occurs, while a Poisson distribution is used to count the number of failures within a predetermined time interval [5]. From a logistics point of view, it is useful to identify the frequency of voyages needed to visit a certain platform. For this purpose, a Poisson distribution would be more appropriate. The required tasks during the O&M phase of offshore wind turbines in Table I are modelled stochastically, using a Poisson distribution with deterministically assumed repair times [7].

TABLE I
OPERATION & MAINTENANCE TASKS OF AN OFFSHORE WIND TURBINE

Task name	Occurence Rate [per year]	Required Asset	Technicians	Task Duration [h]
Manual reset	7.5	CTV	2	3
Minor repair	6.81	CTV	2	7.5
Medium repair	3.35	CTV	3	22
Major repair	1.17	SOV	4	26
Major replacement	0.29	HLV	5	52
Yearly servicing	1	CTV	3	60

The full maintenance demand for the wind farms surrounding Hub West is directly influenced by their respective sizes and capacities per wind turbine. While Table I provides maintenance demand estimates for individual turbines, Table II outlines the seven wind farms under consideration, including their capacities and sizes [8]. The size of the IJmuiden Ver wind farm is estimated based on its capacity of 4000 MW, drawing comparisons with typical turbine sizes, like those in use at Hollandse Kust West (HKW). From this comparison, it is assumed that around 286 turbines would be needed to reach the designated capacity of IJmuiden Ver. Due to the large distance from each base to IJmuiden Ver, the activities requiring a CTV will be performed by an SOV instead.

TABLE II
WIND FARMS IN THE DUTCH NORTH SEA LINKED TO HUB WEST

Wind Farm	Power Capacity [MW]	No. of Turbines	Year of First Operation
Egmond aan Zee	108	36	2007
Prinses Amalia	120	60	2008
Luchterduinen	129	43	2015
HKW	840	60	2025
HKN	759	69	2008
HKZ	1529	139	2023
IJmuiden Ver	4000	286	2027

The trends and perspectives of offshore wind farms are increasingly leaning towards integration with future energy systems, particularly through the complementary generation of hydrogen alongside electricity generated from wind farms [9] [10] [11]. NSE5 and their partners are considering several scenarios for offshore hydrogen production on Hub West. Transmission System Operator TenneT is looking at a total of 8 GW of offshore hydrogen, while Gasunie is aiming for 1 GW hydrogen per 1 GW of wind energy and TNO considers a total of 4 - 8 GW of offshore hydrogen for Hub West. In any case, the hydrogen power plants will be unmanned, meaning they will not be equipped with living quarters.

Pilot programmes from the Port of Rotterdam are developing green hydrogen plants with capacities 100 MW with the opportunity to expand this to 500 MW [12]. Hydrogen plants consist of building blocks, of which each is a stack of 200 electrolytic cells providing up to 5 MW of electricity per cell. Each stack of cells needs to be replaced every 6 to 10 years. The process of replacement takes approximately a week for onshore hydrogen plants, but 2 weeks can be approximated for the same process offshore. Aside from the cell replacements, the expectation is that Service Operation Vessels (SOVs) are used to sail around Hub West, especially in the first few months, to monitor the power plants and their potential inaccuracies or defects [13]. There is a high probability that this will result in daily check-ups, where SOVs stay offshore for one week at a time and will return to their base to switch technicians and the necessary equipment

[13]. An overview of these maintenance activities is listed in Table III, detailing activities such as cell replacement, which occurs at the individual cell level, and daily maintenance, conducted at the platform level.

TABLE III
OPERATION & MAINTENANCE TASKS OF OFFSHORE HYDROGEN PLATFORMS

Task name	Occurence Rate [per year]	Required Asset	Technicians	Task Duration [days]
Cell Replacement	0.125	HLV	20	14
Daily Maintenance	365	SOV	20	1

The third facility considered in this research is the implementation of Carbon Capture & Storage (CCS) facilities, where CO_2 is captured from the air and transported through pipelines to a location where CO_2 is compressed and stored underground. Several Oil & Gas platforms are candidates to be transformed into CCS platforms. The soil under the former Oil & Gas platforms consists of empty gas fields that were once filled with natural gases. The soil below the caprock decreased in pressure due to the extraction of gas, but this pressure can be restored with the storage of CO_2 in these areas.

The goal for 2050 is to be able to store up to 27 MT per annum in total - all of which is planned to be stored around Hub West. Here, five key platforms have been selected to play a big role in the North Sea Region due to their potential for CO_2 storage [14]. Similar to offshore hydrogen power plants, the capture of carbon emissions is not yet realized in the North Sea Region. Expected maintenance activities surrounding the CCS platforms, however, are yearly maintenance operations and the coating repairs of the platforms, also referred to as the painting of them. These activities cause an outage of three weeks and 8 to 12 weeks, respectively. Additionally, 20 days per year are considered per year to perform unplanned maintenance activities, as depicted in Table IV.

