A FACILITY LOCATION MODEL FOR UNCREWED SURFACE VESSELS IN THE MARITIME SURVEY INDUSTRY

The impact of remote and autonomous operations on logistical decision-making regarding harbor facility locations.

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to obtain the MSc. Transport, Infrastructure & Logistics
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TU Delft Delft University of Technology

FUGRO

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THE IMPACT OF REMOTE AND AUTONOMOUS OPERATIONS ON LOGISTICAL DECISION-MAKING REGARDING HARBOR FACILITY LOCATIONS

by

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Associated codes and models are available at
https://github.com/lpmoorlag/Thesis-Final.

Delft University of Technology

A ship in harbor is safe,
but that is not what ships are for.

William Shedd - American Theologist

EXECUTIVE SUMMARY

INTRODUCTION

The maritime industry is preparing for a future where human presence is no longer required on board of ships. The shift from having a crew on board to having land-based technicians manage ships remotely will revolutionize maritime operations. These technological innovations involving autonomy and remote control are considered to be critical to achieve the industry's ambitions to realise carbon footprint reduction, faster decision making and increased workforce well-being. However, the incorporation of autonomous vessels into the existing logistical models is a challenging process as the smaller vessels have particular characteristics in terms of size, operability and endurance. As a result of their smaller size, uncrewed surface vessels (USVs) carry less fuel and have an approximated endurance of mere days instead of months. These vessel attributes consequentially introduced the unprecedented logistical opportunities and challenges that initiated the following research question:

> *How to determine the optimal locations for harbor facilities that maximize the profit of remotely operated vessels servicing maritime infrastructures in the North Sea?*

This research addresses a non-standard facility location problem (FLP) arising in the maritime industry as a result of the limited endurance of remotely operated vessels. The problem that is addressed in this research can be viewed as a *multi-period max profit facility location problem*, in which the vehicles are survey vessels, the customers are offshore assets, and the depots are harbors. This research seeks to locate a number of uncapacitated facilities and assign a heterogeneous fleet of remotely operated vessels and traditional vessels to the located facilities in order to serve the inspection demand nodes. The facilities serve as sites where vessels can refuel and accommodate crew changes. From the selected harbors, uncrewed surface vessels must be able to reach the asset locations of potential clients at the occurrence of an inspection request.

Each remotely operated vessel makes several *one-to-one* trips from a facility location to a demand point and back until the operability limits are met. Each traditional vessel visits demand nodes via centroids from which various inspections can be performed before having to return to harbors for crew changes. The problem involves multiple offshore assets, each of which requires regular service from survey vessels. The goal is to determine the desired harbor locations for the vessels so that all services are fulfilled and the total profit is maximized. Other constraints that must be considered include vessel operability constraints, range constraints and constraints related to the routing behavior of the various vessel types. The planning period is yearly and regarded in multiple non-consecutive time indices.

Compared to other maritime operations studied in the literature, this model is characterized by several non-standard features: the vessel fleet is heterogeneous, vessel performing *one-to-one* trips and vessels traveling through centroids are compared simultaneously, a multi-period timeframe is considered, demand nodes develop over time and possible locations for facilities develop over time. Although some of these non-standard features have already been covered in the available literature, to the best of my knowledge, no previous research has studied facility location problems in the maritime environment considering a heterogeneous fleets that combines the distinctive routing behavior of centroid-like hubs and drone-like *one-to-one* trips simultaneously.

This research assumes that all demand nodes have a predictable recurring and constant demand with a fixed profit that can be collected by each of the vessel types. Furthermore, the model assumes all inspection requests are tendered to a single company. The influence of weather conditions is limited to an approximated number of workable days per vessel type per year and does not affect the travel speed, operability or range of the vessels. Perfect weather conditions are assumed during these operable days.

A mixed-integer linear programming (MILP) model is formulated with the objective of maximizing profits through the allocation of various vessel types at possible harbor locations while explicitly incorporating operability and range constraints. Based on this model, several recommendations will be made regarding the locations of robodocks, the according fleet size & mix and the design of future vessels. The model will be validated numerically using real data provided by geo-data company Fugro. Several analyses are performed to determine critical vessel attributes and strategic harbor locations. Such insights are key considerations for Fugro in the ongoing development of its USV fleet.

RESULTS

Several conclusions were drawn from the outcomes of the simulations. The most significant vessel characteristics are *range* and *operability* as well as *operational costs*. Operational costs are likely to reduce when multiple USVs are deployed and remote crews can oversee several inspection jobs simultaneously. The importance of range and operability should be considered in the light of the North-Sea topology. The allocation of vessels is to a large extend dependant on the inspection jobs in the northern regions of the North Sea. These are further secluded and only within reach from few harbors. Therefor, altering USV characteristics that benefit the accessibility of these isolated assets have a considerable impact on the performance of the overall system. However, in reality these secluded inspection jobs in the northern regions are subject to severe weather conditions and consequentially not as attractive for USV operations as the model suggests. When validated against real world observations, the indicated importance of said vessel characteristics turn out to be disproportionately affected by the generalization of operability assumptions in their disregard of geographically specific weather conditions.

The most profound conclusion of this research is the interchangeability of precluded harbor facility locations. When determining the optimal harbor locations, it turns out that many different combinations of harbors and vessel fleets can approach the optimal profit. Given that all demand nodes are being serviced by a single company, a tremendous increase in the complexity of the model is perceived in the many different ways in which many different vessels can respond to precluded facilities from other neighbouring facilities. Consequentially, the effective attribution of vessels to another set of harbors will be able to approach a similar profitability from the given workscope. Hence, the determination of a facility location is only as good as the allocation of the fleet that will be located at these facilities. As a result, the relative importance of a single facility in the final set of located harbor facilities is limited when considering the exhaustive set of nodes, harbors and vessels of the entire North-Sea.

Additionally, transits from harbors to demand nodes were found to play a minor role in profit returns compared to operations at the assets. This is a rather confronting outcome considering the limited attention paid to the actual operations of asset inspections in this research. However, this outcome is reasonably intuitive: whereas facility location problems are commonly applied for distribution centres or drone deliveries where services at the demand are largely trivial, in this research the demand nodes play a significant role throughout the entirety of operations. In stead of delivering packages or goods, a multi-day service is being performed at the demand nodes. In contrast to the facility location problem in this research, where the complexity lies within the harbor locations, transit times, transit speeds and vessel characteristics, while the operations at the nodes are largely overlooked. This is a disproportional oversimplification of the observed system in the sense that the core of the activities, and actually the longest time of the operations is not spent in transit but rather *at* the demand node.

All in all, this research provides a first piece of reflection regarding MIP problems for autonomous operations in the maritime industry that can be addressed by future researchers studying this topic. In short, my research has pointed out that the complexity of USV operations in the maritime industry is difficult to capture within an acceptably sparse facility location problem. Furthermore, future researchers are advised to consider the demand nodes in more detail. In fact, vessels spent most of their time performing operations at the inspection nodes, rather than in transit. Additionally, given the specific inspection requirements related to each job, their irregular inspection demand and the developments of new assets in the future, it will be interesting to address the stochasticity in the operational phase.

The final advise regarding the complexity of the model results from the application of traditional vessel routing via centroids. The routing via these centroids allows the model to make calculated decisions between traditional vessel and USVs, and allows the final outcomes to be validated with real world data. However, in trying to incorporate an important part of the complexity of the system, the centroid routing is an oversimplification in itself that makes the simulations extensively cumbersome and the comparing of results more ambiguous. That being said, the validity of the model as a whole was reasonably adequate. Despite long running times and heavy mathematical computations, the simulations were able to provide intuitive results that allowed this research to draw relevant conclusions regarding the future development of remote operations.

PREFACE

Before you lies the final product that marks the completion of my journey at the Technical University of Delft. This report is the final part of the graduation program to obtain the Master degree in Transport, Infrastructures & Logistics at the faculty of Civil Engineering.

This research was conducted in collaboration with the geo-data company Fugro. I have been extremely lucky to collaborate with Lex Veerhuis and Ivar de Josselin de Jong during the entirety of the project. Through every step of the research I was able to count on their support; from narrowing down the development of this technology into a suitable research question, to discussing insightful topics regarding the parameters of the model. I want to express my gratitude and appreciation for the personal supervision of Lex Veerhuis; for encouraging me throughout the process, helping me focus on the research goal and keeping me engaged through several site visits, including a business trip to Aberdeen. Lastly, I would like to thank all the friendly people at Fugro for providing me with a warm and open workspace.

Coming from a family of inland waterway shippers, the decision to study a topic within the maritime industry was inspired by my roots. I am thankful for the unique opportunity I have been given to explore the future of remote and autonomous operations and witness the first steps of this new technology within the maritime environment. Ultimately, this research has encouraged me to pursue my interests by starting a career in the maritime industry, following in the footsteps of my father, grandfather and great-grandfather.

Finally, I want to thank the members of my graduation committee for their time and commitment. They provided thorough support and valuable feedback, and directed me in many new and inspiring directions. I would like to thank professor Maknoon for his fast judgements and endless suggestions to improve the model. I would also like to thank professor Jiang for her supervision and guidance during this research and for always being available as a sparring partner to discuss an appealing and convincing storyline. Lastly, I want to thank the chair of my committee, Prof. Dr. Rudy Negenborn, for his direct and honest feedback that helped shaping this final deliverable. It was a great experience to be able to host everyone at the Fugro office as soon as the COVID-19 restrictions eased and it was a pleasure to work with you all.

Lucas Moorlag
Delft, August 2022

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INTRODUCTION

You are either the one that creates the automation,
or you are the one getting automated.

Tom Preston - Founder of Github

RESOUNDING in the dramatic words of Tom Preston, the impact of automation technologies has been inconceivable. Following the rapid developments in the automotive industry, the maritime industry is preparing for a future in which human presence is no longer required in the logistical chains or on board of ships [1]. The transition from having a crew on board to having land-based technicians manage ships remotely will revolutionize the global supply chain by introducing new services and more efficient schemes [2].

Automated operations dictate the world around us, optimizing anything from social-media engagement to self-driving vehicles, and has the potential to revolutionize global transportation systems, infrastructures and logistics. The latest technologies in the maritime industry include uncrewed vessels and automated refueling stations, so called *robodocks*. An offshore environment consisting of uncrewed vessels and autonomous docking platforms will fundamentally change the maritime industry and consequentially introduce unprecedented logistical challenges.

In order to determine the optimal locations for autonomous docking platforms in the logistical network of the changing offshore environment, this research will cover the application of a facility location problem (FLP). This first chapter covers the state-of-the-art of remote and autonomous operations and the uncertainties regarding autonomous maritime operations. After, a discussion of the existing knowledge gap will introduce the research question that is studied in this thesis.

1.1. BACKGROUND INFORMATION

This section covers the relevant background information to provide an understanding of the critical topics discussed in this research. First, the state-of-the-art in remote and autonomous operations will be discussed, followed by its applications in the maritime industry, which will be the main focus of this research. Finally, an overview of the uncertainties regarding the developments of remote applications in the maritime industry will introduce the research gap and the consequential research questions.

1.1.1. REMOTE AND AUTONOMOUS OPERATIONS

Automation is the application of machines to tasks once performed by human beings or to tasks that would otherwise be impossible [3]. *Big Data*, *Deep Learning* and the *Internet of Things* drive this strong technology push [1]. As the world has gotten familiar with remote working and contactless interactions during the COVID-19 pandemic, remote and autonomous operation technologies have rapidly emerged for commercial and personal use [4]. While lawn mower and vacuum cleaning robots have been around for a while, the recent developments in sensors, telecommunications, and computing have sparked interest in an extensive range of autonomous vehicles such as self-driving cars, aerial drones and subsea robots [2]. Remote operations are widely applicable and can be found across industries ranging from military purposes to warehouse logistics, firefighting, surveillance, delivery services and mining [[5];[6]].

The current state-of-the-art regarding artificial intelligence for automation control of ground vehicles is predominantly applied under controlled circumstances in closed environments such as ports, mines or households [7]. Until now, tech giants including Google, Tesla and Uber have had limited success with autonomous cars outside of environments with substantial predictability and structure. Whereas aerial drones and self-driving cars have been prominently featured in recent headlines, relatively little public attention has been paid to uncrewed surface vessels (USVs). Despite this lack of media attention, USVs have attracted research interest for their applicability in scientific and industrial sectors, and great emphasis has been placed on USV intelligence and autonomy [8]. In fact, while the roads are still considered a complex space with excessive unpredictability for vehicles to operate comfortably outside of narrow restrictions, USVs have already proven to be significantly successful in open waters outside of closed environments[1]. Despite the lack of public attention, the attainability of uncrewed and autonomous vessels is much more solvable and no longer a question of *if*, but a question of *when* [9].

The answer: *now*.

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[1] Appendix I: AMS Institute: Amsterdam gets world's first fleet of autonomous boats.

1.1.2. AUTONOMY IN THE MARITIME INDUSTRY

Besides the introduction of small cargo boats in city centres, fully electric and autonomous oceangoing container vessels are under construction at this very moment. The Yara Birkelenad has recently embarked on its first autonomous journey on coastal waters. It is not just the voyage itself that will be autonomous in the future. Using electric equipment and cranes, discharging and loading can be done automatically [10]. Berthing and unberthing will not need human intervention or require special implementations dockside because the Yara Birkeland will be equipped with an automatic mooring system [[11]; [12]]. The vessel's self-propelling capability is guided by GPS, radar, cameras and sensors so that the electric ship can navigate itself around other boat traffic and also dock at recharging stations on its own.

From city centres to offshore environments, applications for USVs are in abundance. Environmental monitoring, search and rescue, hydrology surveying, and national security applicability have all led to a strong demand for the development of innovative uncrewed surface vessels from commercial, scientific, and military communities. [[13]; [14]; [15]; [16]; [17]; [18]; [19]]. Whereas self-driving cars are still under development, autonomous ships are already operational and even developing autonomous docking. In the words of Levander [20]: forget autonomous cars, autonomous ships are here.

The rapid developments regarding uncrewed and autonomous vessels in the maritime sector are aimed to create vessels that are safer, more efficient, and cheaper to operate [2]. In terms of safety, 75 to 96 percent of marine accidents result from human error, often a result of fatigue [21]. Remotely controlled and autonomous ships would reduce the risk of such mistakes and hence the risk of collisions. A smaller vessel with no crew onboard will consequently have a lower risk of impact to crew members, other ships or structures, and the ship itself.

Another advantage of remotely controlled and autonomous ships comes from their ability to be designed with a larger cargo capacity and lower wind resistance [2]. With no crew to accommodate, certain features of today's ships, including the deck house, the crew quarters, and elements of the ventilation, heating, and sewage systems can all be eliminated. This will facilitate more efficient designs to make the ship lighter and sleeker, cut fuel consumption and reduce operation and construction costs.

Finally, intelligent ships will provide owners and operators with a way to respond to the growing shortage of people who have the requisite maritime skills. This seems counterintuitive at first; with more and more mechanical and electronic systems on board, ships are becoming increasingly complex, requiring skilled technicians to keep them working. However, through remote operations, productivity can be majorly improved as crew can be placed on-shore and perform jobs for several vessels form the same location without requiring intermediate travel between the ships. At the same time, seafaring as a career is growing less attractive, with fewer people from developed nations wanting to spend consecutive weeks or months away from home and family. Remote and autonomous operations could facilitate the transfer of jobs requiring high levels of education and skills to ports of call or to operations centers on land, making such careers more interesting to young people entering the industry [20]. Technical and digital innovations involving autonomy and remote control are considered to be the key aspects in achieving the industries ambitions in the light of carbon footprint reduction, faster decision making and increased workforce wellbeing [22].

Figure 1.1: Advantages of remote and autonomous operations

In conclusion, uncrewed vessels result in lower operational costs and eliminate on-board crew cost, risks associated with human error and threats to crew safety [23]:

- USVs can be operated with fewer and remote personnel, which means lower commuting costs while increasing workforce efficiency [24].
- Having less people in the field reduces the risk of human injury and contributes to social benefits of a more regular workload for staff in the field and the staff operating the vessels remotely.

These substantial improvements drive the rapid developments in the field of remote and autonomous vessels that will revolutionize maritime operations. However, although a bright future is expected for remote operations, there are still many uncertain factors that need to be overcome.

1.1.3. UNCERTAINTIES

Driven by the benefits described in the previous section 1.1.2, the maritime industry finds itself on the brink of implementing remote and autonomous vessels into its fleets. There may be a considerable first-mover advantage to the players that are able to adopt automated operations [25], albeit uncertainty prevails as the introduction of remote vessels has only recently started by merely a handful of operators. Although remotely controlled ships can be designed without the requirements of crew related features and allow for significantly smaller hulls, the incorporation of autonomous vessels into the logistical models for existing fleets is a challenging process as the smaller vessels have completely different characteristics in terms of size, work-scope, operability and range.

First of all, smaller USVs cannot carry the same equipment as large traditional vessel, limiting their work-scope. Additionally, smaller vessels cannot withstand the same levels of wave heights. This limits their window of operation to shorter periods with lower swells. As a result of their smaller size, USVs carry less fuel and consequentially have an approximated endurance of mere days instead of several months. On top of that, the already limited range is highly unpredictable as the specific designs are unprecedented and their relative performance is still unknown. Similar to the operability, the endurance of the USVs is heavily affected by environmental conditions like wind and currents. Currently, the unpredictability of the USV range has consequences in twofold:

1. It is uncertain which vessel designs will prove most suitable to perform offshore operations. Hence, different types of USVs with unique characteristics will be added to the fleet over time.

2. The development of remotely operated vessels goes hand in hand with the development of the required infrastructure to support the vessels. The introduction of technologies like autonomous docking and berthing catalyses the demand to determine efficient facility locations for the USVs. At the logistical heart of the remote operations, automated docking stations will play a crucial role.

Not only vessels and harbors are undergoing technological advancements, the offshore environment in which they operate is also undergoing vast changes. The offshore energy industry is undergoing a major transition from oil & gas to sustainable windfarms, floating solar panels and hydrogen plants [26]. The fishing industry is developing an infrastructure for aquafarming and environmental monitoring, and coastal resilience is high on the agenda of governments[27]. Even traditional seafaring routes are set to change due to the booming oversea container shipments as a result of accelerating e-commerce. The smelting of polar ice caps due to climate change might even introduce a Transpolar Sea Route [28]: a maritime highway that would outperform the Suez route [29]. At the same time, regulations by the International Maritime Organization (IMO) are pushing ambitious sustainability targets for the entire maritime industry.

As a result of all these developments, the offshore network of the future will have both an increasing amount of uncrewed vessels and autonomous docking facilities as well as a progressively diverse workload. This will fundamentally change the maritime industry and consequentially introduce unprecedented logistical opportunities and challenges. These are the driving challenges behind this research.

1.1.4. THE RESEARCH GAP

Much logistical research in maritime operations and remote operations has been done regarding vehicle routing problems, fleet size & mix optimization and other location routing problems to enhance efficiency. Uncrewed vessels are less prevalent in the media than drones and self-driving vehicles. This is also reflected in the amount of available literature regarding the logistical challenges introduced by USVs when compared to charging infrastructure facility problems for aerial drones and self-driving vehicles. While there is substantial academic literature to determine efficient locating of facilities and routing of vehicles, no research was found to study facility location problems regarding maritime operations, yet considering the limited range of the USVs, the harbor locations will become critical components for the efficiency of offshore operations.

Research regarding the performance of facility locations is crucial to overcome the logistical challenges that are introduced by the combination of new vessels, new docking stations and new offshore infrastructures. The manyfold of uncertainties as previously described in section 1.1.3 require a thorough analysis to determine optimal harbor locations in the future offshore network. The long term investments related to the research and manufacturing of new types of USVs and docking stations emphasise the iterative and dynamic nature of the problem. The sunk costs attributed to preceding decisions regarding the acquiring of vessels and robodocks have a remaining impact on the future strategy of the robodock locations. Considering the importance of efficient facility locations to accommodate the rapid development of remote and autonomous technologies and the associated uncertainties, this research explores how an efficient network of robodocks for a remotely operated fleet of USVs can be designed. This research aims to find an approach to make informed decisions on harbor facility locations for robodocks to accommodate USV operations. In a broader sense, the maritime application of facility location problems as studied in this research can be treated as an addition to existing research in the field of facility location problems associated with remote operations such as aerial drones and robotaxis. The facility location problem will be covered in more detail in chapter 2, The Literature Review.