TABLE IV
OPERATION & MAINTENANCE TASKS OF CARBON CAPTURE & STORAGE FACILITIES

Task name	Occurence Rate [per year]	Required Asset	Technicians	Task Duration [days]
Yearly Maintenance	1	SOV	20	21
Unplanned Maintenance	20	SOV	20	1
Painting	0.167	HLV	40	70

For this research, three vessel types are considered as logistic assets to perform the activities outlined in Tables I, III, and IV. The first type is a Crew Transport Vessel (CTV), a smaller vessel used to transport technicians to facilities closer to shore. These vessels typically operate within a travel time of 30 minutes to one hour and lack sleeping accommodations, requiring them to return to base after their shift, which can last up to 12 hours. The larger vessels in this study include Service Operation Vessels (SOV) and Heavy Lift Vessels (HLV). Both vessel types are equipped with sleeping accommodations for technicians, allowing them to stay offshore for extended periods of one to two weeks before needing crew rotation. HLVs, also known as Jack-Up Vessels (JUV), are specialized for heavy lifting tasks, such as the installation of large equipment and structures.

Vessels in the North Sea Region currently operate from Den Helder, chartered to offshore locations. In future logistic scenarios, three configurations can be modeled: shore-based, SOV-based, and island-based. In the shore-based scenario, vessels continue their current operations, returning to the shore after each voyage. In the SOV-based scenario, an offshore location serves as a hub where resources are transferred vessel-to-vessel before being returned to shore. In the island-based scenario, offshore energy hubs are supported by an island serving as a base. Adding new bases would require modifications to the existing single-base operations.

III. METHODS

A Fleet Size & Mix Problem can be described for multiple situations. The maritime vessel fleet size and mix problem in the literature primarily has looked into the maintenance activities of offshore wind farms. Several studies looked at vessel fleet size and mix problems that arise while maintaining offshore wind farms using a fleet of maintenance vessels. [5] focuses on establishing the best vessel assignment while minimizing costs by formulating an Integer Programming Model. Other studies [4] [15] divide the problem into multiple stages using Stochastic Programming. [4] solves the vessel fleet problem in two stages - first, decisions are made on what vessel to charter subject to uncertainty in the demand of maintenance tasks and weather conditions. The second stage of the model looks into ways to support maintenance tasks using the chartered vessels determined from the first stage of the model. Another study [15] proposes a stochastic three-stage programming model. The fixed costs of acquired or chartered vessels and their bases are minimized in the first stage, followed by the minimization of the expected cost of the vessels chartered. Finally, in the third stage, the expected costs of using the vessels, downtime costs of delayed maintenance tasks, penalty costs and transportation costs are considered. [16] introduces a branch-and-cut algorithm and an Adaptive Large Neighbourhood Search (ALNS) heuristic. The problem consists of a periodic vehicle routing problem while determining an optimal fleet size and mix of heterogeneous offshore supply vessels, their weekly routes and schedules for servicing the offshore oil and gas installations, and the berth allocations at the supply base.

Other studies related to offshore maintenance activities focus more on demand and fleet policies. [17] proposes a framework to compare a number of different fleet management policies and analyze the impacts of these strategies in a discrete-event simulator that realistically represents the offshore operation scenario. The outputs of different scenarios are compared to each other, to analyze the effects their elements have on the output. The main difference between the scenarios is whether an aggregated or disaggregated fleet is used - in the aggregated fleet, one vessel can carry a combined set of goods while the vessels in the disaggregated fleet carry only one type of good. [18] compares two alternatives for vessel routing, one based on a fixed schedule and another based on the demand of offshore platforms. With a fixed schedule, the route for a vessel is predetermined and each location will be visited 2, 3 or 4 times a week whereas routing and planning in the second policy are based on the demand pattern of the locations.

A primary requirement for a logistics service provider is ensuring the availability of assets necessary to meet generated demand. This objective can be approached through various strategies, with the effectiveness of each evaluated through specific Key Performance Indicators (KPIs). In this research, two KPIs are emphasized which are in line with the system's primary objectives: (1) minimizing the number of vessels required in the fleet mix and (2) minimizing the total distance travelled. Cost-related KPIs are not included, as cost elements are highly stochastic and difficult to project accurately in future scenarios.

IV. MODEL

Let B be the set of both onshore and offshore bases, from where the vessels can depart. Each vessel leaving a base can be used to serve a location $i \in N$ to perform maintenance activity $a \in A$. Each vessel can stay offshore for its Maximum Duration of Use (MDU) before it has to return to base for fuel, exchange of technicians, pick-up of supply, etc. The MDU of a vessel depends on the vessel type, whether the vessel is a Crew Transfer Vessel or a Service Vessel.

The model consists mostly of deterministic parameters, where the set of locations consists of a total of 4 bases, 7 wind farms, 5 CCS platforms and 1 Hydrogen platform, consecutively defined as $B = \{0, 1, 2, 3\}$ for the bases and $N = \{4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16\}$ for the offshore locations. The solution will be described as a number of routes $r \in R$, where each route lasts at most the MDU hours.

In this model, the constraints have been deliberately simplified to focus solely on the demand and the duration of each visit. Specifically, each activity must be completed, and the duration of each visit cannot exceed the maximum duration of time. A key aspect not incorporated into the model is the capacity of the vessel in terms of the number of technicians it can transport. In practice, technicians are typically deployed to different wind turbines within a wind farm to carry out various tasks simultaneously. However, this model prioritizes compliance with the MDU constraint, thereby offering a lower bound on the number of activities that can feasibly be completed on each route. This approach allows for a more conservative estimation of operational capacity while ensuring that time constraints are respected.

- $d_{i,j}$ are the distances between locations i and j. The maximum speed of the vessel type affects the time tt_{bi} it takes to travel from one location to another.
- u_a the duration of each maintenance task $a \in A$
- f_{ai} the frequency of maintenance activity $a \in A$ at location i
- vs_v the vessel speed.
- MDU the time limit in hours of how long vessels can stay offshore before they have to return to their base.
- R_{max} the maximum number of routes that can be assigned to a vessel within the given time frame
- M representing a large number equal to the number of total activities of demand.

The decision variables for this part of the optimization problem are:

- x_{bir} = 1 if route r travels from base b and includes node i and = 0 if otherwise.
- $y_{air} \geq 0$ is a non-negative integer variable, counting the number of activities at node i that are completed during route r.
- $T_r \geq 0$ is a continuous variable counting the duration of each route r.
- δ_b is a non-negative integer variable, counting the number of vessels allocated to base b.

$$\text{Minimize} \sum_{b\in B}\sum_{i\in N}\sum_{r\in R} x_{bir}$$

Subject to:

$$\sum_{b\in B}\sum_{i\in N} x_{bir} \leq 1 \forall r \in R \tag{1}$$

$$\sum_{a\in A} y_{air} \leq M \sum_{b\in B} x_{bir} \forall i \in N, r \in R \tag{2}$$

$$\sum_{a\in A}\sum_{i\in N} y_{air}u_a + 2tt_{bi}\sum_{b\in B}\sum_{i\in N} x_{bir} \leq MDU \forall r \in R \tag{3}$$

$$\sum_{r\in R} y_{air} \geq f_{ai} \forall a \in A, i \in N \tag{4}$$

$$\frac{\sum_{i\in N}\sum_{r\in R} x_{bir}}{R_{max}} \leq \delta_b \forall b \in B \tag{5}$$

Constraint 1 makes sure that each route leaves from one base and visits one location only while Constraint 2 assures that that location is only visited if and only if that location has activities that need to be completed. Constraint 3 is a time constraint respecting the Maximum Duration of Use of the vessels. The demand of the locations is met by enforcing Constraint 4, while 5 determines the number of routes and vessels per base.

This optimization problem is formulated using Mixed-Integer Linear Programming (MILP) and solved through an exact optimization approach, specifically with the commercial solver Gurobi. MILP is widely recognized modelling method in the optimization of Vehicle Routing and Scheduling problems, as appears in the literature. This method is especially valuable for the logistics of offshore facilities expected to operate by 2050, providing a structured way to handle decision-making for long-term, complex scenarios. The ability to perform scenario analysis and sensitivity testing within the MILP framework further enhances its suitability, allowing stakeholders to explore a range of future conditions and make informed decisions that will remain robust over the span of several decades.

V. Results

The geographic scope of this study encompasses the region surrounding Hub West in the North Sea. Within this area, four potential base locations are considered, along with seven wind farm sites, five carbon capture and storage facilities, and one hydrogen power plant. Tables I to IV represent the demand frequencies on a yearly basis, but due to computational constraints, it is necessary to reduce the dataset to a manageable subset. Given that the activities follow a repetitive pattern, their frequency can be effectively analyzed over both short and long time periods. Although the data is provided on an annual basis, this repetition allows for extrapolation over extended periods or examination within shorter time frames. Since the maximum operational duration of CTVs is limited to a single working day, the activity frequency can be analyzed on a daily basis. For SOVs and HLVs, which can remain offshore for up to a week, a monthly analysis is more appropriate.