1.1.5. THE CASE STUDY

To determine an approach to establish strategic locations for charging facilities, location routing problems will be studied based in the context of the real robodock location problem faced by the geodata service provider Fugro in the management of its Uncrewed Surface Vessels in the North Sea. The goal of this case study is to determine the optimal locations for robodocks in combination with according fleet size & mix in order to serve the current and future offshore assets. The outcomes of the case study will be analysed to make accurate recommendations regarding the robodock locations and USV fleet to accomodate Fugro's remote and autonomous operations.

1.1.6. THE RESEARCH SCOPE

This research is conducted in order to obtain the final 30 EC in completion of the master degree Transport, Infrastructures and Logistics at the Delft University of Technology. Considering the limited time and resources, several simplifications were made to narrow down the research question into a manageable, yet justifiable scope:

- The addressed maritime survey industry is limited to assets within the North-Sea.
- The assets are represented by demand nodes that have a recurring and constant demand with a fixed profit that can be collected by all the vessel types.
- The future demand is addressed through several sets of nodes in different time indices of 5 to 10 years. These represent distinct scenarios in terms of changes in demand over a given period and not consecutive single years.
- The amount of days it takes to complete inspection jobs are fixed to the type of vessel that executes the inspection.
- The characteristics of the designs for only two types of uncrewed surface vessels are taken into account and only one type of traditional survey vessel is considered.
- The traditional survey vessels are routed through centroids in order to approximate and compare their distinct routing behavior to that of USVs.
- The influence of weather conditions is limited to an assumed number of workable days per vessel type per year and does not affect the travel speed, operability or range of the vessels.
- All inspection requests are tendered to a single company.

1.1.7. SCIENTIFIC CONTRIBUTIONS

Integrating a heterogeneous fleet of traditional vessels based on routing via centroids, in combination with a fleet of USVs that follow the drone-like behavior of *one-to-one* trips will provide a simultaneous assignment of vessels to demand nodes To the best of my knowledge, no previous research has studied facility location problems in the maritime environment considering a heterogeneous fleets that combines the distinctive routing behavior of centroid-like hubs and drone-like *one-to-one trips*.

In this research, a new variant of the FLP is introduced, based on a real harbor locating problem faced by geo-data company Fugro in the development of its future USV fleet and robodock assembly. The problem setting is described as follows.

Each remotely operated vessel makes several *one-to-one* trips from a facility location to a demand point and back until the operability limits are met. Each traditional vessel visits demand nodes via centroids from which various inspections can be performed before having to return to harbors for crew changes. The problem involves multiple offshore assets, each of which requires regular service from survey vessels. The goal is to determine the desired harbor locations for the vessels so that all services are fulfilled and the total profit is maximized. Other constraints that must be considered include vessel operability constraints, range constraints and constraints related to the routing behavior of the various vessel types. The planning period is yearly and regarded in multiple non-consecutive time indices.

Compared to other maritime operations studied in the literature, this model is characterized by several non-standard features:

1. the vessel fleet is heterogeneous.
2. vessel performing *one-to-one* trips and vessels traveling through centroids are compared simultaneously.
3. a multi-period timeframe is considered.
4. demand nodes develop over time.
5. possible locations for facilities develop over time.

Although some of these non-standard features have already been covered separately in the available literature, to the best of my knowledge, no previous research has studied facility location problems in the maritime environment considering a heterogeneous fleets that combines the distinctive routing behavior of centroid-like hubs and drone-like *one-to-one* trips simultaneously.

1.1.8. LIMITATIONS

The proposed model creates a visual representation of the vessel routes and harbor locations, which has proven to be helpful for the validation of the model behavior and intuitively communicating the model behavior. However, they also point out some shortcomings in relation to actual marine traffic.

1. The routing decisions are not based on real marine traffic.

The model considers the vessels to navigate in a straight line through open water, like drones that do not follow a fixed network but rather fly directly through continuous space. However, in reality, the North-Sea coastlines display some curves that do not always match the straight navigation behavior of the vessels. In some instances this results in the vessels covering sizeable distances over land. Consequentially, this oversimplification drives the optimal outcome of the model in a direction that is infeasible in the real world.

2. No specific equipment requirements for assets inspections will be considered. Every vessel will be able to execute the same operations at each demand node.

Other than oversimplifying the types of infrastructures that are inspected, neither does the model does not take different types of inspections into account. Different types of vessels can deploy different types of inspection equipment. Each having its own characteristics in terms of operability, speed of operations. Ignoring the fact that not every vessel is able to carry the same types of equipment allows each vessel to execute operations at each demand node. Therefor, the relative considerations between vessel assignments are only based on operation time, transit time and related costs.

3. Weather conditions will only be taken into account to a certain extend: a strongly limited number of operable days for the smaller vessels.

As mentioned in the first assumption, the North-Sea can be a rough environment. The vessels have a distinct allowance in regards to wave heights. This means that larger traditional vessels can sometimes continue operations while a smaller USV has to come back into port. This means in bad weather circumstances the smaller vessels will not be leaving port for inspections while the traditional vessel might. The attainment of the *yearly operational days* that are considered per vessel per year therefor heavily depend on the timing of extreme weather events.

Other critical limitations resulting from the assumptions are:

4. The scope is limited to the offshore operations in the North-Sea.
5. No corrective maintenance is taken into account.
6. All demand is tendered to a single party.
7. Demand nodes are split up into windparks or oil & gas platforms. Each with a respectively similar revenue and respectively similar work scope for the operations

1.2. THE RESEARCH QUESTION

The knowledge gap in section 1.1.4 indicates the uncertainty regarding the developments of the facility locations and its effect on the logistical network. The goal of this research is to determine the optimal harbor locations from where a fleet of USVs can serve the inspection demand of offshore inspection demand. In order to attain this goal, an optimization model will be constructed to determine harbor facility locations that will yield the maximum profit over an extended period of time. Hence, the following research question is formulated:

> *How to determine the optimal locations for harbor facilities that maximize the profit of remotely operated vessels servicing maritime infrastructures in the North Sea?*

This research addresses the challenges of strategic decision making in a dynamic environment, considering technological developments that will alter the characteristics of vessels, robodocks and North-Sea assets over time.

1.3. SUBQUESTIONS

In order to provide an answer to the main research question, the following 4 sub questions have been identified. The first sub question covers the conventional location decision problems and the types of methods from the available literature. Building from sub question 1, the second subquestion aims to translate the characteristics of the system components including USVs, harbors and offshore assets into a suitable model. Once an initial static base scenario has been constructed in subquestion 3, subquestion 4 is addressed to understand the dynamic development of the several components overtime and how this will affect the strategic decision making regarding harbor facility locations. The subquestions are described in more detail in the remainder of this section. By answering all the subquestions, relevant conclusions can be drawn to answer the main research question. These questions are aimed to design an approach that can be used for future decision making on charging facility locations in the general field of autonomous logistical operations.

1. What are the critical considerations regarding the available methods to formulate a facility location problem in the maritime environment?

2. What are the unique characteristics of the system components in the offshore service industry?

3. How to develop, verify and validate a facility location model for an initial static base scenario?

4. What is the impact of further developments of the system components in future scenarios on the initial facility location model?

SUB QUESTION 1

What are the critical considerations regarding the available methods to formulate a facility location problem in the maritime environment?

In order to seize the complexity of the problem, a model will be constructed to simplify the environment. First, to explain the choices for specific harbor facility locations, the drivers that affect these decisions must be understood. Therefor, this sub question will consider how similar scheduling or routing problems for remote and autonomous operations and problems in the marine environment are currently dealt with, what the key performance indicators are to determine the efficiency of facility locations and how stochastic demand in a developing offshore environment can be taken into account. In addition, this subquestion aims to provide an overview of what can be learned from available methods of facility location problems in other environments.

SUB QUESTION 2

What are the unique characteristics of the system components in the offshore service industry?

The application of USVs requires a specific model that will be derived from other fields of research, building from sub question 1. Sub question 2 covers the components that will be interacting in the aforementioned model. To answer this sub question, a discussion of the characteristics of USVs compared to other remote vehicles, the locations of critical assets in the future inspection market of the North-Sea and the requirements for harbors facilities that accommodate refueling and maintenance of USVs will be provided. The combined knowledge of subquestion 1 and subquestion 2 will pave the way to accurately implement the system components into a suitable model.

SUB QUESTION 3

How to develop, verify and validate a facility location problem for an initial static base scenario?

The main goal of this research question is to determine the optimal harbor locations from where a fleet of USVs can serve the offshore inspection demand. To attain this goal, an optimization model of a facility location problem will be constructed. Building from the results in sub questions 1 and 2, an initial base model can be constructed by introducing the static mathematical formulations, which will subsequently be implemented in Python.

SUB QUESTION 4

What is the impact of further developments of the system components in future scenarios on the initial facility location model?

In other words, how will the inclusion of a time perspective with future developments of the system components affect the strategic location decisions? The model will have a certain time horizon on which stochastic demand in a developing offshore environment will affect the outcomes of the facility locations. These developments should therefor also be taken into account throughout the modeling phase. The collective outcomes of the model behavior that emerges, will be the result of iterative decisions. This sub question explores the decisions for certain facility locations through verification and validation of the model results in combination with expert interviews to ultimately understand the drivers of the strategic decisions for robodock locations that will be used to answer the main question.

1.4. STRUCTURE OF THE REPORT

This report provides a discussion of the results that were found while answering the sub questions. After which, an answer to the main research question will be formulated. In chapter 2, a comprehensive review of the literature related to maritime operations and facility location problems is discussed. Furthermore, chapter 2 presents the research gaps that are form the foundations of this research. In chapter 3, the methodology for this research is described, including a generic facility location model resulting from the discussion of modeling types. Hereby the first sub question is answered. Chapter 4 illustrates the model design of the system to which the facility location models will be tailored, and discusses its components. This chapter also describes the case study that will be used in this research and formulates an answer to sub question 2. The third sub question is answered in chapters 5 and 6, that describe the tailored mathematical model and the verification tests regarding the model behavior. Thereby sub question 3 is answered. Chapter 7 analyzes the model results. Then, the model outcomes are generalized in a discussion regarding the research method and its limitations in chapter 8, before the main research question is answered in chapter 9. Apart from the conclusion, this final chapter also presents suggestions for further research. In short, the thesis is structured as follows:

- Chapter 1 presents the research background and the structure of the report.
- Chapter 2 provides a comprehensive review of literature related to the maritime industry.
- Chapter 3 presents the methodology regarding to construct a generic facility location problem suitable for the research.
- Chapter 4 covers the model design including the system's components.
- Chapter 5 presents the tailored facility location problem that will be modeled.
- Chapter 6 describes model behavior in a static scenario.
- Chapter 7 analyzes the model results.
- Chapter 8 provides a discussion of the research and its limitations.
- Chapter 9 provides the conclusions of the research and suggestions for further research.

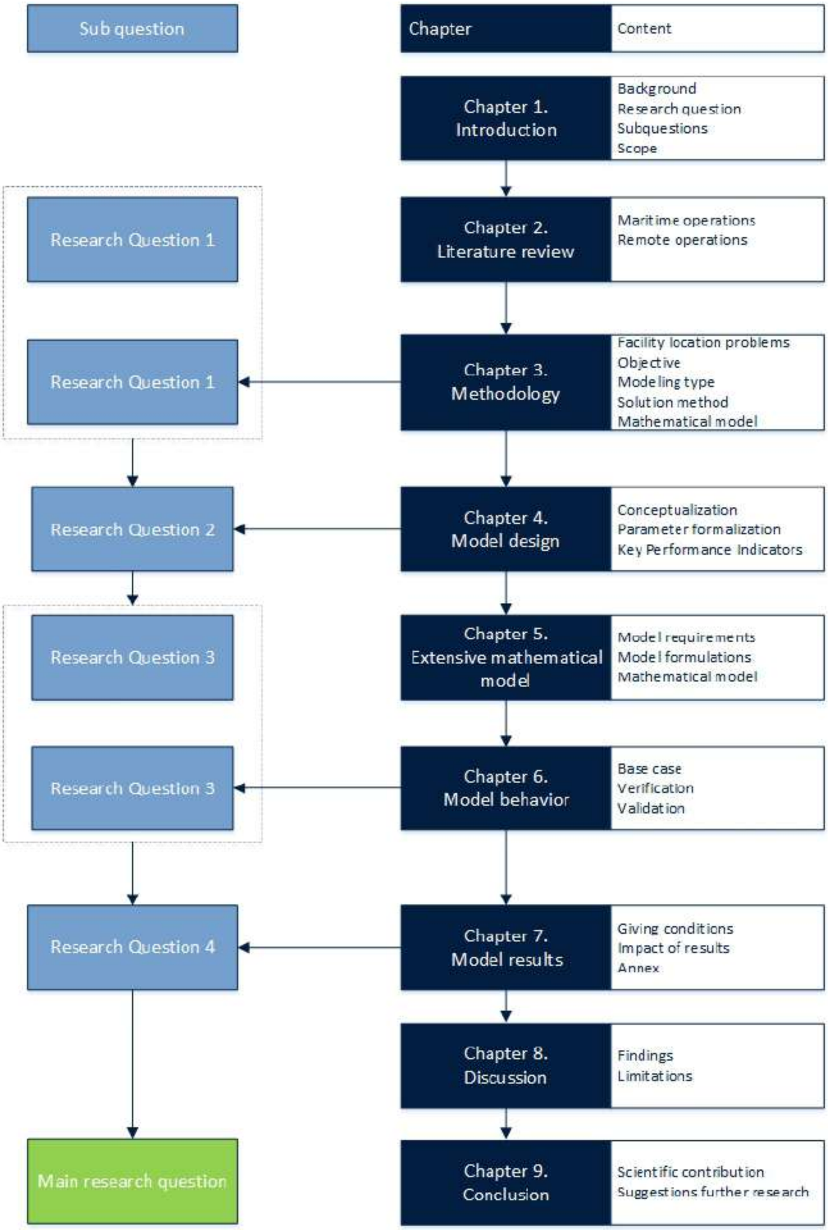

Figure 1.2: Structure of the report

2

THE LITERATURE REVIEW

The best adaptations are those that use the tools at hand the best,
not those that can identify what the best of all tools would be.

Koen van Dam - Postdoc at Imperial College London

CHAPTER 2 explores the available literature in the field of logistics research regarding maritime operations and remote operations to analyse the applicable tools that are commonly applied in this field of research. This literature review provides a comprehensible starting point in understanding the state-of-the-art in facility location problems. First, the research in traditional maritime operations will be discussed, followed by an analysis of relevant research in the broader context of remote operations. After, an overview of the applied methods related to the traditional problems will be provided. The chapter will conclude by identifying the relevant adaptations that can be tailored to fit the specific USV characteristics and implemented in the mathematical formulations that will be applied in the next phase of this research.

2.1. INTRODUCTION

USVs have the potential to revolutionize maritime activities like Unmanned Aerial Vehicles (UAVs) have transformed onshore and aerial operations. Unlike ground-transportation modes, UAVs do not follow a fixed network but rather fly directly through continuous space. Similarly, USVs navigate in a straight line through open water. Much like the range constraints of USVs, the limited flight range of drones introduces the demand for recharging stations. Optimization methods for UAVs are needed to design an efficient network of station locations and delivery routes [30]. Facility location problems resemble a large amount of these optimization methods. FLPs are used to strategically determine the desired location for facilities, like warehouses and distribution centers. While FLPs have been researched for UAVs and ground vehicles to some extend, little research has been done to the relatively new unmanned surface vessels [8]. In the following section, section 2.2, an overview will be provided of the optimization methods that are largely represented in the research regarding conventional maritime operations. After, the developments in other fields of transportation research will be observed and compared to the specific facility location problem that is studied in this research.

2.2. LOGISTICS RESEARCH IN MARITIME OPERATIONS

Transportation models in the field of maritime operations have mostly been studied for scheduling and routing optimization of offshore activities. These activities range from supply vessel routing for offshore oil & gas (O&G) installations to technician scheduling for wind park maintenance. Mardaneh et al. [31] introduced a non-standard vehicle routing problem (VRP) in the oil and gas industry to schedule a series of round trips for a heterogeneous fleet of vessels transporting food and water replenishments for offshore production facilities. The paper presents a mixed-integer linear programming (MILP) model that minimizes total cost, validated with real data provided by O&G company Woodside. In the upcoming wind energy sector, cost efficiency is considerably more important than in the traditional oil & gas sector. Hence, more and more research within the maritime industry is being conducted regarding efficient logistics for wind park operation & maintenance (O&M). The following section will discuss the relevant contributors in this field of research.

2.2.1. WIND FARM OPERATION & MAINTENANCE

Offshore wind turbines are among the fastest growing electrical generation systems worldwide [32]. Nevertheless, offshore wind is still dependent on governmental subsidies and far more costly than conventional energy sources [33]. This is largely due to high operation and maintenance costs, which include transportation costs, technician salaries and costs of spare parts, accounting for up to a third of the overall lifetime costs [34]. In the future, wind farms will be located further offshore where rough weather and greater distances from shore make the turbines more difficult and expensive to access [[35]; [36]]. Extensive research has been conducted in O&M to make offshore wind a competitive alternative by reducing costs through efficient use of maintenance vessel fleets and maximum utilization of good weather periods. [37].

Gundegjerde et al. [37] used optimization models to determine the optimal fleet size & mix for maintenance of an offshore wind farm. Instead of optimizing the fleet, Dai et al. [38] aimed to reduce the operation and maintenance cost in offshore wind farms and present a mathematical formulation for a routing and scheduling problem using a fixed heterogeneous fleet of vessels while taking into account the fleets various operational limits regarding wave heights. Irawan et al. [39] presented a similar model, incorporating multiple vessels, multiple periods, multiple bases and multiple wind farms. The algorithm, based on a decomposition method where a mixed integer linear program is solved, outperforms Dai et al. [38] as it obtains the optimal solutions in a relatively short computational time. Stålhane et al. [40] on the other hand, calculated downtime costs more precisely, but only consider a model spanning one time period. Santos et al. [41] addressed multiple time periods and included weather windows based on wind speed and wave heights. A distinction is made between the probability of occurrence of a weather window and the respective waiting time between the four seasons of winter, spring, summer and autumn. Similarly, Besnard et al. [42] included environmental constraints based on historical data for each of the four seasons.

O&M is currently only performed by heavy-duty vessels that are capable of conducting offshore operations for long consecutive periods with significantly more endurance than USVs. Determining efficient harbors that will only occasionally be used, results in marginal profits at best. Hence, in O&M, finding strategic harbor locations is not yet considered to be a relevant issue. This also becomes evident from the focus on scheduling and routing problems compared to facility location problems in the available literature. Despite this current lack of interest from the maritime industry in facility location problems, the researchers from the reviewed literature face the same challenges in other aspects, such as the incorporation of heterogeneous fleets, determining optimal vessel fleet size & mix and achieving maximum utilization of weather windows. This indicates that studying an operational model that incorporates the complexity of the USV components and the uncertainties that characterize offshore operations could be a valuable contribution to the available literature regarding routing and location problems in maritime operations.

2.2.2. EMISSIONS

As inferred from figure 1.1, *Advantages of remote and autonomous operations*, from section 1.1.2 of the previous chapter, reducing the carbon footprint is one of the main advantages of remote and autonomous operations. Although the maritime industry is facing several fierce restrictions from the International Maritime Organisation regarding the reductions of emissions of ocean going vessels[2], remarkably, no studies regarding emissions in relation to routing have been conducted in the field of maritime logistics. Surprisingly, no studies were found that consider vessel emissions as a relevant key performance indicator of routing efficiency. This can be partly explained given the conservative nature of the offshore industry as *green logistics* are a prevalent research topic in other industries. Nonetheless, many similarities can be drawn between logistics research in the offshore sector and the onshore sector. The following section discusses the relevant logistics research in remote operations outside of the maritime environment.

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[2] Appendix II: Roadmap of IMO regulations

2.3. LOGISTICS RESEARCH IN REMOTE OPERATIONS

Self-driving intralogistics vehicles, automated guided vehicles and other autonomous systems are state-of-the-art in many transport modes in closed environments on land[3]. In parallel, there are wide-ranging approaches of autonomous control concepts in modern aviation and maritime operations. They share the same strategic goals: strengthening and centralizing key support functions as well as increasing workforce efficiency and safety. When deciding the optimal location for a vacuum cleaner robot hub, the loss of efficiency is minimal, but on a larger scale, efficient hub locating becomes critical for the success of operations when considering hubs to recharge robo-taxis, to distribute medical supplies with drone during disasters or to navigate long distances overseas. Consequentially, aerial drones and self-driving cars are prominently featured in scientific research. The following section of the literature review will cover their applications in remote operations to present the resemblances they bear to USVs.