The Objective Function presented is designed to minimize the number of routes generated by the model. The number of routes essentially influences the number of vessels required and the total distance travelled. When the objective shifts to minimizing the total distance as described in relation to the KPIs mentioned, the objective function can be reformulated to prioritize distance minimization. In this case, the function becomes $min \sum_{b\in B} \sum_{i\in N} \sum_{r\in R} 2d_{bi}x_{bir}$. Another objective based on the KPIs focuses on minimizing the size of the vessel fleet. This objective is closely tied to the minimization of routes, as fewer routes naturally translate to fewer vessels considering the given demand, a relationship captured by Equations 5 and **??**. The relations between the different objective functions can be reflected in the results presented in this section, where the results for the minimization of routes are presented as Obj1, the minimization of distance as Obj2, and the minimization of vessels as Obj3. These results are acquired by solving the Mixed Integer Linear Problem (MILP) model using Gurobi Optimizer version 11.0.3 build v11.0.3rc0 (linux64 - "Red Hat Enterprise Linux 8.10 (Ootpa)"). A 32-thread solver was used on a system with an Intel(R) Xeon(R) Gold 6248R CPU @ 3.00GHz, featuring 48 physical cores and 48 logical processors [19].

The results for CTVs in Table VI show that all routes, despite the different objective functions, are assigned to the IJmuiden base. This route assignment is plausible given that the CTVs in this scenario are exclusively used for servicing the OWFs, with the IJmuiden base being considerably closer to the OWFs compared to the other bases. For the results of SOVs and HLVs in Tables VIII and X, the distances for the minimization of routes and the minimization of distance are identical. However, the allocation of routes to bases is significantly altered when minimizing the number of SOVs, with all SOVs forced away from the IJmuiden base. This outcome can be explained by the activities assigned to the SOVs in Tables I to III, which show that a substantial portion of the activities for SOVs are performed at an HPP platform. Detailed results show that all 18 routes leaving from the Island base are sent to perform activities at the hydrogen plant when minimizing the routes and the distance. This is logical given that the island base is assumed to be located in the same area as the hydrogen plant, as there is effectively no travel distance between the Island and the HPP. This also explains how the distance is equal to zero for the 18 routes allocated to the Island base in Table VIII. A comparison of the results across the three objectives reveals that the minimization of routes and the minimization of distance results in the same number of vessels as well as the same amount of distance travelled, whereas the minimization of vessels saves the use of one vessel, but results in an increase in the distance by almost 80%.

Similar to the results of the SOVs, Table X shows that the total distances for the minimization of routes and the minimization of distance are identical to each other for every base. Moreover, the other variables related to the activities, routes, and vessels appear to show identical values as well. As for the minimization of vessels, almost all activities seem to be allocated to a different set of routes compared to the results for the other two objectives. With more than triple the distance travelled compared to the minimization of routes and total distance in Obj1 and Obj2, respectively, the minimization of vessels in Obj3 results in one vessel less than the total vessels required for the other objectives.

TABLE VI
CTV Results

Base	Number of Activities			Number of Routes		
	Obj1	Obj2	Obj3	Obj1	Obj2	Obj3
Den Helder	0	0	0	0	0	0
Ijmuiden	38	38	38	27	27	27
SOV	0	0	0	0	0	0
Island	0	0	0	0	0	0
Total	38	38	38	27	27	27
Base	**Number of Vessels**			**Total Distance**		
	Obj1	Obj2	Obj3	Obj1	Obj2	Obj3
Den Helder	0	0	0	0	0	0
Ijmuiden	27	27	27	1112.45	1112.45	1112.45
SOV	0	0	0	0	0	0
Island	0	0	0	0	0	0
Total	27	27	27	1112.45	1112.45	1112.45

TABLE VIII
SOV RESULTS

Base	Number of Activities			Number of Routes		
	Obj1	Obj2	Obj3	Obj1	Obj2	Obj3
Den Helder	6	6	0	4	4	0
Ijmuiden	91	91	0	16	16	0
SOV	24	24	0	16	17	0
Island	244	244	365	18	18	55
Total	365	365	365	54	55	54
Base	Number of Vessels			Total Distance		
	Obj1	Obj2	Obj3	Obj1	Obj2	Obj3
Den Helder	1	1	0	172.06	172.06	0
Ijmuiden	4	4	0	1005.1	1005.1	0
SOV	4	5	0	442.72	442.72	0
Island	5	5	14	0	0	3192
Total	14	15	14	1619.9	1619.9	3192

TABLE X
HLV RESULTS

Base	Number of Activities			Number of Routes		
	Obj1	Obj2	Obj3	Obj1	Obj2	Obj3
Den Helder	11	11	44	11	11	32
Ijmuiden	8	8	24	7	7	24
SOV	44	44	21	44	44	20
Island	51	51	25	37	37	23
Total	114	114	114	99	99	99
Base	Number of Vessels			Total Distance		
	Obj1	Obj2	Obj3	Obj1	Obj2	Obj3
Den Helder	3	3	8	473.17	473.17	2490.9
Ijmuiden	2	2	6	323.28	323.28	3003.73
SOV	11	11	5	1217.47	1217.47	994.78
Island	10	10	6	0	0	725.95
Total	26	26	25	2013.92	2013.92	7215.36

VI. VALIDATION

Out of the three considered location facilities, only the offshore wind farms are currently operational. Due to the fact that the other facilities are not yet implemented in the North Sea Region, the validation of the model will be centered around a base scenario of the current logistical activities of the North Sea region, exclusively consisting of the servicing of existing Wind Turbines and Oil & Gas Platforms. The collected data for this analysis has been acquired from Peterson Energy Logistics, spanning the recent years of 2019 (pre-covid) and 2021 to 2023. It is important to note that (1) the collected dataset does not contain all activities of 2023 as it was collected before the end of the year, (2) it is not reported by the logistic service operator how many technicians are transported during each trip, and that (3) this dataset is exclusively confined to Service Vessels, thereby excluding information pertaining to CTVs and HLVs. While the model considers the three vessel types CTV, SOV, and HLV, the validation of the model is conducted using only SOV data due to limited data availability.

The base scenario includes the four bases Aberdeen, Den Helder, Great Yarmouth, and IJmuiden, multiple offshore ports, and platforms. The available data is from the perspective of the logistic service operator, meaning the specific activities carried out at the offshore locations are neither specified nor detailed. From these offshore activities, a subset of activities related to offshore tasks can be identified. The ratio of offshore activities compared to other vessel activities for each year are:

2019: 54.2%
2021: 58.5%
2022: 55.9%
2023: 55.9%

TABLE XII
BASE CASE: DISTINCT NUMBER OF VESSELS ON A MONTHLY BASIS

	Jan	Feb	Mar	Apr	May	Jun
2019	11	10	10	11	12	12
2021	9	10	10	8	8	8
2022	11	12	12	13	14	16
2023	12	12	11	13	14	13

	Jul	Aug	Sep	Oct	Nov	Dec
2019	11	13	13	12	12	11
2021	10	13	11	16	16	12
2022	12	12	11	10	12	11
2023	13	12	9	-	-	-

The data presented in Table XII reflects the number of vessels deployed on a monthly basis, which consistently hovers around 12 vessels per month, ranging between a minimum of 8 and a maximum of 16 vessels. By comparing these figures with the percentages of offshore activities per year, it is possible to estimate the number of vessels required for offshore maintenance activities on a monthly scale. These percentages serve as a useful guideline for understanding the proportion of offshore activities conducted throughout the year. When combining these percentages with the vessel numbers in Table XII, a reasonable estimate can be made that approximately 4 to 10 vessels with an average of seven per month are utilized for offshore operations in the North Sea region.

These numbers are compared to the outcomes of the model to evaluate the model's reliability and validity. While the activities in the two cases are not directly comparable due to their different natures regarding their facility demands, the number of vessels can still be assessed across both cases. Validating the model against the current base serves as an essential benchmark to assess the model's reliability and operational soundness. The base scenario for SOVs shows that the offshore facilities that are currently active in the North Sea Region require approximately seven vessels per month and around 10 to 15 vessels a year to fulfill their offshore activities, assuming that vessels are used multiple times a year and can be chartered from multiple bases. A comparison to the model's outcomes makes it evident that the computational outcomes yield vessel requirements that are about double those of the base case. This discrepancy relates to the fact that all activities originally planned for completion once per year - or even once every few years - are now scheduled to be fulfilled (once) within a single month. Other plausible explanations could be that the vessels can be allocated to multiple bases in the base case, whereas the model considers a scenario where the vessels do not travel from one base to another, or the number of HPP platforms and its high demand.

The activities related to the hydrogen platform as presented in Table III show that SOVs are used only for the daily maintenance activities of the HPP. Given that each of the eight platforms has to be visited daily, the hydrogen platform shows a much higher visiting frequency compared to other activities done at OWFs and CCS facilities. However, due to the shorter duration of activities at the hydrogen platform, multiple activities can be completed within a single route. In contrast, activities at the CCS platforms require more time, allowing only one activity per route for some of the activities. Consequently, the number of routes and, therefore, the number of vessels needed, is comparable for both the CCS and hydrogen platforms. The detailed results for SOVs verify that a large portion of the routes is travelled to visit the hydrogen platforms and that the routes allocated to the IJmuiden and the Island bases are used to perform activities at the CCS platforms and the hydrogen plant. In short, the discrepancies in the number of vessels in the base case compared to the results of the model can be associated with the activities related to CCS platforms and the hydrogen plant.

Though the outcomes are not necessarily comparable, they may suggest important differences in activity demands rather than a direct one-to-one confirmation. Since the future scenario encompasses expanded activities related to the larger OWFs and other offshore facilities such as the hydrogen plant and CCS platforms, the increase in projected requirements can reasonably be expected due to the greater complexity, frequency, or duration of operations needed in the future. This does not necessarily indicate an issue with model accuracy but rather reflects the operational intensity anticipated in the future case relative to the current baseline. Therefore, even if model results exceed current figures, the discrepancy can be justified as a logical extension of the more extensive future demands. There remains considerable research to be conducted regarding hydrogen platforms, particularly in determining the feasible capacity of such plants. The current assumptions, including the daily maintenance activities — where a vessel is sent to each platform every day throughout the year — are still subject to further evaluation and debate.