2.3.1. ELECTRIC VEHICLES

The near future requires solutions based on electric vehicles (EVs) [43]. EVs are considered a premium solution in land transportation systems because they can significantly reduce the dependency on oil and minimize transportation-related CO^2 emissions [44]. However, unlike traditional fossil fueled vehicles, EV technology has a limited range and needs regular recharging [45]. Consequentially, EV charging station planning has become an emerging research problem.

Liu [46] presents an integrated multi-criteria decision-making approach to select proper locations for electrical vehicle charging facilities with a multi-objective optimization method. Chung and Kwon [47] conducted a case study for traffic flow data of a Korean expressway network. The authors formulate a multi-period optimization model based on a flow-refueling location model for strategic charging station location planning. The facility location problem studied by Chung and Kwon [47] is frequently applied in relation to logistical models concerning drones.

2.3.2. UNMANNED AERIAL DRONES

Drones are on the verge of becoming a proven commercial technology for civil applications in many public and private sectors [48]. Drones have already been successfully applied for the delivery of packages and surveillance or monitoring tasks in the agriculture and energy sector [49]. Drones are even entering the maritime industry to increase safety and security by replacing humans in specific dangerous tasks such as tank or hull inspections [50]. Similar to the range constraints of USVs, the limited flight range of drones requires recharging stations. Optimization methods are needed to design an efficient network of station locations and delivery routes for drones [30].

Lynskey et al. [51] proposed an algorithm to optimally place drone ports to minimize the average distance drones must travel based on a set of potential drone port locations and tasks generated in a given area. Lynskey et al. formulate an MILP that ensures clusters of

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[3] Appendix III: Additional research regarding autonomous operations in closed onshore environments

tasks belonging to each drone port are within the drone's coverage in such a way that the drone can perform a maximum number of operations before returning to a drone port to recharge. The research of Lynskey et al. [51] is one of many examples that features drones in the context of facility location problems.

A typical shortcoming of the research regarding facility location problems for drones when applied in a maritime environment is the homogeneity of the similar drones on which these models are based. In contrast, the studied vehicles in this research consist of nonidentical vessels with distinct designs that follow particular rules.

2.3.3. CENTROIDS

A simplified representation for the routing of a traditional vessel in an MILP can be found in the available literature regarding centroids. A centroid is a geometric property that represents the coordinates of the *middle* of the shape, like a weighted average [52]. With respect to routing applications, a centroid is an artificial central node that functions as a hub where a vessel needs to *depart from* and *return to* in between visits to surrounding demand nodes.

Fisher et al. [53] describe a common variant of the vehicle routing problem in which a vehicle fleet delivers products stored at a central depot to satisfy customer orders. In their research a generalized assignment heuristic for vehicle routing is proposed that makes use of a set of 'seed customers' which 'seed points' are used to initialize the heuristic partitioning the plane into *n* small cones for each customer. This concept of creating centroids is further developed by Agatz [54] as a heuristic to determine home delivery time slots. One zip code will serve as the seed, or representative, for the customers served in a particular time slot. The estimate of the cost to serve a set of zip codes in a time slot is based on the sum of the distances between the zip codes and the seed. The estimate of costs across zip codes in a different time slot is represented by the costs of travel between seeds. A single seed, as depicted in figure 2.1, can similarly be represented as a centroid that a traditional vessel must pas through before visiting an offshore demand node.

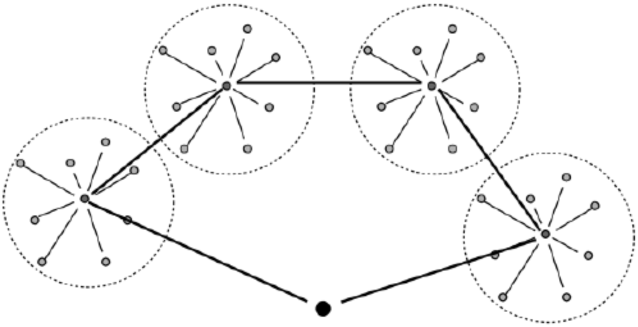

Figure 2.1: Routing with seeds from Agatz et al. [54]

Integrating a heterogeneous fleet of traditional vessels based on routing via centroids, in combination with a fleet of USVs that follow the drone-like behavior of *one-to-one* trips, will provide a simultaneous assignment of vessels to demand nodes as depicted by the representation in figure 2.2. To the best of my knowledge, no previous research has studied facility location problems in the maritime environment considering a heterogeneous fleets that combines the distinctive routing behavior of centroid-like hubs and drone-like *one-to-one trips*.

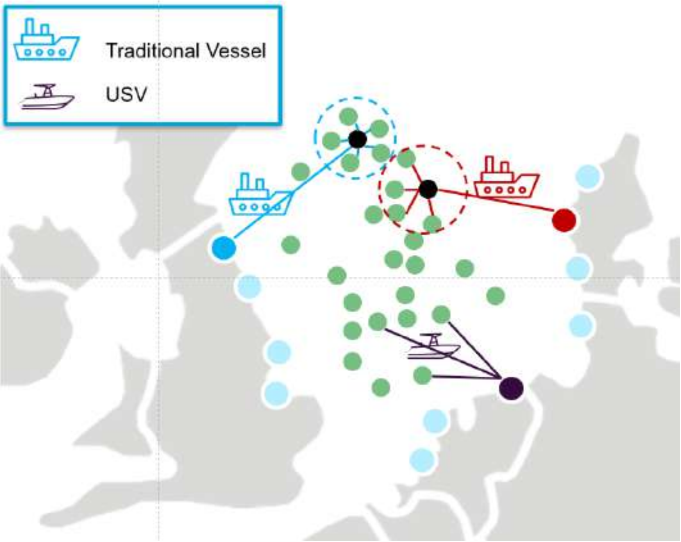

Figure 2.2: Representation of different routing behavior

2.4. CONCLUSION

Because uncrewed surface vessels have only recently been developed, a study in the field of logistical research regarding these new vessels is yet to be conducted. However, relevant research regarding the efficient logistics of other remotely operated vehicles has been done outside the scope of maritime applications. In the field of automation many applications of facility location problems for drones and robotaxis that include range constraints, *one-to-one trips* and charging hubs have been studied. In line with the routing challenges related to autonomous operations across different sectors, this paper focuses on developing the first strategic facility location system for uncrewed surface vessels in the maritime operations.

Within the logistical research regarding the maritime industry, similar challenges such as incorporating a heterogeneous fleet, determining the optimal vessel fleet size & mix and achieving maximum utilization of weather windows are addressed. This indicates that studying an operational model that considers the complexity of the USV components and the uncertainties that characterize offshore operations, could be a valuable contribution to the available literature regarding routing and location problems in maritime operations. Compared to other maritime operations studied in the literature, this model is characterized by several non-standard features:

1. The vessel fleet is heterogeneous.
2. Vessel performing *one-to-one trips* and vessels travelling through centroids are compared simultaneously.
3. A multi-period timeframe is considered.
4. Demand nodes develop over time.
5. Possible locations for facilities develop over time.

Although some of these non-standard features have already been covered in the available literature, to the best of my knowledge, no previous research has studied facility location problems in the maritime environment considering a heterogeneous fleets that combines the distinctive routing behavior of centroid-like hubs and drone-like *one-to-one trips*.

An overview of the identified research gaps and possible fields of contributions of this research is provided in the form of a matrix on page 23[4]. Following the same structure of this chapter, the first column covers the relevant logistics research conducted in the maritime industry. No research was found that covers a combination of facility location problems, heterogeneous fleets and one-to-one trips in the maritime environment. The second column marks the available research regarding facility location problems, which chapter 3 will continue to cover. This is an especially interesting research topic in the

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[4] *Note that the relevance of the research by Chauchan et al. (2019), Kim et al. (2019), Ribiero et al. (2019) and Schermer et al. (2019) as featured in the matrix will be discussed in chapter 3.*

field of drone applications. A typical shortcoming of drones in facility location problems is that most of these studies are based on homogeneous sets of similar drones. The only research that covers heterogeneous fleets in regards to drone applications are vehicle routing problems where trucks can deploy drones to perform additional delivery services. Interestingly, none of these studies in logistical processes consider the aspect of sustainability and emissions in their models. In fact, Chauhan et al. (2019) are the only ones that briefly mention the possibility to consider emissions when dealing with urban logistics. The final two rows cover the research from Agatz et al. and Fisher et al. These studies are the only relevant work addressing centroids that were relevant to this research for the representation of traditional vessel routing. However, these researches do not show other similarities in regards to fleet heterogeneity or type of modeling problem.

Table 2.1: Analysis of articles published related to relevant transportation problems

Reference	Maritime application	FLP	Heterogeneous fleet	Multiple periods	Emissions	Real case	Field of research
This research	✓	✓	✓	✓	✓	✓	**FLP with heteregenous fleet**
Gundegjerde et al.	✓		✓				Stochastic Fleet Size FSP
Vieira et al.	✓		✓	✓		✓	Vessel Planning VRP
Mardaneh et al.	✓			✓		✓	Vessel Scheduling VRP
Raknes et al.	✓			✓			Multi Vessel Routing WRRP
Dai et al.	✓			✓		✓	Offshore Maintenance Routing VRP
Santos et al.	✓						Offshore Maintenance Simulation
Irawan et al.	✓			✓			Offshore Maintenance Routing VRP
Chauhan et al.		✓				✓	Max Coverage FLP for Drones
Lynskey et al.		✓					Drone Ports Locations FLP
Kim et al.		✓		✓			Emergency Planning FLP
Amiri et al.		✓					Two-Echelon Supply Chain LRP
Schermer et al.			✓				Drone Location TSP
Ribiero et al.				✓		✓	UAV routing
Agatz et al.						✓	VRP using interconnected centroids
Fisher et al.				✓			VRP using centroids as seeds

**Note: FLP = facility location problem, VRP = vehicle routing problem, WRRP = workover rig routing problem, TSP = traveling salesman problem, LRP = location routing problem, optimization*

3

METHODOLOGY

Methodology is intuition reconstructed in tranquility

Paul Lazarsfeld - Austrian-American sociologist

FROM the reviewed literature in the previous chapter it became evident that the relevant models regarding facility location problems for UAVs show a strong resemblance to the challenges that result from the implementation of USVs. Other than having a near-identical abbreviation, UAVs and USVs have a similar feature in terms of limited flight range, which imposes the characteristic of *one-to-one* trips and the requirement for strategically located recharging facilities. This chapter focuses on the construction of a methodology to answer subquestion 1: *What are advantages and disadvantages of the available methods to formulate a facility location problem in the maritime environment?* An intuitive methodology will follow from a composed discussion of the different objectives, modeling types and solution methods related to facility location problems. After understanding the underlying principles of this commonly practiced problem, chapter 4, will cover the characteristics and the giving conditions that result from the case study specifications. Chapter 5 will provide the adaptation of the facility location problem that is complemented by the specific conditions following from the case study in 5.

3.1. FACILITY LOCATION PROBLEMS

Facilities are often constructed for a long time span and require substantial financial investments [55]. Therefor, FLPs are used to strategically determine the desired location for facilities, like warehouses, distribution centers or other types of hubs. [56]. The locations of robodocks are crucial for efficient operations. From the selected harbor locations, the USVs must be able to reach the asset locations of potential clients at the occurrence of an inspection request. Momentarily, for its piloting project, harbor locations are identified pragmatically; project based with high mobilization costs, uncertainty about available facilities and inefficient staff use as a consequence. To overcome these deficiencies, USVs need be positioned across strategic locations in the North-Sea region, being able to swiftly respond to survey and inspection demands from a client.

Hence, an optimization method using an appropriate facility location problem adaptation could be exercised to decide where to locate these facilities. The following sections summarize notable objectives in facility location problems followed by the corresponding modeling types and solution methods.

3.1.1. OBJECTIVE FUNCTION

Facility location problems can be assessed by several models that serve different objectives depending on the problem context. These models can focus on travel times, distances, uncertainties, costs, coverage, or a combination of these objectives [57]. This section provides the various objectives that are addressed with facility location approaches following the most prevalent problem types covered by Boonmee et al. [58]

MINISUM

The minisum facility location problem, also known as the p-median facility location model defined by Campbell [59], selects or locates a known number of p facilities and minimizes cost (in the form of time, distance or transport cost) between the facility and the demand point it is dedicated to [58]. The number of installed facilities is known, given by p, and the objective is to minimize total transportation cost. In other words, facilities are located such that the sum of all weighted costs between demand points and solution facilities is minimized for the given number of located facilities [[60]; [61]]. This is an uncapacitated problem, which means the facilities have no capacity constraints [62].

The minisum method is commonly used for a warehouse problem. Many studies have focused on minisum problems, particularly for reducing transportation costs from supply to demand locations. In this context, Chowdhury et al. [63] provided a continuous approximation model to determine the potential of UAVs as a mode of transportation to supply emergency commodities. The study aims to minimize the overall system cost, therein determining the optimal locations for the distribution centers with their corresponding inventories and service regions under UAV routing constraints and stochastic demand in a disaster-affected area.

MINIMAX

Minisums tend to favor clients clustered in population centers, while neglecting clients who are spatially dispersed. Discrimination of this kind regarding accessibility may negatively impact remote clients in the case of providing emergency services by ambulances, fire brigades or police stations [62]. Accordingly, some studies in the field of humanitarian logistics criticize having a cost minimization objective [64] and argue that minimizing logistic costs is only appropriate for commercial activities, yet never in respect to humanitarian operations [65].

Instead of minimizing total weighted costs, the minimax problem, also known as the p-center problem [58] aims to minimize the maximum distance between supply and demand nodes, given p facilities. Ye et al. [66] proposed an extension of the p-center model for emergency warehouse locations to minimize the loss resulting from disasters. Another minimax facility location problem application is for minimizing worst system performance [67].

MAX COVERING

The maximize coverage method is a calculation method for the uncapacitated facility location problem, which aims to find a set of facilities that serve the maximum possible number of demand points. Instead of minimizing total weighted costs the objective of the maximum covering problem is to ensure maximum coverage of demand nodes within a specific range of the available facilities. The maximal covering problem also uses a fixed number of facilities p, but instead maximizes the number of demand nodes covered within a certain distance of the facilities [58].

Chauhan et al. [68] presented an integer linear programming formulation with the objective of maximizing coverage while explicitly incorporating the drone energy consumption and range constraints. The model seeks to locate a pre-specified number of capacitated facilities and assign drones to the located facilities to serve the demands of demand points. The facilities serve as drone launching sites for distributing resources. Each drone makes several one-to-one trips from the facility location to the demand points and back until the battery range is met. The planning period is short-term. Therefor, the recharging of drone batteries is not considered in this specific research. Jia et al. [69] located medical supply hubs for emergency response using a maximal covering problem.

FIXED-CHARGE

In a fixed-charge problem, the capacitated model has to decide about the number of facilities and total transportation cost. In a capacitated model, each facility has a capacity and the same *fixed charge*, the operating costs. The objective is to find the location and number of facilities and the associated user allocation to minimize total weighted cost.

MULTI-OBJECTIVE

A multi-objective facility location problem consists of two or more objective functions. By assigning weight to the different objectives, a priority of the objectives can be assigned [70]. Alternatively, a combination of maximizing coverage while minimizing facilities can be applied. The maximize coverage and minimize facilities approach is a variation on the maximize coverage method [71]. The solution methods are both applied to uncapacitated FLPs.

IMPLICATIONS

In the problem that is faced in this study, a facility location model is constructed to strategically determine the desired location of the ports. Strategically, in this sense, is synonymous with *most profitable*. The objective of the model is to determine which combinations of vessels and harbors will most profitably execute inspections at the assets by taking into account the combined costs of vessels, operations and harbors. Whereas the minisum facility location problem selects its facilities to minimize costs in the form of transport between facilities and demand points, this research takes the summed transportation costs as one of the cost factors to consider when determining the maximum profit. Hence, the objective that is considered in this research rather aims to construct a maximize profit function, while making use of the facility location problem framework to determine the most profitable harbor locations with the most profitable combination of vessels. Furthermore, there are no specific capacity constraints imposed on the facilities. To call it a multi-objective facility location problem as it optimizes both the facility locations and the fleet size &mix is a bit of a stretch, especially since the objective function does not consist of two or more separate objective function. Rather, this research deals with an *uncapacitated profit maximising facility location problem*, that incorporates the cost function of trips, vessels and harbors.

3.1.2. MODELING TYPE

According to Boonmee et al. [58], there are four main model types in facility location problems: deterministic, dynamic, stochastic, and robust. This section discusses each of the leading modeling types with corresponding applications in the literature.

DETERMINISTIC

The deterministic facility location problems involve selecting facilities with all parameters, such as the asset and facility location, capacity and fixed cost, being known and constant over time [58]. The deterministic problem formulation is the basis for the dynamic, robust, and stochastic models. However, there are many studies regarding facility location problems that exclusively involve deterministic optimization. Vieira et al. [72] proposed a static model and a service demand per type of offshore installation while disregarding the weather impact on the voyage duration. Hence, no periodic nor stochastic data is used.

DYNAMIC

One common feature of real applications is the dynamic nature of problems. Scenarios including costs, demand or resources often vary over the planning horizon. From the location point of view, this gives rise to different types of multi-period, or dynamic, problems [73]. Contreras et al. [73] presented a dynamic (or multi-period) hub location problem. Dynamic facility location problems involve multiple time periods where demand points, environmental factors, operating costs, and number of facilities are bound to potential changes [58]. In this context, Raknes et al. [33] introduced a dynamic mathematical model that considers maintenance task scheduling by transporting technicians using a vessel fleet of dedicated vessels that can stay offshore for several shifts, modeling both vessels that must return to an onshore depot between each shift and vessels that can stay offshore for multiple periods without going back to the depot. Simulation is used to evaluate the performance of the model to make strategic decisions regarding the facility locations.

STOCHASTIC

In stochastic optimization, a probability distribution is assigned to uncertain parameters [58]. Research by Kim et al. [74] presented a drone facility location problem that determines the locations, numbers and transport capacities of drone facilities. Considering the uncertain characteristics of drone operation simultaneously, a stochastic facility location model is developed for a disaster-affected region where drones can be used as a mode of transportation for emergency supplies to demand points. Similarly, Chowdhury et al. [63] provided a continuous approximation model to determine optimal locations for distribution centers under stochastic demand in a disaster-affected region.

ROBUST

Robust optimization is used for problems where some parameters are uncertain. Uncertain parameters are characterized by discrete scenarios or continuous ranges [58]. A study by Chauhan et al. [75] aimed to locate a prespecified number of facilities and assign drones to serve the demand while respecting drone range constraints. This paper extends the earlier work done by Chauhan et al. [68] and presents an integer linear programming formulation to maximize coverage using a robust optimization framework.

IMPLICATIONS

Given the iterative nature of the USV problem, where the development of the USV capabilities and offshore asset developments as well as the seasonal weather influence will have a periodically changing effects, a dynamic solution seems the most fitting modeling type to solve the facility location problem problem. Different scenarios for different time steps in future years will be constructed to to incorporate the uncertainties that arise from future developments of variables and system components.

The stochastic effects of weather are accounted for by enforcing periodically changing weather conditions. This study will exclusively incorporate the offshore assets' periodical, preventive inspection demand and disregard the stochasticity related to potential corrective inspection demand. Thus, an *uncapacitated multi-period profit maximizing facility location problem* will be constructed.

3.1.3. SOLUTION METHOD

There are two main approaches used to solve facility location problems: exact and heuristic [67]. Exact algorithms are used to find the optimal solution to a problem. However, many facility location problems, including p-center and p-median problems, have been known to be NP-hard, meaning the time to solve the problem increases exponentially with respect to problem dimensions [76][77][78]. To address this issue, heuristic algorithms are applied because they require less computing time. However, the results are sub-optimal compared to exact algorithms [58]. Hence, simplicity is essential when building an FLP model [79].