VII. Verification

The stability of the model's outcomes can be evaluated by systematically adjusting key variables and the model's behaviour can be explored under different conditions. Key variables of this model include the Maximum Duration of Use (MDU) of the vessels, along with the specific durations of the activities. Multiple elements of the model are affected when the charter period of an SOV or an HLV can be extended from one week to two weeks. A higher MDU not only allows more activities to be completed within a single route but also reduces the number of routes that can be assigned to a vessel within a given month. Note that this scenario can only be applied to SOVs and HLVs, as the MDU for CTVs is only one working day and can not be extended to last longer than one working day.

Another key factor in the model involves the activities, their durations, and their respective quantities. Ongoing research is still exploring the full potentials and capacities of both Offshore Wind Farms (OWFs) and Hydrogen Power Plants (HPPs). Current wind farms in the North Sea Region generally consist of turbines with capacities ranging from 11 to 14 MW [8]. While the capacities for Hollandse Kust West have been established for their implementation in 2025, the capacities for IJmuiden Ver remain undetermined. Given the uncertainty surrounding the size of the IJmuiden Ver wind farm, multiple scenarios are explored in this analysis. Here, two scenarios are considered to address this uncertainty. Larger capacities for the turbines of IJmuiden Ver are considered with capacities of 16 and 18 MW per turbine, resulting in a wind farm size of 250 and 223 turbines, respectively.

In addition to the uncertainty surrounding the total capacity of IJmuiden Ver, there is also a lack of consensus among stakeholders regarding the total capacity of the offshore hydrogen plant. Various stakeholders are evaluating hydrogen capacities ranging from 4 to 8 GW, with some, like Gasunie, considering even higher capacities. The data input used for the initial calculations assumes a total capacity of 8 GW, comprised of 8 platforms, each equipped with 200 electrolysis cells. Given the uncertainties around this due to ongoing research and pilot programmes, this analysis will incorporate a range of potential capacities, with scenarios considering total capacities of 4 GW and 12 GW. These variations directly affect the demand for preventive maintenance, as an increase in the capacity of Hydrogen Power Plant (HPP) facilities would lead to a larger number of platforms, ultimately resulting in a higher demand for daily maintenance at HPP platforms. This analysis will assess how such uncertainties could influence the operational needs and strategic planning for future offshore maintenance activities regarding the requirements for SOVs and HLVs, as CTVs are not involved in the O&M activities of the offshore hydrogen plant.

Conclusively, this sensitivity analysis primarily focuses on SOVs and HLVs, as none of the scenarios impact activities related to CTVs. This approach adequately tests the model's sensitivity, as analyzing these vessel types captures the effects different scenarios have on the overall results. By concentrating on SOVs and HLVs, the model remains robust and responsive to potential operational changes across scenarios.

TABLE XIII
SENSITIVITY ANALYSIS SOV

	Number of Activities					
	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Min. Routes	365	-2.7%	-33.4%	+33.2%	-2.2%	-1.1%
Min. Dist	365	-2.7%	-33.4%	+33.2%	-2.2%	-1.1%
Min. Ves	365	-2.7%	-33.4%	+33.2%	-2.2%	-1.1%
	Number of Routes					
	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Min. Routes	54	-46.3%	-16.7%	+16.7%	-2%	0%
Min. Dist	55	-45.5%	-16.4%	+16.4%	-4%	0%
Min. Ves	54	-46.3%	-16.7%	+16.7%	-2%	0%
	Number of Vessels					
	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Min. Routes	14	+7.1%	-14.3%	+14.3%	0.0%	0.0%
Min. Dist	15	+6.7%	-13.3%	+13.3%	-6.7%	0.0%
Min. Ves	14	+7.1%	-14.3%	+14.3%	0.0%	0.0%
	Total Distance Travelled					
	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Min. Routes	1619.9	-46.1%	-0.0%	-0.0%	-6%	0%
Min. Dist	1619.9	-46.1%	-0.0%	-0.0%	-6%	0%
Min. Ves	3192	-40.6%	-0.0%	-0.0%	-4%	15%

The reduction to 250 turbines represents a roughly 12.5% decrease in wind farm size compared to the initial 286 turbines, while a reduction to 223 turbines marks a decrease of about 20%. The latter introduces a more significant impact as shown in Table XIII, as it results in fewer visits to IJmuiden Ver. These changes in wind farm size do not produce a linear effect on the number of activities, routes, vessels, or total distance travelled. The smaller scale of the IJmuiden Ver wind farm appears to reduce the number of activities, routes, and vessels by less than 5%, and decreases the total distance travelled by less than 10% in the minimization of routes and distance. This reduction is primarily due to the activities at IJmuiden Ver being fully supported by SOVs, making the wind farm's size a key factor in the sensitivity analysis of SOV usage.

Extending the MDU for SOVs from one week to two, as well as the scenarios addressing the capacities of offshore hydrogen plants, exhibit more significant changes in the model's results. Across all three objective functions, a reduction can be observed in the number of activities. This can be attributed to the fact that activities with a duration longer than the MDU are now being divided into fewer segments to comply with the extended MDU. As the total number of routes decreases when the MDU is extended, the number of required vessels increases. The detailed results reveal that the number of routes per base is reduced by half, except for those assigned to the IJmuiden Base. Under the original MDU of one week, a single vessel could be allocated to four routes per month. With the extension of the MDU to two weeks, however, each vessel can now only be assigned to two routes per month. As a result, even though the number of routes is halved, the same number of vessels is still required on a monthly basis for most bases for all other bases except the IJmuiden Base, as fewer routes are being serviced by the same number of vessels. The number of routes assigned to IJmuiden, however, remains unchanged despite the reduction in routes, leading to a doubling of vessels required to service the same number of routes. This explains the overall increase in vessel demand following the extension of the MDU. A detailed analysis of the results reveals that the routes departing from IJmuiden exclusively serve wind farms, which are unaffected by the extended MDU, as they must be visited once per month regardless of the maximum duration of use limit. Overall, despite the increase in the number of vessels, the reduction in the number of activities and the number of vessels also leads to a reduction in the total distance travelled.

TABLE XIV
SENSITIVITY ANALYSIS HLV

	Number of Activities					
	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Min. Routes	114	-36.8%	-21.1%	+21.1%	0.0%	0.0%
Min. Dist	114	-36.8%	-21.1%	+21.1%	0.0%	0.0%
Min. Ves	114	-36.8%	-21.1%	+21.1%	0.0%	0.0%
	Number of Routes					
	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Min. Routes	99	-45.5%	-17.2%	+17.2%	0.0%	0.0%
Min. Dist	99	-45.5%	-17.2%	+17.2%	0.0%	0.0%
Min. Ves	99	-45.5%	-17.2%	+17.2%	0.0%	0.0%
	Number of Vessels					
	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Min. Routes	26	+7.7%	-19.2%	+15.4%	0.0%	0.0%
Min. Dist	26	+7.7%	-19.2%	+15.4%	0.0%	0.0%
Min. Ves	25	+8.0%	-16.0%	+16.0%	0.0%	0.0%
	Total Distance Travelled					
	BASE	MDU	4 GW	12 GW	223 WTB	250 WTB
Min. Routes	2013.5	-38.1%	0.0%	0.0%	+0.0%	+0.0%
Min. Dist	2013.5	-38.1%	0.0%	0.0%	+0.0%	+0.0%
Min. Ves	7215.8	-67.0%	-57.6%	+29.2%	0.0%	-0.0%

The results for the sensitivity analysis of Heavy Lift Vessels in Table XIV show a 0% difference in the different sizes for the IJmuiden Ver windfarm. This can be explained given the fact that an HLV is used on offshore windfarms with an occurrence rate of 0.29 times a year, as presented in Table I, meaning that its required frequency for wind farms is even lower on a monthly basis. As a result, reducing the number of turbines in a wind farm has little impact on the outcomes across the various objective functions.

As with the sensitivity analysis conducted for SOVs regarding the extension of the MDU from one week to two, the number of activities decreases here as well, due to longer tasks being divided into fewer but larger portions. This reduction in activities directly leads to fewer routes, as fewer tasks need to be completed and each route can now fulfill a larger number of activities. Despite this decrease in routes, the number of vessels required still increases, as was also observed in the case of the SOVs. The underlying reason is similar: while activities and routes are reduced at each base following the extension of the MDU, the number of vessels remains unchanged, since fewer routes can be assigned to each vessel. However, for the IJmuiden base, both the number of activities and routes remain constant, resulting in a higher vessel demand. This is because the activities tied to IJmuiden are all associated with OWFs, and thus remain unaffected by the extension of the MDU.

For the Operations & Maintenance activities of offshore hydrogen plants, HLVs are exclusively used for cell replacement. Each platform contains 200 cells, meaning that changes in plant capacity directly and linearly affect the number of activities requiring HLVs. This linear relationship is evident in the corresponding columns for 4GW and 12 GW capacities in Table XIV, where the percentage values for a 4 GW and 12 GW plant mirror each other in terms of the number of activities and routes. Although the percentage change in the number of vessels does not follow the same mirrored pattern across the different objective functions, the results remain consistent and logical when aligned with other values. Regarding travel distances, there are no variations when minimizing routes or distance, as the additional travel is only between the Island base and the HPP, with a distance of zero. However, when minimizing vessel numbers, routes are allocated to different bases, leading to a shorter total distance for a 4 GW capacity and a longer distance for a 12 GW hydrogen capacity.