Regarding a dynamic hub location problem, similar to the one proposed in this research, Contreras et al.[73] observe that considering an empty initial set of open hubs is NP-hard when the planning horizon consists of a single period. When a nonempty initial set of open hubs is considered, the problem is also NP-hard when the planning horizon consists of two or more time periods.

EXACT

Exact algorithms have been extensively used in facility location problems for humanitarian logistics. Balcik and Beamon [80] presented a variant of the maximal covering location model to determine the number and location of distribution centers and the number of relief supplies needed for people affected by earthquakes. Khayal et al. [81] developed a model of a distribution plan for dynamically changing demand over different periods. These studies, among others, have used exact algorithms to solve problems within reasonable time. However, a common recommendation is to use heuristic algorithms to efficiently solve more complex problems [67].

HEURISTIC

Commonly used heuristic algorithms in facility location problems include genetic algorithms, tabu search algorithms, greedy algorithms, and locate-allocate heuristics. Comes et al. [82] used a greedy algorithm to solve an uncapacitated facility location problem and determine robust locations of health care centers. Jia et al. [69] developed a genetic algorithm, locate-allocate heuristic, and Lagrangean relaxation heuristic to propose solution approaches for facility locations of medical supplies in response to a large scale emergency within a short computational time. Salman and Yucel [83] used a tabu search algorithm to select facility locations and maximize total expected demand.

Chauhan et al. [68] consider FLPs to be complex problems for which state of the art MIP solvers may require unacceptably long running times to find feasible solutions, even for relatively small problem sizes. To better balance solution quality and running times, novel greedy and three-stage heuristics are developed before generating Gurobi solutions at a small fraction of the running time. Tan et al. [84] study a short-term scheduling plan for offshore windfarms using the solver Gurobi for its optimization. Schermer et al. [48] formulate an MILP using state-of-the-art solver Gurobi to obtain solutions for small- and medium-sized instances for a Drone Station Location Problem.

Heuristics are often applied in the context of disaster management, drones can become a useful mode of transportation in humanitarian logistics because they do not need preexisting paths to make deliveries. While trains, boats, and trucks follow restricted pathways, drones can move anywhere and everywhere. Therefore, if a natural disaster strikes and roads are damaged, drones can be used as an alternative to serve the destroyed region. Although integrating drones into humanitarian logistics seems efficient and convenient, some features of drones, such as the limited payload or the limited flight time, must be considered. Therefore, studying the operation methods that take into account the uncertain conditions of drone operation is imperative.

In disaster management, applying heuristics or meta-heuristics to reduce computational times can be crucial to yield quicker results for the allocation of drones to the disaster-affected areas. Therefor, heuristic algorithms are employed because they take less running time. However, the results are sub-optimal compared to exact algorithms [58]. The FLP concerned in this research does not thrive on the quickness of its results, but rather on generating optimal outcomes. Hence, in this research, heuristics as a means to improve run times is not regarded to be a necessary consideration.

3.1.4. PRELIMINARY CONCLUSION

Considering the importance of efficient hub locations for successful operations of remote technologies, the proposed research aims to construct a facility location problem. The objective of the model is to determine which combination of vessels and harbors will most profitably execute inspections at the assets by taking into account the combined costs of vessels, operations and harbors. Hence, the objective that is considered in this research rather aims to construct a maximize profit function, while making use of the facility location problem framework to determine the harbor locations with the most profitable combination of vessels. Furthermore, there are no specific capacity constraints imposed on the facilities. As such, an *uncapacitated multi-period profit maximizing facility location problem* will be constructed.

There appears to be a wide application of MIP solvers in the literature regarding hub location problems. To overcome the expected computational difficulties of the proposed complex model, this research will adopt the MIP solver Gurobi to run the model optimization. To avoid sub-optimal solutions and limit the scope of this research, no further heuristics or meta-heuristics will be developed. Furthermore, as computational times are not critical in this research, there is no argument to adopt heuristics as a means to improve run times. Though, it must be noted that a concept of 'seed nodes' as introduced by Fisher et al. [53] and Agatz [54] will be considered as a way to represent the travel behavior of traditional vessels. These will pass through artificial centroids, represented as a hub where traditional vessels need to depart from, and return to in between visits to surrounding demand nodes.

The following section will present the mathematical formulation of the uncapacitated profit maximising facility location problem.

3.2. THE MATHEMATICAL MODEL

3.2.1. DEFINITIONS

Table 3.1: Definitions of sets, parameters and decision variables

Sets		
	I	Set of demand locations
	J	Set of possible facility locations
	K	Set of vehicles
Indices		
	$i \in I$	-
	$j \in J$	-
	$k \in K$	-
Parameters		
	p	Maximum number of facilities
	d_{ij}	Distance in knots between node i and j
	w_i	Demand at location $i \in I$
	f_j	Facility costs at facility $j \in J$
	r_k	Range capacity of vehicle $k \in K$
	s_k	Travel speed of in knots/hour vehicle $k \in K$
	c_k	Travel costs of vehicle $k \in K$
	v_k	Vessels costs of vehicle $k \in K$
	l_k	Duration of performing an operation for vehicle $k \in K$
	o_k	Maximum days of operations for vehicle $k \in K$
Decision Variables		
	x_{ijk}	$\begin{cases} 1, & \text{if customer } i \text{ is served by the } k^{\text{th}} \text{ vehicle from facility } j \\ 0, & \text{otherwise} \end{cases}$
	y_j	$\begin{cases} 1, & \text{if a facility is located at } j \\ 0, & \text{otherwise} \end{cases}$
	z_{jk}	$\begin{cases} 1, & \text{if the } k^{\text{th}} \text{ vehicle is assigned to facility } j \\ 0, & \text{otherwise} \end{cases}$

3.2.2. MATHEMATICAL FORMULATION

Objective function:

$$max \quad \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} w_{ij}x_{ij} - \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} 2c_k x_{ijk} - \sum_{i\in I}\sum_{k\in K} v_k z_{jk} - \sum_{j\in J} f_j y_j \tag{3.1}$$

Subject to:

$$\sum_{j\in J} x_{ij} = 1 \quad \forall i \in I \tag{3.2}$$

$$\sum_{j\in J} y_j \leq p \tag{3.3}$$

$$z_{jk} \leq y_j \qquad \forall j \in J, k \in K \tag{3.4}$$

$$\sum_{j\in J} z_{jk} \leq 1 \qquad \forall k \in K \tag{3.5}$$

$$d_{ij}x_{ijk} \leq r_k z_{jk} \qquad \forall i \in I, j \in J, k \in K \tag{3.6}$$

$$\sum_{i\in I}\sum_{j\in J} l_k x_{ijk} + \left(\frac{d_{ij}x_{ijk}}{s_k}\right) \leq o_k \qquad \forall k \in K \tag{3.7}$$

$$x_{ij}, y_j, z_{jk} \in \{0,1\}, \quad \forall i \in I, \forall j \in J, \forall k \in K \tag{3.8}$$

Objective function (3.1) maximizes the total profit at the demand nodes, minus the travel costs, vessel costs and facility costs. Constraint (3.2) makes sure that each demand node is covered and assigned to exactly one facility, while constraint (3.3) limits the total number of facilities that can be built. Constraint (3.4) assures that vehicles can only be assigned to located facilities and constraint (3.5) assures that vehicles can only be assigned to one facility. The range constraint on the vessels is enforced by (3.7) and (3.8) limits the maximum days of operations for the vehicles. Finally, constraint (3.8) defines the domain of the variables. Note that the *2* in (3.1) and (3.7) are there to make sure that both the trip from the facility to the demand node, as well as the return from the demand node to the facility are accounted for.

3.3. CONCLUSION

Having provided the relevant background, literature review and mathematical model, this section will shortly reflect on **sub question 1:** *what are the critical considerations regarding the available methods to formulate a facility location problem in the maritime environment?*

From the relevant literature, several studies regarding vehicle routing problems in the field of maritime operations and numerous facility locations regarding drones and automated vehicles were covered. Compared to other maritime operations studied in the literature, the USVs are characterized by several non-standard features that resemble drones and automated vehicles to some extend. Additionally, to address the fleet heterogeneity, other researches have been covered to introduce the notion of centroids for traditional vessels. To the best of my knowledge, no previous research has studied facility location problems in the maritime environment considering a heterogeneous fleets that combines the distinctive routing behavior of centroid-like hubs and drone-like one-to-one trips.

With regards to facility location problems, the aim of this research is to determine the optimal facility locations to support vessels, ensuring that all demand nodes are fulfilled over a given planning horizon. To overcome the expected computational difficulties of the proposed complex model, this research will adopt the MIP solver Gurobi to run the model optimization. The problem that is addressed in the model can be viewed as a *multi-period max profit facility location problem*, in which the vehicles are survey vessels, the customers are offshore assets, and the depots are harbors.

For a comprehensible understanding of all the critical considerations to formulate a facility location problem, some disadvantages must be noted regarding the application of facility location problems in the maritime environment. First of all, an FLP oversimplifies the many stochastic factors that affect the system. This also means that only recurrent and constant demand is being considered and that no corrective inspection jobs are being considered, despite representing a large share of the total work scope. Another main difficulty in solving FLPs is the huge number of variables and constraints needed to model them. For this reason, formulations with fewer variables and constraints should be preferred to reduce the computational burden. The complexity of the maritime environment will be hard to capture in a sparse facility location model.

The next chapter will provide further details of the case study, providing background and further explanations regarding the developments of the model components. Hence, the chapter is split up into the following distinct sections. This will extend the set of parameters and decision variables and add more dimensions, giving conditions and constraints to the model.

1. the set of demand nodes $i \in I$ in the North-Sea.
2. the different types of possible harbor locations $j \in J$.
3. the versatile fleet of vessels $k \in K$.

4

THE MODEL DESIGN

A mathematical model cannot answer the questions of why there should be a universe for the model to describe. Why does the universe go to all the bother of existing?

Stephan Hawking - Theoretical Physicist

UNFORTUNATELY, this section will not provide an answer to the question why the universe goes to the bother of existing. Taking the universe for granted, this chapter provides an overview of the concepts from the universe that are considered case study of this research.

In other words, this section will elaborate on the system components and requirements and translate them into the giving conditions that will be incorporated in the mathematical model from the previous chapter. The beginning of the chapter will introduce the maritime inspection industry, after which each section will start providing background on the relevant developments regarding each specific model component and conclude with the specific characteristics that will be integrated in the extended mathematical model. After obtaining the required real-world data, the mathematical model can be extended. Chapter 5, The Extensive Mathematical Model, will reiterate the conclusions drawn from this current chapter. In chapter 4, The Model Design, various simulations will be tested in order to validate the outcomes with corresponding real-world data.

4.1. CONCEPTUALIZATION

4.1.1. INTRODUCTION TO THE MARITIME SURVEY INDUSTRY

Roberts [85] discusses the history and economics of the marine inspection market. By big business standards, the worldwide offshore survey market is one of many fish in a large sea. As a consequence, forces outside of the surveying group's control exist, such as seasonal workload, technological innovation, and the effects of political bargaining and government action. Safety and inefficiency are the highlighted drivers as pipelines, cables and platforms can represent a significant operational hazard. The utilization of offshore assets represent a vital aspect to modern human life, any failure in these systems can generate serious impacts on humans and have devastating effects on the environment. Therefore, periodic inspection of offshore assets is crucial.

Geophysical and geotechnical site characterization surveys as well as inspection surveys for offshore structures are a complex undertaking. These projects are reliant on large vessels and substantial project crews to stay offshore for exteneded periods of time, typically ranging from weeks to months. Rough seas and remote areas inflict limited internet connectivity during the execution of the surveys which forces most activities to be physically executed on a vessel. This includes operational activities (such as deployment, recovery and maintenance of subsea robots and sensors) as well as data-related activities (data processing, quality control and field assessments). After long periods at sea, the vessels return to port where the acquired data is offloaded in bulk for processing, analysis and final reporting in an office or cloud environment, which can take up to several weeks to complete [22].

With nearly ten thousand employees worldwide, Fugro is a world-leader in collecting and analyzing this periodic inspection data from infrastructures. The company has a fleet of 25 vessels, which are used for geological research at sea, and to support offshore projects by contractors, governments and oil and gas companies. This chapter provides an in-depth overview of the system components that are part of the case study of this research, including North-Sea assets, USVs, ROVs, robodocks and ROCs. The remainder of this chapter will start with the developments surrounding offshore assets and continue to cover the capabilities and limitations of USVs and robodocks as well as the required supporting instruments that enable this new technology. The chapter consists of several sections that follow the overview of the developments of the components in the industry as depicted in figure 4.1 below.

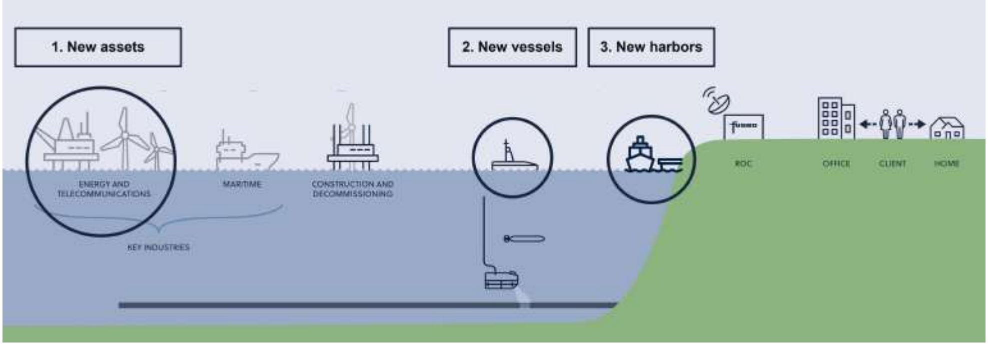

Figure 4.1: Overview of the components in the maritime inspection market:
the set of demand nodes (North-Sea assets) $\{i_t \in I_t\}$;
the set of vehicles (traditional vessels and USVs) $\{k_t \in K_t\}$;
the set of facilities (robodocks and harbors) $\{j_t \in J_t\}$

4.1.2. THE SET OF DEMAND NODES $\{i_t \in I_t\}$: NORTH-SEA ASSETS

BACKGROUND

The demand nodes in the facility location problem represent the offshore inspection jobs. These range from traditional marine assets such as oilrigs, cables and pipelines to more recent assets such as offshore wind parks. This case study is limited to the scope of the North-Sea. Currently, over 90% of the worldwide installed offshore wind capacity is in European waters [41]. Marine assets in the North-Sea have specific characteristics in terms of the inspection type, inspection duration and the likelihood of inspection demand. For example, during the life cycle of offshore wind farms, operators want to maximize the uptime of wind turbines to generate as much energy as possible.

Offshore inspection work is notoriously unpredictable. Assets have periodical, preventive inspection demand as well as unforeseen, corrective inspection demand. Regulations concerning the frequency of preventive inspections differs across countries. Corrective inspection demand can be required at any given moment, for example after the occurrence of a storm. Preventive maintenance consists of planned operations that are executed with the intention of prolonging the lifetime of a turbine or other system components and prevent failures. These operations can include visual inspections, changes of consumables and oil sampling [86]. When and how often to execute preventive maintenance operations will depend on the operator's maintenance strategy and the type of asset that are installed. Normally, the frequency is suggested to be 1 or 2 visits to each offshore infrastructure every year [87].

Corrective maintenance operations need to be executed due to unforeseen failures to the system. These failures result in asset breakdowns and loss of income due to production stops. On top of the uncertainty for demand, for both current and future assets, the question remains whether the inspection service will be tendered to Fugro and not some competitor.

In the future, new types of assets with specific inspection demand characteristics will be developed in the North-Sea. As the North Sea transitions from fossil to renewable energy[5], synergies between gas & wind infrastructures are explored [88]. The most promising developments, as depicted in figure 4.2 are electrified oil & gas production, carbon capture storage and hydrogen conversions. Ultimately, these synergies should result in an integrated energy system on the North-Sea (figure 4.3). The viability of the inspection demand related to these infrastructures, including CCS fields, hydrogen pipelines and floating solar & wind installations as well as the emerging of new services such as seabed mapping and biodiversity monitoring still remain to be proven.

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[5] Appendix IV: Offshore wind installations by country
Appendix V: Roadmap of the North-Sea energy transition

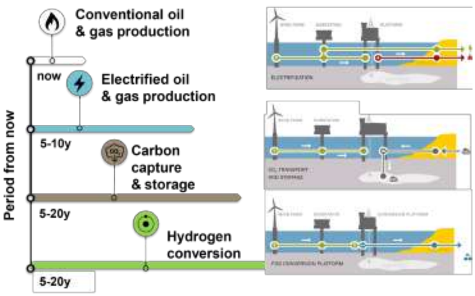


Figure 4.2: Timeframe for platform adjustments

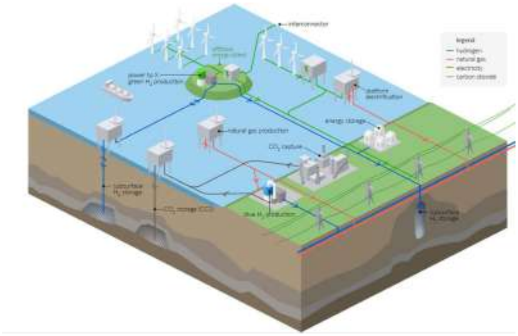


Figure 4.3: Integrated energy systems

MODEL IMPLICATIONS

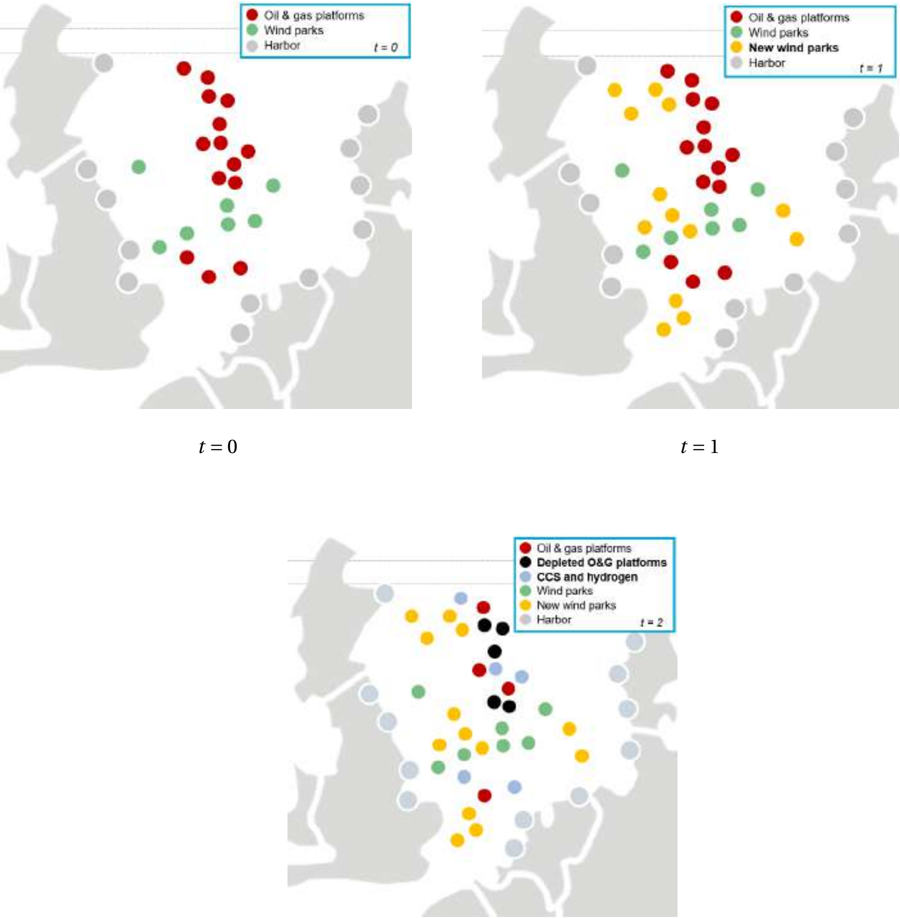
The characteristics that are taken into account when considering North-Sea assets are their relative profit. Here, a distinction is made between inspections for offshore windparks and oil & gas infrastructures. As offshore windparks require a less extensive data report regarding the inspection of assets, these jobs tend to be less valuable than the inspection jobs of oil & gas infrastructures. The ballpark estimates that are used in this research are prescribes that each oil & gas infrastructure inspections yields a revenue of €1.000.000, while inspection jobs at offshore wind parks yield 75%. This means that in this research the assumption is made that every inspection job at an offshore wind park yields a revenue of €750.000. The costs related to the inspection jobs are based on the costs for the daily operation of the vessels and the time it takes them complete the inspections and the costs of transit in between.