VIII. Discussion

By integrating the operational and maintenance needs of various facilities that have not been implemented yet, this research provides a foundational basis that may incentivize operators to consider more integrated policies for vessel fleet management in offshore environments. The findings of this study indicate that the operational phase of HPPs will likely require more intensive maintenance activities, especially regarding daily maintenance within the first few operational years. The activities corresponding to the maintenance of HPP may alter standard vessel allocation strategies compared to the current operations where SOVs are primarily used for offshore wind farms and oil and gas platforms.

For the Service Operation Vessels (SOVs), the model estimates a fleet of 15 - 16 vessels, substantially higher than the base scenario of seven vessels per month on average. This discrepancy may be explained by the model's approach of scheduling all maintenance activities within a single month, including those typically planned for once a year or even less frequently. Additional contributing factors include the size of the hydrogen power plant (HPP) platforms and its high operational demands, which require more SOVs, as well as the model's restriction of vessels to single bases rather than allowing inter-base allocation, as does occur in the base case. Additionally, some activities at IJmuiden Ver technically require only a CTV. However, due to the considerable distance from any of the bases considered, an SOV is assigned to this location instead. The results indicate that three SOVs are necessary to cover the activities at the IJmuiden Ver wind farm. Nevertheless, assigning a single SOV with daughter vessels to support these tasks could also suffice, as the presence of the SOV itself is not strictly required for all activities.

The model results also indicate a need for 25 to 26 HLVs or to complete the corresponding activities within a one-month timeframe. This high estimate may appear excessive, particularly given the high chartering costs associated with these vessels. This requirement likely stems from the model's deterministic scheduling, which seeks to ensure all major activities are fulfilled within a single month. A more realistic scheduling approach would distribute these tasks across an extended timeframe, better aligning with resource availability and cost constraints, suggesting the model's outputs reflect a highly conservative scenario that could be adjusted for operational feasibility.

Limitations and Challenges

This research model simplifies offshore operations due to data and computational limits, omitting factors like technician capacity and simultaneous task handling, which restrict vessel efficiency. The model assumes sequential operations and doesn't factor in equipment handling times, which would add time-based constraints and complexity. A lack of data on current Crew Transfer Vessels (CTV) and Heavy Lift Vessels (HLV) prevented thorough validation, as only Service Operation Vessel (SOV) data, primarily from oil and gas, was available, differing significantly from future offshore facility demands.

IX. Conclusions and Further Research

This research explores a future North Sea Region scenario for the European Green Deal's net-zero greenhouse gas emissions target, focusing on the Hub West and its three key offshore facilities: Offshore Wind Farms (OWFs), Carbon Capture Storage (CCS), and Hydrogen Power Plants (HPPs). Currently, only OWFs are operational, requiring Crew Transfer Vessels (CTVs) for routine servicing and minor repairs, Service Operation Vessels (SOVs) for major repairs, and Heavy Lift Vessels (HLVs) for major component replacements. For CCS, an SOV is expected annually for maintenance and up to 20 days of corrective tasks, with HLVs for six-year painting cycles. Similarly, HPPs will likely require daily SOV visits initially, with HLVs for periodic replacement of electrolysis cells every 6-10 years.

Given the problem structure and linked objectives, an exact solution method was selected. Mixed-Integer Linear Programming (MILP), widely utilized in optimizing Vehicle Routing and Scheduling Problems, was chosen as it offers an effective way to optimize the logistics involved while generating strategic insights that are applicable over extended periods. The mathematical model developed to address this problem incorporates both route and vessel constraints, generating a set of feasible routes that encompass all required activities for each location. Routes for CTVs are generated on a daily basis, while those for SOVs and HLVs are created on a monthly basis, reflecting differences in their Maximum Duration of Use (MDU).

To determine an optimal vessel fleet mix, it is essential that logistics service providers stay well-informed about the decisions and developments made by other stakeholders involved in the maintenance activities of offshore facilities. These stakeholders play a critical role in defining facility capacities and operational needs, which directly impact vessel requirements. In an assumed scenario where offshore wind farms will have a maximum turbine capacity of 14

MW each and the hydrogen plant will operate with eight platforms of 1 GW each, logistics service providers can consider an initial upper bound of 27 CTVs, 14 SOVs, and 26 HLVs to meet operational demands. However, these estimates represent a conservative upper limit; the actual number of vessels required could be reduced when accounting for (1) the capacity constraints of technicians on each vessel, keeping in mind a drop-off and pick-up system, (2) the consideration of vessel overlap, where two vessel types can be used simultaneously and (3) stochastic elements like weather uncertainties, cost variability, and delays to improve the model's robustness. This approach would enable planners to develop risk-mitigation strategies and adjust for disruptions, while also capturing potential cost fluctuations in ad-hoc or emergency maintenance. Ultimately, a stochastic model would enhance strategic decision-making for complex offshore operations.

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