Considering the limited scope of this research, several assumptions are made to construct a simplified model of this complex environment:

- The scope is limited to the offshore operations in the North-Sea.
- Each asset is expected to request an inspection once in every given time frame, meaning no corrective maintenance is taken into account.
- All demand is tendered to a single party.
- Demand nodes are split up into windparks or oil & gas platforms. Each with a relative revenue and similar work scope for the operations
- The exact number of days is defined by the speed of the vessels that execute the operations.
- No specific equipment requirements for assets inspections will be considered. Every vessel will be able to execute the same operations at each demand node.
- Weather conditions will only be taken into account to a certain extend: a strongly limited number of operable days for the smaller vessels.

Given the rapid developments that are occurring in the North-Sea, a time-index t is added to current and future infrastructures. This way the model can account for wind parks that are being built in years to come, as well as oil & gas fields that will be depleted in the future, and ultimately the development of carbon capture storage field, hydrogen conversions and energy islands. The model will take 3 distinct scenario's into account for the time-indices $t \in T$. These are non-consecutive years, but discretized years based on infrastructure availability:

- $t = 0$ represents the current topology of the active North-Sea infrastructures.
- $t = 1$ represents the future scenario in 5-10 years. This includes the wind-parks that are currently under construction.
- $t = 2$ represents the future scenario in 10-15 years. This includes the construction of energy islands. It assumes that the depletion of wells on the hand, will even out the inspection demand with the emergence of carbon capture storage, hydrogen conversions and floating structures on the other hand.



$t = 0$ $t = 1$

$t = 2$

Figure 4.4: Representations of the topology of active North-Sea assets throughout the distinct time indices.

After integrating several data-bases including the North-Sea Transition Authority and the *Nederlandse Olie & Gas Portaal*, and validating findings through interviews with industry experts, an extensive list of offshore assets and harbors was constructed for current and future scenario's. Plotting this data[6] resulted in the map depicted in figure 4.5 on the next page.

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[6] Appendix VI: Coordinate database used during simulations

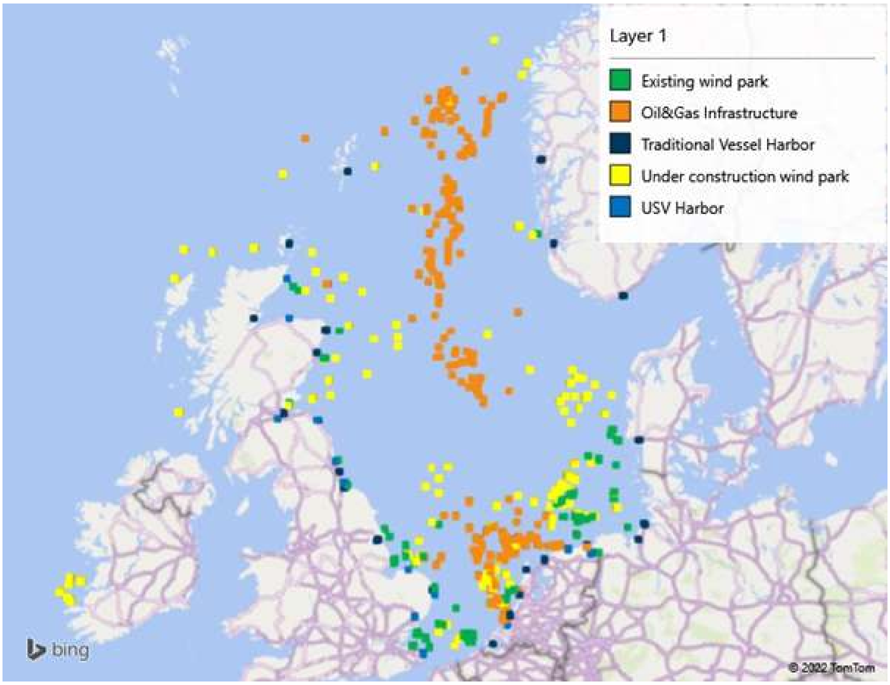

Figure 4.5: Scattered nodes of the North-Sea assets that will be used for the modelling part of this research

This map contains the dynamic North-Sea assets that will be used as input for the model in the remainder of this research. The constructed map in figure 4.5 shows justifiable similarities to the published figures 4.6 and 4.7.

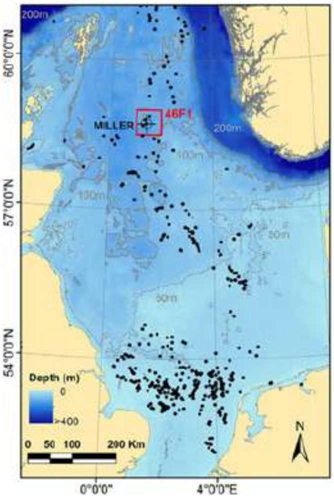

Figure 4.6: North-Sea oil&gas platforms

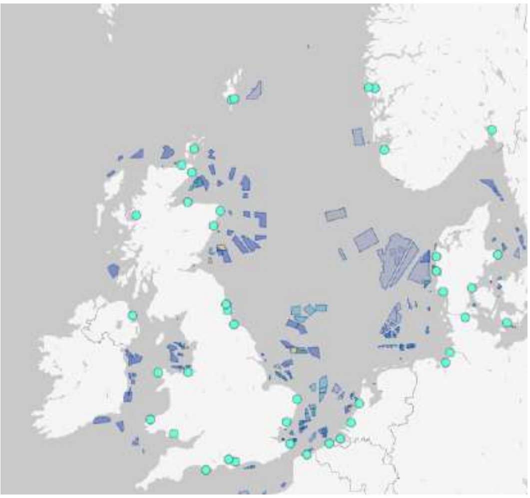

Figure 4.7: Windparks and main ports in the North-Sea

Figure 4.6 depicts a map of the North Sea locations of offshore oil & gas platforms [89] and figure 4.7 shows current and future wind parks together with main ports. A discussion of the ports will be provided in section 4.1.5 at the end of this chapter.

For the future scenarios some wells will be depleted. According to the Oxford Institute of for Energy Studies [90], the gas production in the Netherlands will completely stop by 2040. The production platforms can be converted to carbon capture storage or hydrogen production units. However, the reuse options of these platforms is limited, as depicted in figure 4.9 by the large gap between possible reuse options and number of objects to be decommissioned. Though, as several market size studies of the survey industry have pointed out, a larger demand is expected even after the decommissioning of these objects. Therefor it is assumed that the depletion of wells will even out the inspection demand with the emergence of new assets. More background regarding these developments is provided in the next section. This Annex will be separately taken into consideration during the model construction.

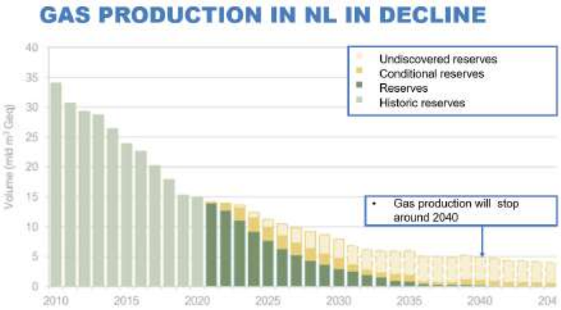

Figure 4.8: Gas production decline in the Netherlands

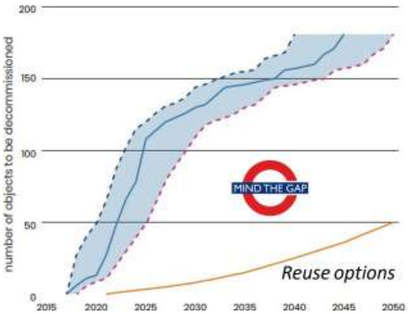

Figure 4.9: Reuse & decommissioning report 2018 [91]

ANNEX PART I

As part of the annex, a separate feature of this model will consider a future scenario in which oil & gas production will stop around 2040 while several production platforms continue operations as carbon capture storage hubs on top of the depleted wells, and function as hydrogen conversion platforms for the energy supplied by connected wind farms. Furthermore, as wind turbines are moving offshore rapidly, energy islands become an attractive alternative for projects over 100 kilometers offshore. They can provide an ideal logistical solution for the USVs limited range. With the central locations within the North-Sea of the energy islands transit times and distances will be significantly reduced. The results and implications of the model will be discussed in the annex of chapter 7.

While traditional energy supplies will be depleted over time, new offshore assets such as floating wind structures will be developed and other survey such as coastal mapping will become more important given the rising sea-levels. Overall, the offshore survey is expected to continue growing [92]. This will be reflected in the future time indices of the model simulations.

These future scenario's will not be considered when the model runs for the initial time frames will be ran. The routing decisions regarding vessel investments and harbor locations model are intended to have a lasting impact on decisions in following time indices. As a result, the assumptions regarding the asset locations of hydrogen conversion platforms and energy islands were taken into account for the whole model, they would remain to have a considerable impact on the model outcome for initial scenarios. Hence, scenario $t = 2$ is ran separately from rest of this research and its findings will be reported in the annex.

4.1.3. THE SET OF VEHICLES $\{k_t \in K_t\}$: TRADITIONAL VESSELS AND USVS

BACKGROUND

In the previous section the changing topology of the assets in the North-Sea was explained. As offshore wind farms are constructed further from the coast, maintenance and inspection with crewed vessels becomes increasingly risky, time-consuming and expensive [93] To overcome this challenge, the industry is turning to remote and autonomous technological solutions that can support offshore wind farms far out at sea. Faster maintenance vessels with more favourable operational limits are required for better operations, especially as wind farm projects are moving to harsher environments; to greater depths and farther from shore [41].

Currently, offshore inspections are performed by large heavy-duty vessels (figure 4.10) that staff over 40 people to perform continuous operations, staying offshore up to several months before returning. However, these operational processes are about to be change. Today's businesses are increasingly focused on making a collaborative impact on society and contributing to a sustainable planet. Businesses are challenged to become more sustainable and socially engaged and at the same time lead the digital change. The integration and adoption of USVs will significantly benefit the overall environmental impact of marine expeditions and operations. Different sizes of USVs will allow certain types of vessels to operate further offshore, while also reducing the carbon footprint. The remotely operated USVs enable safer, faster and sustainable operations by bringing this staff on shore throughout the entirety of the project. However, due to the limited range of USVs they can only operate offshore for 2 weeks before returning to shore for refueling. This poses a logistical challenge for Fugro's offshore operations. With the first USV operational in the industry (figure 4.11), it will be interesting to look at what the future might hold. As the industry becomes increasingly convinced about the benefits brought by remote and digital solutions, it only seems a matter of time until this new way of working unlocks its full potential.

Figure 4.10: Fugro's Atlantis Dweller:
A (70 meter) traditional survey vessel:

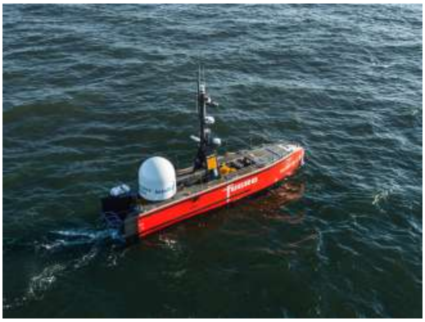

Figure 4.11: Fugro's Blue Essence:
A 12-meter USV

Supporting the transition to sustainability, safety and efficiency, a solution based on USVs will play a vital role as an attractive, competitive and secure alternative of traditional vessels. The USV in combination with a Remotely Operated Vehicle (ROVs), as depicted in figure 4.12, allows for missions, such as deep-water bathymetry, to be undertaken with less human personnel and less environmental impact while also reducing the operational costs compared to traditional crewed vessels. USVs are capable of automated path-following, heading hold and position keeping. The USVs are intended for missions to be undertaken solo or as part of a larger group of crewed or uncrewed vessels. USVs can be routed to specific points along the assets to gather photographs, imagery, and bathymetric data. The key characteristics of the USV are summarized as follows:

- Endurance of up to 16 days offshore.
- Emissions of less than 5% of standard ocean-going survey vessel.
- Operational cost reduction of 20% compared to traditional survey vessels as a combined result of a reduced day rate despite more operational days per inspection.

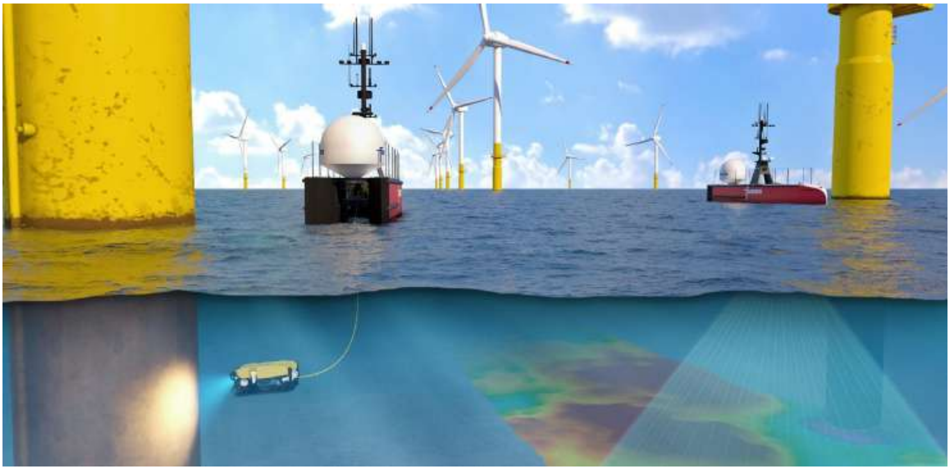

Figure 4.12: USVs performing survey work at an offshore wind park.

However, due to the USV's range constraints and operational limitations, not all demand is suited for USV inspections. The operational limitations are overlooked in this study, as the work scope of each inspections job at the demand nodes is assumed to be covered by each vessel type. Despite disregarding the operational limitations, the range constraints and the endurance of the USVs are taken into account. As in fact, the time to complete the work scope of the inspection demand nodes is longer than the endurance of the 12-meter USVs (the endurance of the USVs reaches up to 14 days of offshore operations, while the days required to execute an inspection is over 20), the 12-meter USV needs to return to shore to refuel halfway through each inspection. As a consequence, the 12-meter USV is limited to a range that lies within 'one day of sailing'. Otherwise, the USV will not be able to complete the workscope with one intermediate return for refueling. Therefor, it is unrealistic to assign inspection jobs to the USVs that are beyond one day of transit distance.

An 18-meter USV with extended endurance is currently being developed to overcome the intermediate refueling constraint. This 18-meter USV is intended to have roughly double the endurance. This should enable 18-meter USVs to execute offshore operations without having to return for refueling halfway through a project.

Lastly, a given vessel type has limiting operational weather requirements [37]. The requirements can be related to waves (wave heights, period and direction) and wind (wind speed and direction). Vessels also have safety weather requirements. These requirements are either less strict than or correspond to the operational weather requirements. When a weather parameter reaches one of the safety weather requirements for a vessel type, all vessels of this type have to return to a safe haven, in most cases the vessels' base. Some vessels need to return to their base after one operative shift, while other, larger vessels with accommodation possibilities can stay offshore and operate several shifts before they need to return to their base.

MODEL IMPLICATIONS

The endurance and operability of USV's to stay out on open waters will most likely remain a weakness compared to a conventional crewed vessel. As this impacts the operational range and the ability to meet client demands, it will be likely that USVs will increase in size to (increasing endurance and operability) and quantity (ability to serve demand). Therefor, plans to design 12 meter, 18 meter and even 24 meter adaptations of the USV with different characteristics are being made.

Apart from the traditional vessels, this research only considers the 12 meter and the 18 meter versions of the USVs. Furthermore, each vessel type is assumed to be able to perform inspections at each demand node. The 24 meter vessel is still a long way from being developed, but could be implemented in future extensions of the model. A sensitivity analysis in chapter 6 will make specific recommendations regarding the importance of the different characteristics regarding the design of the 24-meter USV.

The characteristics that are considered as model input for the traditional vessel, 12-meter USV and 18-meter USV are provided in table 4.1 below. Each vessel has different characteristics in terms of:

1. Range [Maximum distance in knots that can be reached within one day of sailing]
2. Speed of navigation [Knots per hour]
3. Operability [Maximum days of operations per year]
4. Costs of operations. Day rate including fuel costs, employee wages and vessel depreciation [Euro's per day]
5. Tonnes of CO^2 emissions per kilometer [tonnes of CO^2 per day]

4.1.4. THE ROV

Remote Operated Vehicles (ROVs) are not included as an integral part of the Mathematical Model of the facility location problem. However, they are an important component of remote and autonomous operations and are thus not left out of this research :discussed in this section. ROVs are tethered underwater vehicles equipped with video cameras, sonars, pipe-trackers and navigation, positioning sensors and integrated job specific tooling. ROVs inspect subsea system pipelines and other subsea equipment in water depths where divers cannot operate at depths as great as 4000 metres. ROVs are typically used for exploration drilling, inspection projects such as pipeline surveys and platform & subsea structures inspections, and construction support of subsea infrastructure installations. Overlooking the different configurations of ROVs should be noted as a limitation of the model. The demand nodes will not incorporate specific ROV requirements to perform inspection. Hence, the model will allow each type of USV to perform inspections at all demand nodes.

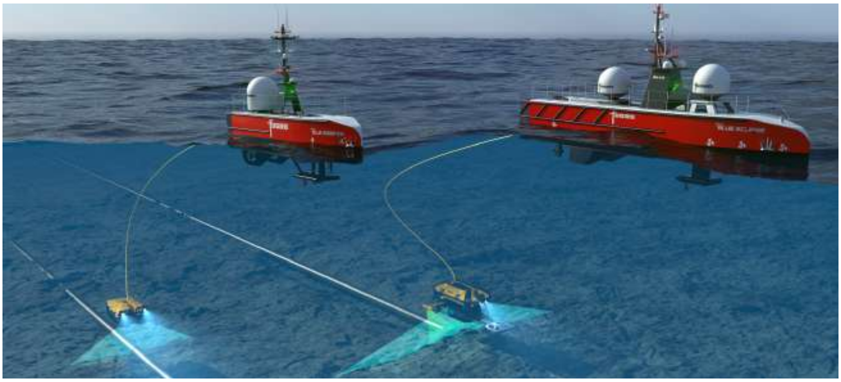

Figure 4.13: Pipeline inspections performed by a 12-meter and 18-meter USV with different ROVs

4.1.5. THE SET OF FACILITIES $\{j_t \in J_t\}$: ROBODOCKS AND HARBORS

BACKGROUND

In between the execution of offshore inspections, vessels need to come back to shore for crew changes, replenishment's and maintenance. This happens on a regular basis each 6 to 8 weeks. Crew changes are often a costly and logistically challenging undertaking, aligning flight's, taxi's and hotel's for the inbound and outbound crew. USVs, operating crewless, offer another benefit in this regard. However, although the benefits of USVs are substantial, these technological advancements have simultaneously introduced new challenges. Offshore robotic solutions work most efficiently when there is an automated local, in-field facility that can accommodate the systems for safety, recharging and data transfer. Without offshore support of onboard personnel, USVs and other autonomous robotic solutions will have to regularly travel large distances to coastal locations ports for recharging and data transfer. This consumes time and fuel that could otherwise be used to deliver operation and maintenance plans. Considering the limited range of the USVs, a crucial consideration for the efficiency of operations lies within locating the optimal harbor locations form where the vessels will set sail.

To allow for fully remote operations, and limited on-site support crew, there will be a requirement to dock and recharge USVs autonomously and perform maintenance activities in ports without people interference. First attempts towards autonomous docking have been undertaken, referring to the robodock developments, funded by Netherlands Enterprise Agency from the Dutch Ministry of Economic Affairs and Climate Policy (RVO (Rijksdienst voor Ondernemend Nederland)) [94].

Fugro is developing an automated docking platform from which uncrewed vessels can perform inspection and maintenance operations. This robodock platform will enable various uncrewed vessels to carry out inspection as well as serving as a recharge station. Effectively eliminating the need for autonomous assets to return to shore, robodock will incorporate storm-resistant docking points, automated launch and recovery, and charging points. The platform will also facilitate data download to and communication with the onshore ROCs, and ongoing monitoring of wind farms [95]. In the words of Fugro's Director of Remote Inspection Ivar de Josselin De Jong:

> *"Roboock is a technological innovation that will allow the offshore industry to accelerate the adoption of remote and autonomous solutions by creating an uncrewed platform which can support remote inspections. Removing human workers from extreme environments reduces risk in offshore operations and provides a scalable solution to support the industry transition towards a safer and more liveable world."*

Robodock stations could offer coastal security and coastguard operations support, aiding in maritime search and rescue, and shipping traffic and environmental monitoring. In the future, they could even be located at emerging North-Sea Energy Hub Islands or at wind park transformer platforms. At these locations, robodocks could also offer a number of potential applications within the scientific community. These include advanced monitoring, research and acquisition of environmental and metocean data via the addition of sensors to the robodock platform, or cameras for advanced subsea flora and fauna surveys. In this way, the platform could help scientific researchers gain a better understanding of the pressures affecting marine and coastal environments.

Figure 4.14: Robodock platform in a small harbor

Following from a series of expert interviews a set of Port Selection Criteria were determined. Some basic conditions should be available at the ports are for the robodocks to operate efficiently:

1. Connectivity: wired fibre internet connectivity, as well as 4G network coverage.
2. Power supply: to power the operations at the pontoon.
3. Logistics: crane access from road and crane ability to reach from cradle to the water.
4. Water depth: at least 3 meter to fit USV depth including the possibility for pontoon mooring.
5. USV Accessibility: no locks or time windows that limit the freedom of operations.

The costs for the robodock are based on the port dues at the selected harbor locations. Since these are generally smaller harbors than for the large traditional vessels, the port dues are also considerably lower: around €10.000 per year. As the USVs will frequently be in and out of the robodock ports, the robodock pontoons will be required at the same location throughout the operational time of the USVs. Considering the fact that the USVs will only be operated for 150 up to 200 days per year, the port dues are an estimated €6.000.

The large ports where traditional vessel harbors are generally more expensive than the marina-like ports that are open to the small-sized USVs. However, the port dues only need to be paid during crew changes of the traditional vessel, which happens each 6 to 8 weeks. Contrary to the set price for the robodock, this means that a traditional vessel will be out at sea, performing 4 to 5 inspection jobs from a single centroid before it returns to port. There the crew change will generally take one or two days. The port dues and crew accommodations are estimated at around €2.000. However, there is a continuous cost of roughly €10.000 per day that includes the personnel wages and vessel depreciation costs. Therefor, a harbor cost of €22.000 is considered during the berthing of the traditional vessel in between jobs. In chapter 7, a sensitivity analysis will indicate effect of this assumption on the model outcome.

MODEL IMPLICATIONS

After a series of expert interviews the locations of traditional vessel harbors and robodock harbors were narrowed down. From a large set of harbors, yacht and marinas, the potential USV locations were selected based on the viability of the aforementioned 5 conditions that are required for robodock compatibility. The traditional vessel harbors were selected in accordance with the harbors most commonly used by Fugro.

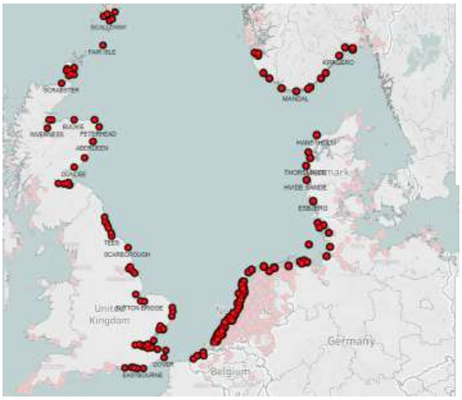

Figure 4.15: All North-Sea harbors

Figure 4.16: Selected Harbors

To conclude the harbor section, the notable implications are:

- Traditional vessels can perform 5 inspection jobs before requiring a crew change.
- Traditional vessel harbors contribute to the costs based on crew changes in between operations per vessel.
- Robodock harbors contribute to the costs based on yearly port dues, independent of the number of USVs allocated per facility.
- Energy island and robodock locations at offshore transformator substations will only be considered for the final time index $t = 2$, and separately ran as earlier described.

4.1.6. THE ROC

Although ROCs will not be covered as an integral part of the Mathematical Model of the facility location problem, they are the final fundamental component of the remote and autonomous operations and therefor described in this short section.

The transition to remote maritime operations will relocate the entire crew to a safer environment ashore. Uncrewed working will require the digitization of workflows so that crew members can perform their duties from an onshore location, resulting in a better work-life balance. Through this digitalized method of operations, customers could benefit from quicker data delivery and as a result allow for faster decision-making.

USV technology does not replace the need for skilled personnel within the industry; rather, it has the potential to allow them to work more efficiently and in a safer Remote Operation Center (ROC) environment. The ability to deploy, manage and operate uncrewed vessels from ROCs anywhere in the world reduces the number of individuals required to work in harsh and potentially dangerous offshore environments.

A global network of Remote Operation Centers delivers insights to manage offshore projects safely. ROCs are the foundation of a globally integrated remote and autonomous future that is highly scalable.

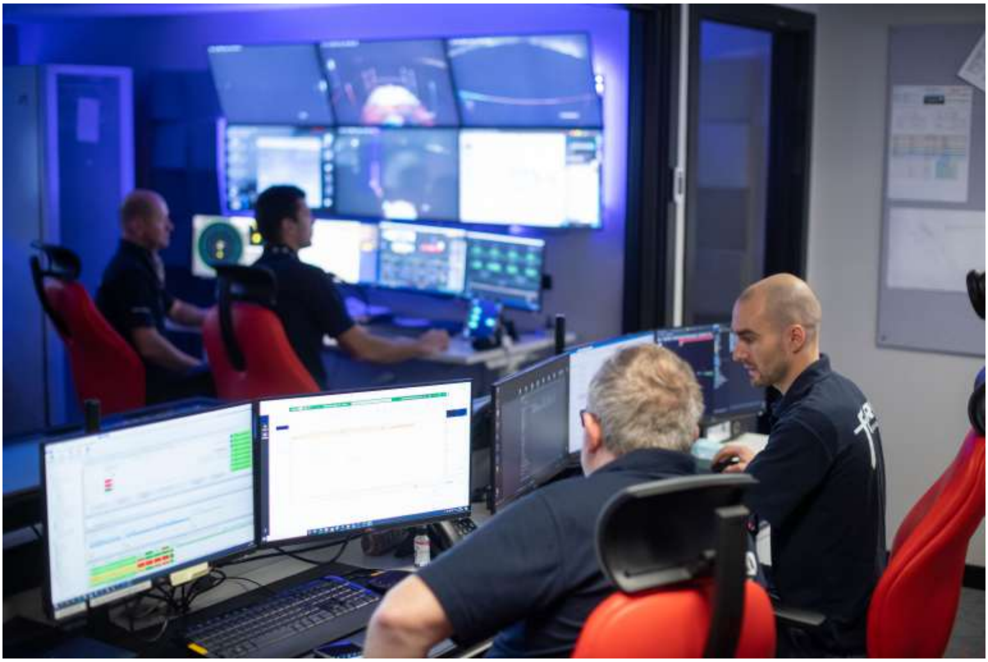

Figure 4.17: Fugro's Remote Operations Center in Aberdeen

An overview of the model components that are taken into account in each of the different steps of the time sequence is provided below. Newly introduced components in a given time frame are bolded:

Table 4.3: Overview of model components throughout $i_t \in I_t$

	Year		
Component	$t = 0$	$t = 1$	$t = 2$
Infrastructures $i_t \in I_t$	Oil & gas infrastructures Wind parks	Oil & gas infrastructures Wind parks **New wind parks**	Oil & gas infrastructures Depleted O&G paltforms **Hydrogen conversion stations** Wind parks New wind parks
Vessels $k_t \in K_t$	Traditional vessels 1 12-meter USVs 0 18-meter USVs	Traditional vessels 12-meter USVs (≥t=0) **18-meter USVs**	Traditional vessels 12-meter USVs (≥t=1) 18-meter USVs (≥t=1)
Harbors $j_t \in J_t$	Traditional vessel harbors USV harbors	Traditional vessel harbors USV harbors	Traditional vessel harbors USV harbors **Transformator substations** **Energy Islands**

4.3. CONCLUSION

After this elaborate discussion regarding the conceptualization of the system components, the formalized parameters will be further addressed by incorporating them in the mathematical formulations. This way, the complexity of the system will be captured within the model. Before extending the generic mathematical model that was provided in chapter 3.2, we will shortly revisit **sub question 2:** *what are the unique characteristics of the system components in the offshore service industry?*

To answer this question, an overview of the characteristics of the components and their implications on the model will be provided:

- The scope is limited to the offshore operations in the North-Sea.
- Each asset is expected to request an inspection once in every given time frame.
- All demand is tendered to a single party.
- Demand nodes are split up into windparks or oil & gas platforms. Each with a recurring and constant demand with a fixed profit and identical work scope that can be performed by all the vessel types.
- No specific equipment requirements for assets inspections will be considered. Every vessel will be able to execute the same operations at each demand node.
- The influence of weather conditions is limited to an assumed number of operable days per vessel type per year and does not affect the travel speed, operability or range of the vessels.
- The exact number of days is defined by the speed of the vessels that execute the operations.
- Revenues at demand nodes are a fixed amount of €750.000 for wind parks and €1.000.000 for oil & gas infrastructures.
- The number of days to complete the work scope of the assets is a direct result of the speed of the vessel that execute the operations.
- Traditional vessels are able to execute operations at 4 demand nodes before a crew change in one of the ports needs to be arranged.
- Traditional vessels travel via centroid nodes.
- Costs are based on the day rate of vessels and harbor costs.
- Traditional vessel harbors contribute to the costs based on the number of crew changes in between operations per vessel.
- Robodock harbors contribute to the costs based on yearly port dues, independent of the number of USVs allocated per facility.

- Robodocks are able to change location over time; the costs for the mobilization and transportation are estimated at roughly €50.000.
- In future years, original demand nodes from depleted fossil fuel reserves will be directly replaced by carbon capture storage locations, hydrogen conversion stations and floating wind assets.
- Energy island and robodock locations at offshore transorfmator substations will only be considered for the final time index $t = 2$, and separately ran from the other simulations in the annex of chapter 7.

4.3.1. PARAMETER ASSESSMENT

Each parameter is examined to guarantee that the values are reflecting the specific conditions for this case study. For the purpose of acquiring correct parameters, interviews were held with several experts from the survey industry.

4.3.2. KEY PERFORMANCE INDICATORS

The key performance indicators that will be tracked during the simulations are:

- Total profit.
- Number of nodes visited by each type of vessel.
- Number of vessels used for each type of vessel.
- Tonnes of CO2 produced during operations for each type of vessel.
- Harbor locations where the USVs will be located.

Chapter 5 will cover the extended *multi-period max profit facility location problem* considering the aforementioned system components.

5

THE EXTENSIVE MATHEMATICAL MODEL

Mathematics is the only place where truth and beauty mean the same thing.

Danica McKellar - Writer

THIS short, yet beautiful chapter provides a brief overview of the extended mathematical model describing the facility location problem that is encountered in this case study. After chapter 4 has covered the characteristics and the giving conditions, this chapter will provide the necessary adaptations to the facility location problem complemented by the specific conditions following from the case study.

The following sections elaborate on the facility location model that is used to analyse the interaction between the fleet, harbor locations and offshore assets. The model is intended be compatible with the model design and the characteristics as provided in chapter 4. The aim of the constructed model is to capture the complexity of the dynamic environment into a conventional MIP model. Several simplifications and assumptions are made to represent the system as a model. These assumptions are presented and motivated in the first section of this chapter. After, the extended mathematical model will be formulated by covering the definitions of sets, parameters and decision variables, before addressing the updated objective function and constraints of the facility location problem from chapter 3, The Mathematical Model.

5.1. MODEL REQUIREMENTS

For the sake of completeness, the model requirements as discussed in chapter 4, The Model Design, are provided once more in this chapter in the following overview of the characteristics and implications of the model components:

- The assets are represented by demand nodes that have a recurring and constant demand with a fixed profit that can be collected by all the vessel types.
- The future demand is addressed through several sets of nodes in different time indices of 5 to 10 years. These represent distinct scenarios in terms of changes in demand over a given period. Hence, the time indices should not be considered as single, consecutive single years.
- The amount of days it takes to complete inspection jobs is fixed for each type of vessel.
- The characteristics of the designs of only two types of uncrewed surface vessels are taken into account while only one type of traditional survey vessel is considered.
- The traditional survey vessels are routed through centroids in order to approximate and compare their distinct routing behavior to that of USVs.
- Each asset is expected to request an inspection once in every given time frame.
- All demand is tendered to a single party.
- Demand nodes are split up into windparks or oil & gas platforms, each with a recurring and constant demand with a fixed profit and identical work scope that can be performed by all the vessel types.
- The influence of weather conditions is limited to an assumed number of workable days per vessel type per year and does not affect the travel speed, operability or range of the vessels.
- Traditional vessels can execute operations at 4 demand nodes before returning to port for a crew change.
- Costs are based on the day rate of vessels and harbor costs.
- Traditional vessel harbors contribute to the costs based on the number of crew changes in between operations per vessel.
- Robodock harbors contribute to the costs based on yearly port dues, independent of the number of USVs allocated per facility.
- Robodock harbors can be moved over time, but such a move will infer a penalty cost to account for the mobilization and transportation costs.

5.2. MODEL FORMULATIONS

5.2.1. DEFINITIONS

Table 5.1: Definitions of sets, parameters and decision variables

Sets

T	Set of time indices t,
I_t	Set of active demand locations (wind and O&G nodes) in year t
J_t	Set of active potential facility locations in year t
U_t	Subset of all potential USV facility locations in year t
H_t	Subset of all potential traditional harbor facility locations
Q	Set of centroids
V	Set of vessel types with $V = 1, 2, 3$
$K_{V,t}$	Set of all vessels.
$K_{1,t}$	Set of traditional vessels in year t
$K_{2,t}$	Set of 12-meter USVs in year t
$K_{3,t}$	Set of 18-meter USVs in year t

Indices

$i \in I_t$	-
$j \in J_t$	-
$k \in K_{V,t}$	-
$U_t \subset J_t$	-
$H \subset J_t$	-
$t \in T$	-

Input Parameters

p_t	Maximum number of facilities at time t
d_{ij}	Distance in knots between node $i \in I$ and $j \in J$
w_{it}	Demand at demand location $i \in I$ at time t
f_j	Facility costs at harbor $j \in J$
r_k	Range capacity of vessel $k \in K$
s_k	Travel speed of vessel $k \in K$
v_k	Vessel operating costs per day of vessel $k \in K$
s_k	Travel speed in knots of vessel $k \in K$
o_k	Maximum yearly operational days of vessel $k \in K$
l_i	Duration of performing an operation for vessel $k \in K$
$G_{k,t}$	A constant for double transits of 12m-USVs, 2 for $k \in K_{2,t}$, 1 for $k \not\in K_{2,t}$
dc_V	Depreciation costs of vessel type V per year
rc	Costs to mobilize and transport robodock pontoon
M	Arbitrarily large number

Decision Variables

x_{ijkt}	$\begin{cases} 1, & \text{if demand node } i \text{ is served by vessel } k \text{ from facility } j \text{ in year } t \\ 0, & \text{otherwise} \end{cases}$
y_{jt}	$\begin{cases} 1, & \text{if a facility is located at } j \text{ in year } t \\ 0, & \text{otherwise} \end{cases}$
z_{jkt}	$\begin{cases} 1, & \text{if vessel } k \text{ is assigned to facility } j \text{ in year } t \\ 0, & \text{otherwise} \end{cases}$
a_{jkt}	$\begin{cases} 1, & \text{if robodock at } j \text{ and attributed vessel } k \text{ are relocated in year } t \\ 0, & \text{otherwise} \end{cases}$

KPIs

P_t	Total profit in year t
$P_{k,t}$	Total profit of vessel k in year t
$e_{k,t}$	Total tonnes of CO^2 emission by vessel k in year t

5.2.2. MATHEMATICAL FORMULATION

Objective:

$$\begin{aligned} max \quad & \sum_{i\in I_t} \sum_{j\in\{J_t,Q\}} \sum_{k\in K_{V,t}} \sum_{t\in T} w_{it} x_{ijkt} \\ & - \sum_{i\in I_t} \sum_{j\in\{J_t,Q\}} \sum_{k\in K_{V,t}} \sum_{t\in T} v_k l_k x_{ijkt} \\ & - \sum_{i\in\{I_t,Q\}} \sum_{j\in\{J_t,Q\}} \sum_{k\in K_{V,t}} \sum_{t\in T} \left(\frac{2G_{k,t} v_k d_{ij} x_{ijkt}}{24 s_k} \right) \\ & - \sum_{i\in I_t} \sum_{j\in Q} \sum_{k\in K_{1t}} \sum_{t\in T} f_j x_{ijkt} \\ & - \sum_{i\in U_t} \sum_{j\in J_t} \sum_{t\in T} f_j y_{U_t t} \\ & - \sum_{i\in I_t} \sum_{j\in H_t} \sum_{t\in T} dc_V z_{jvt} \\ & - \sum_{i\in U_t} \sum_{k\in K_{\{2,3\}t}} \sum_{t\in T} rc * a_{jvt} \end{aligned} \tag{5.1}$$

Subject to:

$$\sum_{j\in J_t} \sum_{k\in K_{V,t}} x_{ijkt} + \sum_{j\in Q} \sum_{k\in K_{V,t}} x_{ijkt} = 1 \qquad \forall i \in I_t, t \in T \tag{5.2}$$

$$\sum_{j\in J_t} y_{jt} \leq p_t \qquad \forall t \in T \tag{5.3}$$

$$z_{jkt} \leq y_{jt} \qquad \forall j \in J_t, k \in K_{V,t}, t \in T \tag{5.4}$$

$$\sum_{j\in J_t} z_{jkt} \leq 1 \qquad \forall k \in K_{V,t}, t \in T \tag{5.5}$$

$$\sum_{i\in I_t} x_{ijkt} \leq 4 \qquad \forall j \in C, k \in K_{V,t}, t \in T \tag{5.6}$$

$$d_{ij} x_{ijkt} \leq r_k z_{jkt} \qquad \forall i \in I_t, j \in J_t, k \in K_{V,t}, t \in T \tag{5.7}$$

$$\sum_{i\in I_t} \sum_{j\in J_t} l_k x_{ijkt} + \left(\frac{2G_{k,t} d_{ij} x_{ijkt}}{24 s_k} \right) \leq o_k \qquad \forall k \in K_{V,t}, t \in T \tag{5.8}$$

$$\sum_{j\in U_t} z_{jk(t-1)} \leq z_{jk(t)} \qquad \forall k \in K_{\{2,3\},t}, t \in T > 0 \tag{5.9}$$

$$z_{jk(t-1)} \leq z_{jkt} + a_{jkt} \qquad \forall k \in K_{\{2,3\},t}, t \in T > 0 \tag{5.10}$$

$$x_{ijkt}, y_{jt}, z_{jkt}, a_{jkt} \in \{0,1\}, \qquad \forall i \in I_t, j \in J_t, k \in K_{V,t}, t \in T \tag{5.11}$$

The objective function (5.1) consist of 7 terms that define the profit calculation over the entire time frame. The objective is to maximize the total profits. The first term accounts for the total revenue that is generated from the inspections at the assets visited from the harbors. Here, j in the first term can represent both harbors and centroids Q. This set is added to j to account for the fact that traditional vessel will only be allowed to visit nodes from centroids. All the following terms in the objective function are representing a part of the cost, in some way subtracting a share of the first term. The second term invokes the specific vessel costs for a vessel to perform the operations at a demand node. The third term represents the travel costs. Note that the summations over I and J are complemented by centroids Q since both the trips from the traditional harbors to the centroids as well as the trips from the centroids to the demand nodes must be considered. As concluded from chapter 4, the travel costs are defined as a function of both the speed s_k and vessel operating costs v_k of vessel k. Dividing twice the distance (round trip from harbor to demand node) over the travel speed per day and multiplying by the vessel operating costs per day results in the travel costs between nodes. $G_{k,t}$ denotes an additional factor for 12-meter USVs that doubles the trip length (and according travel costs). This is a result of the intermediate refueling that is required halfway through each 12-meter USV operation. The fourth term registers the port dues for crew changes. These are invoked each time a traditional vessel departs to a centroid. The fifth term represents the port dues for robodocks. Contrarily to crew changes, these are paid for per harbor j instead of per vessel k. Hence, here $y_{U_t t}$ is used in stead of $x_{ijk_{1t}t}$. The next term accounts for the depreciation costs of the selected vessels (this is calculated per vessel per year, opposite to the operation costs which are based on the days of operation) and the final term charges a penalty in the form of mobilization and transportation costs if a robodock is relocated to another harbor.

The constraints ensure that each demand location is covered by a vessel from a centroid *or* a facility (5.2). The total of facilities is limited by p_t (5.3). (5.4) assures that vehicles can only be assigned to located facilities and (5.5) assures that vehicles can only be assigned to one facility. (5.6) orders the traditional vessel to return to the traditional harbor for crew changes after executing at most 4 projects from a single centroid. The range constraints of the vessels are enforced by (5.7), while (5.8) limits the days of operations to stay within maximum yearly operational days. Similar to the second term in the objective function, the days of operation is calculated using distance and speed. Dividing the distance in knots by the speed in knots per hour and multiplying by 24 hours results in the number of days that are spent in transit. Once again, $G_{k,t}$ is noted to account for 12-meter USVs having to travel twice to complete a single job. Adding this with the days spent on operations should be less or equal to the maximum yearly operational days of a vessel. Additionally, several constraints are introduced to enforce consistency regarding the vessel fleet throughout the time indices. (5.9) ensures that the decisions to acquire additional USVs in previous time indices will be preserved as giving conditions in the subsequent time indices. Similarly, (5.10) enforces a penalty when a robodock is moved in between consecutive time indices. Finally, (5.11) assigns binary dimensions to the domain of the decision variables.

Considering the introduced heterogeneity of the vessel fleet in combination with the centroid-based routing, some additional giving conditions were defined in order to find proper results for the case study. The following giving conditions were therefor included in the form of additional constraints:

- Traditional vessels only visit demand nodes via centroids.

$$x_{ijkt} = 0 \qquad \forall i \in H_t, j \in J_t, k \in K_{1t}, t \in T \tag{5.12}$$

- If a traditional vessel goes from a centroid to a demand node, the vessel also has to go from a harbor to a centroid.

$$\sum_{j \in J_t} x_{ijkt} \leq M * \sum_{j \in H_t} x_{jikt} \qquad \forall i \in C, j \in Q, k \in K_{1t}, t \in T \tag{5.13}$$

- USVs do not travel through centroids but go directly to demand nodes.

$$x_{ijkt} = 0 \qquad \forall i \in U_t, \quad j \in Q, \quad k \in K_{\{2,3\}t}, \quad t \in T \tag{5.14}$$

5.3. MODEL OUTPUT

Following the objective function and the set of constraints, the model makes simultaneous decisions regarding the vessel fleet in combination with the allocation of the vessels to specific harbors. Both the number of vessels for each vessel type and the harbors for each vessel type are free decision variables. The objective function generates a calculated trade-off between the fleet size & mix and the allocation of said fleet to the potential harbors with the goal of maximizing profit generated by visiting the demand nodes. In other words, the goal is to select the optimal set of harbors and allocate an according fleet to visit the North-Sea assets. The routes of the acquired vessels between the allocated harbors and demand nodes will be plotted on a geographical map of the North-Sea. Furthermore, the model will return the total profit and the tonnes of CO^2 emissions per vessel.

6

MODEL BEHAVIOR

Behavior is shaped and maintained by its consequences.

Burrhus Skinner - American psychologist

WHEREAS human behavior does seem to be shaped by the consequences of it, in this chapter we try to understand the consequences of the model behavior when imposing alterations to the input parameters. In chapter 6, the outcomes of the simulations from the model as described in the previous chapter will be discussed. These outcomes will be verified and analysed on the basis of several experiments to get comfortable with the behavior of the model in its response to alterations of input parameters. In Section 6.1, the model behavior is discussed in two subsections. First, the base case and its outcomes are explained and verified. Then, the large model will be run over a single time index and validated, followed by some experiments and a sensitivity analysis regarding the vessel design. Chapter 7 will continue with a thorough analysis of the multi-period model adhering to the giving conditions of the case study.

6.1. EXPERIMENTAL SETUP

Several experiments will be conducted to verify the model behaves in accordance with our expectations. Once the model behavior has been verified, the outcomes will be tested against real-world observations in the maritime industry. Together with industry experts the simulations will be assessed to validate the credibility of the model outcomes. Finally, to better understand the impact of range, operability, speed and costs on the fleet decisions an extensive sensitivity analyses on the vessel characteristics will be provided in section 6.5.1.These experiments aim to determine the effect of modifying specific characteristics that follow from the weaker assumptions regarding the model definition. Additionally, the sensitivity analyses of the vessel characteristics will be used to make justified recommendations regarding the future vessel design.

From chapter 6, some preliminary conclusions can be drawn regarding the behavior of the model and the expected outcomes of parameter alterations over a single time period. These conclusions will be further tested in the multi-period simulations in chapter 7.

6.2. VERIFICATION

6.2.1. THE BASE CASE SCENARIO

This section begins by discussing the behavior of the model in an initial base situation. The outcomes of the models will then be verified running several experiments with different input variables.

For the following section, the simulations call upon a smaller subset of harbors and assets. Other than that, the initial model was ran with the standard setup as described in the previous chapter, considering a single time frame without restrictions regarding the vessel fleet size & mix. This yields the results depicted in table 6.1 below.

6.2.2. ORDER OF MAGNITUDE

The results are a combination of asset revenues and operational costs. Operational costs include crew costs, transit costs and harbor costs. Each of these is defined with a different order of magnitude. Asset revenues are €1 M for oil and gas infrastructures and €0.75 M for wind parks. Yearly operational costs of vessels range from €4.38 M to €7.3 M while harbor costs for USVs are €2.19 M. Considering the many assumptions, estimations and rounding of these numbers, it makes sense to lose some detail when comparing the model results. This will allow for an accurate comparison of different model simulations, without getting lost in unnecessarily detailed outcomes. Hence, the order of magnitude that is applied to compare the model results is in millions, up to a single decimal representing €100.000. Not only will this allow for a more comprehensible discussion of the results, it will also strengthen the credibility of the research through more intelligible and high-level conclusions.

Table 6.1: The base case scenario

	Profit	Number of nodes visited	Number of vessels used	Tonnes of CO^2 emissions	USV harbor locations
Total	€24.8 M				
Traditional vessel		45	2	5547	
12-meter USV		0	0	0	
18-meter USV		17	1	128	Peterhead[1]

The initial results meet the requirements of the model, providing the most profitable solution in which all inspection demand is met without violating any constraints regarding range, operability and travel characteristics. From the limited subset of feasible robodock locations, only one was selected to harbor a USV. The 18-meter USV was favoured over the 12-meter USV as it is used for certain jobs at a reasonably long range from Peterhead. A larger share of the assets (45 compared to 17) are visited by two traditional vessels with relatively long transits. This is also reflected in the astronomical difference in tonnes of CO^2 emissions produced by the vessels.

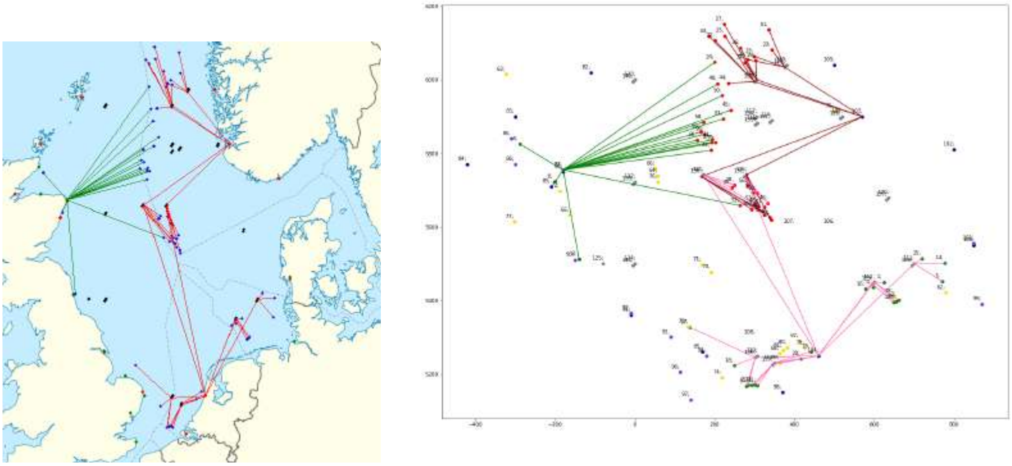

Figure 6.1: Base scenario results, plotted on map and in standard Python representation

6.2.3. VERIFICATION EXPERIMENTS

Various model components and input parameters are adjusted in order to guarantee that the model produces expected behaviour with accurate results. Table 6.2 provides an overview of the model verification procedure and demonstrates whether the predictions regarding single variable alterations are also reproduced in the Python simulations. Explanations regarding the verification status of expectations 4 and 5 will be covered in their respective subsections.

Table 6.2: Model verification expectations

Model expectation	Verification status
1. Precluding USV from optimal harbor results in lower profits	Confirmed
2. Enlarging USV range results in higher profits	Confirmed
3. Exclude 18-meter USVs results in lower profits	Confirmed
4. Decreasing the operational costs of USVs increases the number of USVs	To be validated
5. Removing harbor costs increases the number of robodock harbors	To be validated
6. Decreasing service time of USVs increases the number of nodes visited by USVs	Confirmed

1. Restricting the USV to be located in optimal harbor Peterhead should result in lower profits.

Confirmed: The total profits of the operations decrease from €24.8 M to €24.7 M.

The outcome of this simple restriction provides some interesting indications regarding the model behavior. The results hardly change, as the 18-meter USV is relocated southward at the harbor of Blyth. From here it is unable to reach one of the nodes that was within reach from Peterhead. This node now has to be covered with a traditional vessel that is subsequently based in Norway in stead of in the Netherlands. This results in a slightly less efficient model in which the traditional vessels take over another demand node. As expected, the additional distance traveled by the traditional vessels results in higher travel costs and hence a lower profit. Additionally, a higher amount of CO^2 emissions produced during operations.

Table 6.3: Verification 1 results

	Profit	Number of nodes visited	Number of vessels used	Tonnes of CO^2 emissions	USV harbor locations
Total	€24.7 M				
Traditional vessel		46	2	5702	
12-meter USV		0	0	0	
18-meter USV		16	1	121	Blyth[1]

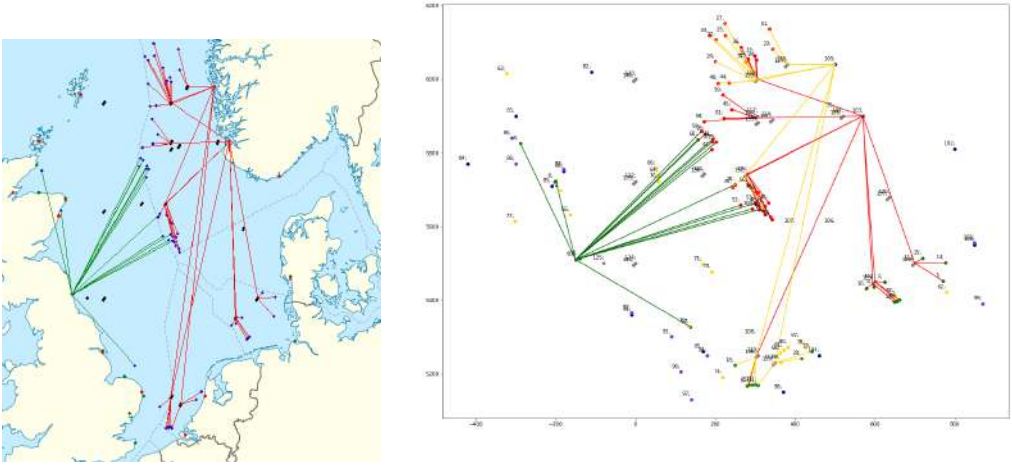

Figure 6.2: Verification 1 results, plotted on map and in standard Python representation

It appears that the perceived changes are a consequence of the limited range of the 18-meter USV, which is now unable to cover the same set of demand nodes. This begs the question whether a larger share of the workscope will be performed if the 18-meter vessels would have a larger range.

2. ENLARGING THE RANGE OF 18-METER USVS SHOULD RESULT IN HIGHER PROFITS.

Confirmed: The total profits of the operations increase from €24.8 M to €28.4 M.

Apparently the range of the 18-meter USV was a binding constraint for the performance of the model regarding the nodes that were previously visited by traditional vessels. As depicted in figure 6.3 below, the complete workscope is now performed by two 18-meter USVs, operated from Peterhead and Wells-next-the-sea. This indicates that previously, the combination of operability and range constraints made it impossible to cover all the work with a single USV. Now that the range constraint is eased, it shows the strong preference of the model towards USV operations compared to traditional vessel operations. More convincingly, it seems to strongly prefer 18-meter USVs over 12-meter USVs.

Table 6.4: Verification 2 results

	Profit	Number of nodes visited	Number of vessels used	Tonnes of CO^2 emissions	USV harbor locations
Total	€28.4 M				
Traditional vessel		0	0	0	
12-meter USV		0	0	0	
18-meter USV		62	4	121	Peterhead[1], Wells-next-the-sea[1]

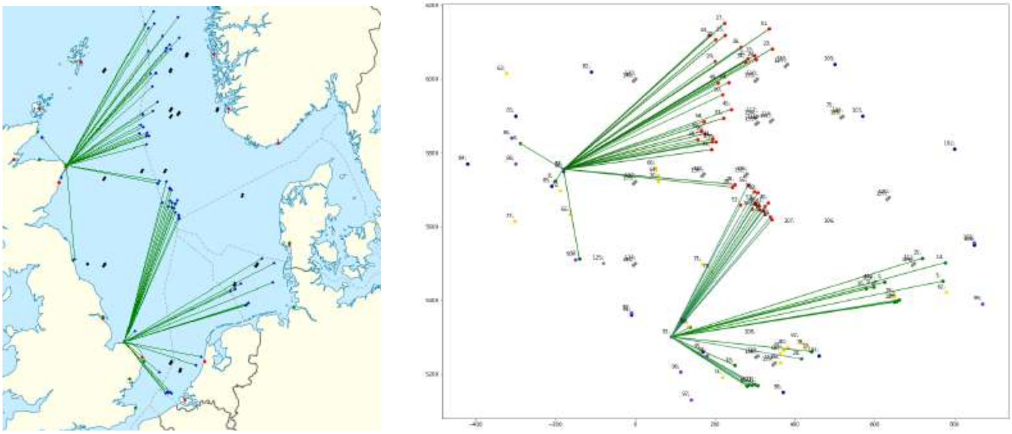

Figure 6.3: Verification 2 results, plotted on map and in standard Python representation

Given the strong preference towards 18-meter vessel compared to the 12-meter USV, it will be interesting to see what happens to the model when no 18-meter USVs are considered. In fact, this will also be the case for $t = 0$ when performing the multi-period model in chapter 7. In current operations, no 18-meter USVs are deployed yet.

3. Removing the 18-meter USVs should result in lower profits.

Confirmed: The total profits of the operations decrease from €24.8 M to €20.5 M.

Similar to the outcomes of earlier experiments, Peterhead is selected to harbor one of the USVs. This time, a 12-meter USV is deployed to inspect the northern assets from Peterhead. In this case, Without any 18-meter USVs that can be deployed, another 12-meter USV will be completing the southern assets from Lowestoft. Adopting two 12-meter USVs appears to be more cost-efficient than operating another traditional vessel for the limited set of assets visited by the USVs (12 in total). However, the implications between the 18-meter USVs and 12-meters in terms of range become painfully visible in the picture below.

Table 6.5: Verification 3 results

	Profit	Number of nodes visited	Number of vessels used	Tonnes of CO^2 emissions	USV harbor locations
Total	€20.5 M				
Traditional vessel		50	2	6201	
12-meter USV		12	2	95	Peterhead[1], Lowestoft[1]
18-meter USV		0	0	0	

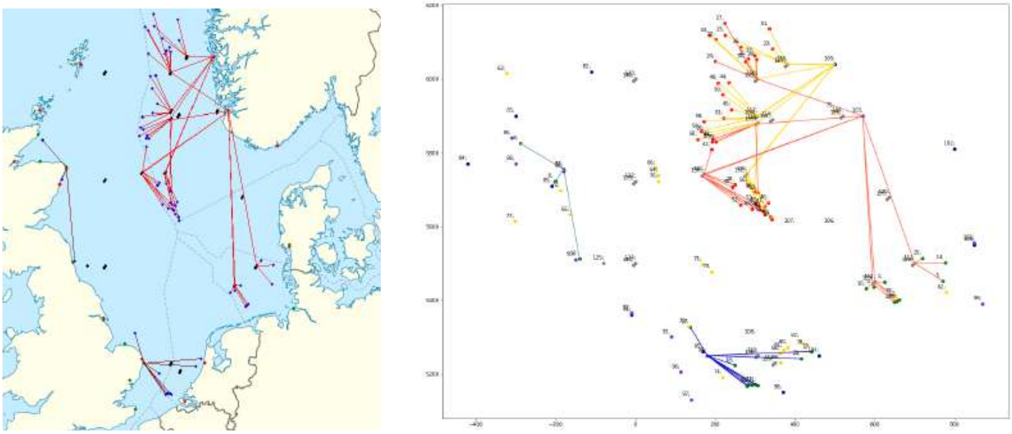

Figure 6.4: Verification 3 results, plotted on map and in standard Python representation

Now that the expectations and predictions of the model behavior in terms of its objective of maximizing the profit in response to altered model input have been verified, the following three experiments will be conducted to explore the coherence regarding the output of other key performance indicators. In the first example, once again, 18-meter USVs will be excluded.

4. DECREASING THE OPERATIONAL COSTS OF 12-METER USV SHOULD INCREASE THE NUMBER OF DEPLOYED 12-METER USVS (WHEN THERE ARE NO 18-METER VESSELS)

Not confirmed: the same number of 12-meter USVs has been acquired.

Explanation: the outlook of the results is exactly the same as in figure 6.4 on the previous page. The same vessels are used to execute the same inspections jobs. However, as the operational costs of 12-meter USVs have decreased, the forthcoming profits for the same operations have increased. The total profits of the operations increase from €20.5 M to €21.3 M. Remarkably, no additional work has been taken over by the 12-meter USVs, indicating they are actively bounded by the range or operational constraints. To better understand the impact of range, operability, speed and costs on the fleet decisions an extensive sensitivity analysis on the vessel characteristics will be provided in section 6.5.1.

5. REMOVING HARBOR COSTS SHOULD INCREASE THE NUMBER OF ROBODOCK HARBORS, CONSIDERING BOTH 12 METER USVS AND 18 METER USVS.

Not confirmed: in this case, the model yields the same number of robodock harbors as the initial model simulation.

Explanation: again including the 18-meter USVs, in line with the previous experiments, the results from this simulation are the same as those from the initial base scenario, except that now the model yields a slightly higher profit. This increase is, unsurprisingly, exactly equal to the removed harbor costs. The inference that harbor costs are not a binding factor for the small model, indicates that harbor costs might not be a critical parameter of the model as its impact on the total profits is relatively insignificant.

6. DECREASING THE SERVICE TIME OF 18-METER USVS SHOULD INCREASE THE NUMBER OF NODES VISITED BY 18-METER USVS

Confirmed: the number of nodes visited by 18-meter USVs increases from 17 to 36.

With a reduced service time, the simulations prefer two 18-meter USVs to be deployed compared to only one 18-meter USV in the base model. Once again the USVs are based in Peterhead and Lowestoft. Furthermore, the strong reduction in the service time presents substantial improvements to the profitability of the model. The total profits of the operations increase from €20.5 M to €30.2 M. This is due to the fact that a significant share of the costs are invoked during operations, reducing the time it takes to perform operations and consequentially reducing the costs of operations significantly.

Although resulting in a profit increase and more nodes visited by the 18-meter USVs, the model is still reliant on traditional vessels to complete to full work scope. This indicates that with the current parameters the USVs will not be able to complete the full work scope of the given set of demand nodes. Either the range of the USVs or the locations of the robodocks need to become more favorable to enable travel to these nodes.

Table 6.6: Verification 6 results

	Profit	Number of nodes visited	Number of vessels used	Tonnes of CO^2 emissions	USV harbor locations
Total	€30.2 M				
Traditional vessel		26	1	3180	
12-meter USV		0	0	0	
18-meter USV		36	2	154	Peterhead[1], Lowestoft[1]

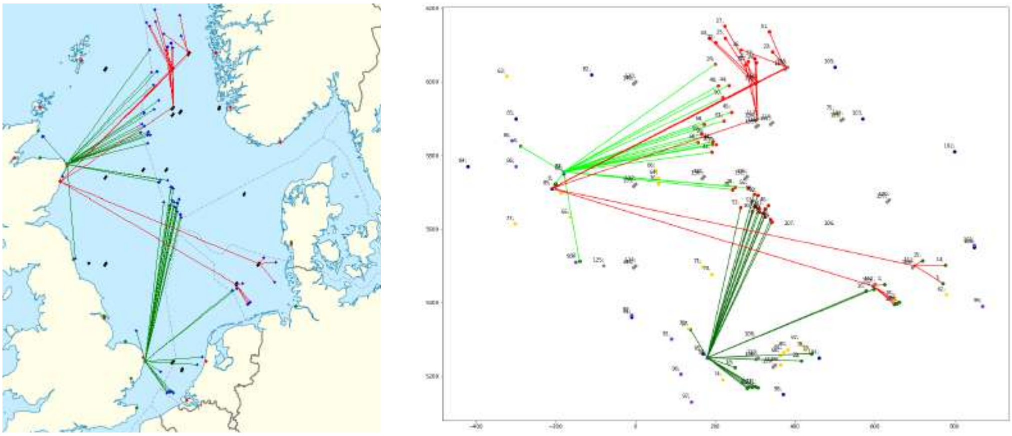

Figure 6.5: Verification 6 results, plotted on map and in standard Python representation

Another interesting aspect to consider, is the notion that the input parameter of service time would not usually fluctuate independently from other parameters. In the model, service time is a separately defined parameter that impacts costs of operations and limits the total number of inspections vessels can perform before reaching their maximum days of operations. In reality, service time could be increased by performing inspections at greater speeds. This should then also be reflected in the parameters of travel speed and range(which is the maximum distance covered in one day of travel, hence a direct result of the travel speed). In the sensitivity analysis for vessel design more attention will be paid to the relative influence of vessel characteristics and the interrelations of travel speed, service time and range.

6.3. THE COMPLETE INPUT MODEL WITH A SINGLE TIME INDEX

For the experiments in the following section, depicted in table 6.7, the full set of harbors and demand nodes as introduced in chapter 4 at time index $t = 0$ will be considered. These experiments aim to determine the effect of modifying specific characteristics that follow from the weaker assumptions regarding the model definition. First of all, centroid throughput, meaning the number of inspection jobs a traditional vessel can do in one trip from the harbor, is relatively overestimated. The impact of this overestimation on the model results will be provided in the next subsection. After, a reduction of the average profits at the assets will be invoked. The sensitivity analysis will conclude this section before providing an overview of the preliminary conclusions.

Centroid throughput, asset profitability and vessel design are tested in this chapter, because these input parameters feature large uncertainties:

- Centroid throughput is overestimated through the assumption that each time a traditional vessel leaves a harbor, it will be able to execute four consecutive projects in near proximity.
- Asset profitability is standardized for oil & gas assets and windparks. Prices are currently averaged at the top of the market, but what happens to the model if inspection prices will drop?
- Vessel design is driving the preference for 18-meter USVs. Through the sensitivity analysis we try to uncover which parameters should be paid extra attention to in the current design process of the 18-meter vessel.

Table 6.7: Experiments for the complete single-period model

Experiment	Value	Take-away
1. Centroid throughput	4 / 3 / 2 / 1	Travel distance is a large contributor to emissions. Travel distance is a minor contributor to costs.
2. Asset profitability	€75.000 / €50.000 / €25.000	Does not change facility locations.
3. Sensitivity analyses vessel design	Range Costs Operability Port availability	Available but risky way to improve profits. Especially interesting for 12-meter USVs Potential opportunity and potential vulnerability Important consideration

6.3.1. BENCHMARK RUN

Table 6.8: Benchmark run single-period

	Profit	Number of nodes visited	Number of vessels used	Tonnes of CO^2 emissions	USV harbor locations
Total	€152.7 M				
Traditional vessel		54	2	6658	
12-meter USV		0	0	0	
18-meter USV		246	15	1827	Peterhead[5], Scheveningen[10]

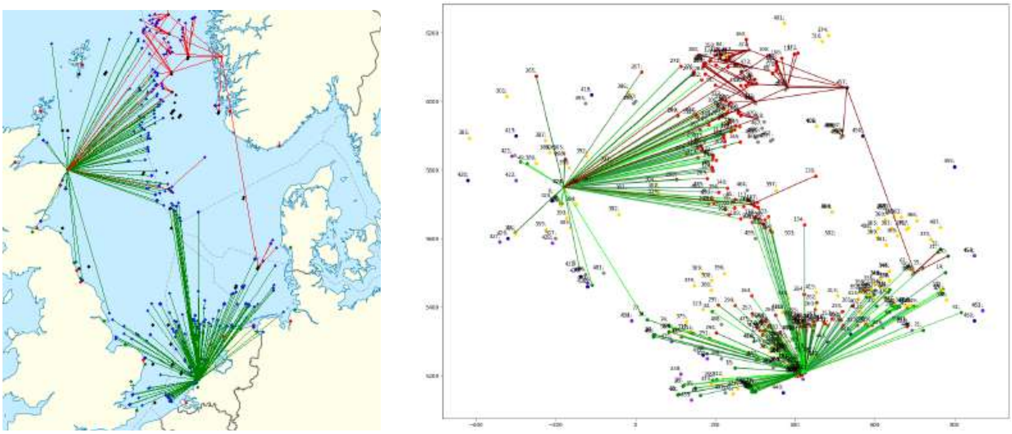

Figure 6.6: Bench mark run single-period, plotted on map and in standard Python representation

Remarkably, if there were no giving conditions and we would apply a green field approach to the current scenario the model gives a strong preference to the utilisation of 18-meter USVs. This seems odd, considering that the current operations in reality do not operate a single 18-meter USV. This result might therefor raise some eyebrows. Although these results might give the impression to be *too good to be true*, a possible explanation could be the following. Given the set of demand, the near-shore inspection nodes will be favorable for the 18-meter USV. While running out of operational days, it is able to tightly plan an inspection at a location somewhat further away. Since the 18-meter USV in this case will already be acquired, this will be cheaper than deploying a new traditional vessel.

In chapter 7, a new set of demand nodes, in the form of constructed windparks in the foreseeable future, will be added to the current set of demand nodes. These are predominantly near-shore and once again tend to be favourable for USV inspections. However, with the abundance of additional nodes near-shore, there will be too many 'left-over' routes to cover completely. For these further offshore located nodes it is more beneficial to deploy a traditional vessel. Some of the nodes located further offshore are not even able to be reached by 18-meter USVs from the given set of harbors. Hence, with the introduction of more near-shore windparks, the results will shift to applying more traditional vessels that perform the inspection demand further offshore. This yields a more intuitive result than the simulation results depicted in figure 6.6.

The perceived importance of distance to nodes and the related transit times begs the question what the influence of centroids are on the model. Being able to do 4 projects in one go is a rather ideal situation. First of all this would require vessels remain offshore for about 80 days (which is well over 8-weeks that was argued in chapter 4) and second of all it would be rather unlikely that the occurrence of inspection demand at each of these 4 projects would be within the same time interval. Therefor, the next check will address what happens if the traditional vessels were only able to execute 3 jobs per centroid.

6.3.2. CENTROIDS: TRAVEL DISTANCE IS A MINOR CONTRIBUTOR TO COSTS.

In the current scenario considering $t = 0$, looking at a reduction of the centroid throughput provides us with some valuable insights[7]. First of all, the results in terms of routing decisions and fleet size & mix only depict minor changes when we considered less centroid throughput. The total profit reductions are minimal:roughly €2 M euros per deduction in the number of centroid throughput. This can be logically verified by the amount of nodes visited (54) while requiring twice the departs from the harbors, which will then face an additional crew change cost.

Additionally, the travel distance will largely increase due to the extra imposed harbor visits in between operations. The correlation on the tonnes of CO^2 emissions caused by this is striking: the total tonnes of CO^2 emissions are almost doubled.

Reducing the centroid throughput to 3 results in a lot more knots traveled by the traditional vessels. This is also apparent from the increase in CO^2 emissions. The traditional vessels still need to perform the inspection demand for the nodes that are unable to be visited by the 18-meter USVs. As a result of the traditional vessel now spending more time in transit, a third vessel is added to comply with the requirement that all asset inspections need to be covered. If the centroid throughput is reduced to 1, only the nodes that fall outside the range of the 18-meter USV from Peterhead remain for the traditional vessels. In that case Lauwersoog is added as a third base from where the 18-meter USVs perform their operations, taking over a reasonable share of work that was previously performed from Scheveningen.

Although profitability is reduced somewhat, no major changes in this regard seem to be a result of reducing the centroid throughput.

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[7] Appendix VIII: Centroid throughput results

6.3.3. ASSET PROFITABILITY: DOES NOT CHANGE FACILITY LOCATIONS

For determining the impact of asset profitability we return to the base scenario where centroid throughput was set to 4. The average profitability for each oil &gas inspection will be reduced from €1.000.000 to €750.000 while the average profitability for each wind park inspection will be reduced from €750.000 to €500.000.

This yields no changes in topology and routes as found in the base scenario run. The same model configuration appears, only now the optimal profit will be reduced to €77.7, which is roughly half of the profit in the base case.

Table 6.9: Bench mark run single-period

	Profit	Number of nodes visited	Number of vessels used	Tonnes of CO^2 emissions	USV harbor locations
Total	€77.7 M				
Traditional vessel		54	2	2297	
12-meter USV		0	0	0	
18-meter USV		246	15	188	Peterhead[5], Scheveningen[10]

6.4. VALIDATION

The model in the current scenario yields a total profit of €77.7 M. The cumulative revenues of all the nodes in this time index is €280.5 M. This approximates the market size estimations from *Appendix VII: Market size for survey industry* in which the total market size is argued to be €265 M. In discussions with industry experts these results were considered to be acceptable ballpark estimates. Furthermore, it was concluded that the constructed facility location problem generates intuitive results and portrays predictable behavior. The incorporation of centroid routing anticipates reasonable representations of traditional vessel routes.

6.5. SENSITIVITY ANALYSES

6.5.1. SENSITIVITY ANALYSIS OF 12 AND 18 METER VESSEL DESIGN

For the sensitivity analysis the full set of harbors and demand nodes as introduced in chapter 4 at time index $t = 0$ will be considered. As introduced in the verification, the characteristics that will be taken into consideration are the speed of operations, the costs of operations and the operability limitations for the operations. Given the tendency of the model to prefer 18-meter USVs, in the sensitivity analysis the parameters regarding 12-meter USVs will be incrementally adjusted towards the 18-meter USVs.

Speed, operability and operation costs are considered because these vessel characteristics can be tweaked during the ongoing vessel design:

- Speed influences transit time, range limitations and the service time of vessels and therefor considered together.
- Operability relates to the days that USVs will be able to operate at sea. More operational days means more potential demand nodes can be visited to recoup vessel expenses.

- Operational costs are a driver of remote and autonomous operations. Through remote operations, crew can be simultaneously assigned to multiple operations, significantly bringing down operational costs.

The results of the sensitivity analysis are depicted in table 6.10.

Table 6.10: Sensitivity analysis for 12-meter USV

			Total profit	Number of nodes visited	Number of vessels	Harbor locations
Transit	6	12-meter USV	€77.7 M	0	0	
Range	144	18-meter USV		246	15	Peterhead[5], Scheveningen[10]
Service	24.6					
Transit	7	12-meter USV	€77.7 M	0	0	
Range	168	18-meter USV		246	15	Peterhead[5], Scheveningen[10]
Service	23.3					
Operability	167	12-meter USV	€77.7 M	0	0	
		18-meter USV		246	15	Peterhead[5], Scheveningen[10]
Operability	184	12-meter USV	€77.7 M	0	0	
		18-meter USV		246	15	Peterhead[5], Scheveningen[10]
Operation costs	3750	12-meter USV	€78.3 M	33	3	Scheveningen[3]
		18-meter USV		213	13	Peterhead[3], Scheveningen[10]
Operationan costs	2500	12-meter USV	€81.7 M	63	7	Scheveningen[5], Lauwersoog[2]
		18-meter USV		180	11	Peterhead[6], Scheveningen[5]

The sensitivity analysis for the 12-meter USV confirms the previous hypotheses. As perceived in table 6.10, the 12-meter USV cannot be deemed a worthy opponent of the 18-meter USV. In fact, the 18-meter USV outperforms his smaller counterpart in the performance of almost every characteristic. The only part where the 12-meter USV might have an edge can be found in the cost component. Turning this aspect into its strength might have some interesting consequences for the whole system, leading to higher profits and a more diverse fleet. With an operational cost reduction of 50% the model will yield the following results:

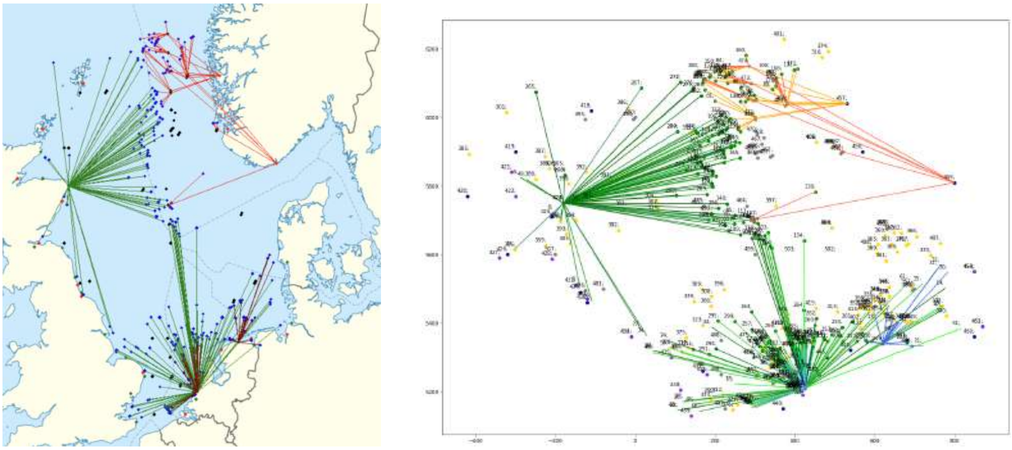

Figure 6.7: Sensitivity analysis for 12-meter USV, plotted on map and in standard Python representation

Operational costs could be a valuable distinctive aspect for 12-meter USVs

As depicted in figure 7.1, in the case of an operational cost reduction for the 12-meter USVs, the model will incorporate seven 12-meter USVs. They will be based in Lauwersoog and Scheveningen to take over the work of 4 previously deployed 18-meter USVs. The operational costs are considered to this large extent because USVs are aimed to strongly reduce the costs during operations. Without requiring personnel to be on-site, no crew will be wasted on transits and experts can be assigned to multiple projects simultaneously. In an ideal case, this could imply that a single crew can be assigned to two (or more) projects at the same time. This would cut the wages of the operational cost in half.

However, the same conclusion holds for the 18-meter USV. This further underlines the importance of defining clear use-cases in which the 12-meter USV can perform a fundamentally diverse range of tasks compared to its 18-meter counterpart. Given the influence costs seem to have, one suggestion would be to discover the possibilities for a cheaper 12-meter USV, that could perform near shore projects such as waterway surveys or coastal protection inspections. These projects are expected to surge in the coming years. In order to incorporate such jobs in the current model, the question would be, first of all, where these inspections will likely be performed, and secondly, what the profitability of these types of projects will be. This notion will be further addressed in the discussion. For now, given the model preference towards the larger USVs, it is more interesting to uncover the impact of the characteristics of the 18-meter USVs on the model outcomes.

6.5.2. Sensitivity analysis of 18 meter vessel characteristics

To take a closer look at these characteristics a specific experiment setup is constructed. The following sensitivity analysis is based on the model configuration, ran at time index $t = 0$ without allowing the allocation of traditional vessels and 12-meter USVs. Because the 18-meter USV will not be able to complete the full workscope in this case, the constraint that enforces all demand to be covered will be lifted. This yields the following benchmark results against which the alterations in input parameters will be compared.

Table 6.11: Benchmark for sensitivity analysis for 18-meter USV

	Profit	Number of nodes visited	Number of vessels used	Tonnes of CO^2 emissions	USV harbor locations
Total	€66.3 M				
18-meter USV		238	14	1761	Peterhead[4], Lowestoft [3], Scheveningen[7]

The same characteristics as previously addressed for the 12-meter USV are now taken into account. Table 6.12 contains the sensitivity analysis for the 18-meter USV. In the final row an extra potential harbor node (Stavanger) is added to the model to put the results of the vessel characteristics into perspective.

Table 6.12: Sensitivity analysis for 18-meter USV

18-meter USV	Parameter value	Total profit	Percentage change	Number of nodes visited	Number of vessels	Harbor locations
Range	192	€66.3 M		238	14	Peterhead [4], Lowestoft[3], Scheveningen [7]
+50%	288	€82.7 M	+25	300	18	Peterhead [8], Scheveningen [10]
+100%	380	€82.7 M	+25	300	18	Peterhead [8], Scheveningen [10]
Operational costs	6000	€66.3 M		238	14	Peterhead [4], Lowestoft[3], Scheveningen [7]
-25%	4500	€73.4 M	+11	253	15	Peterhead [4], Lowestoft [5], Scheveningen [5], Lauwersoog [1]
-50%	3000	€85.0 M	+28	253	15	Peterhead [4], Lowestoft [5], Scheveningen[5], Lauwersoog [1]
Operability	200	€66.3 M		238	14	Peterhead [4], Lowestoft[3], Scheveningen [7]
+20%	240	€78.6 M	+18	246	12	Peterhead [3], Wells-next-the-sea[2], Berghaven[7]
+40%	280	€85.1 M	+28.5	253	11	Peterhead [3], Lowestoft[4], Lauwersoog [4]
-20%	160	€52.0 M	-22	247	18	Peterhead [5], Wells-next-the-sea[13] Berghaven[10]
Norway port	0	€66.3 M		238	14	Peterhead [4], Lowestoft[3], Scheveningen [7]
	1	€157.0 M	+236	300	18	Peterhead [1], Berghaven[8], Cuxhaven[2], Stavanger[7]

INCREASING RANGE IS AN AVAILABLE BUT RISKY WAY TO IMPROVE PROFITS.

First of all, a potential gain can be attained rather easily in the field of USV range. As assumed in the model, inspection jobs that are over one day of sailing will not be assigned to 18-meter USVs. This assumption is made because in the early stages of USV operations it seems highly unlikely that USVs will perform operations that demand long transits. Not only will the long transits have a negative impact on the efficiency of the inspection jobs, it will also require the USVs to be further away from safe havens and out in more dangerous sea conditions. Though, with more confidence in the range of the 18-meter USV will potentially lead to a large gain in profits. Currently, this is a substantially binding constraint on the model output as can be inferred from the increase in the number of nodes visited with 192 knots of range compared to 288 knots of range. This range is in fact already available given the large fuel capacity and endurance of the intended designs for the 18-meter vessel. Though it must be noted, this is also a risky approach. Applying the larger range will mean that the USV will be way further out at sea. Not only will it then be further away from the safety of ports, also the conditions further out at sea will be substantially rougher.

OPERABILITY IS A POTENTIAL OPPORTUNITY AND POTENTIAL VULNERABILITY.

Another design characteristic to take into consideration is the operability. As depicted by the red row in table 6.12, if the intended operability of 200 operable days per year will not be achieved, this will result in significant losses in terms of profit. The model now assigns more vessels to make up for the limited number of nodes each that can be visited with each vessel. This results in a much lower profit per vessel and a much lower profit overall.

STRATEGICALLY LOCATING FACILITIES IS AN IMPORTANT CONSIDERATION.

Apart from indicating the relative importance of range and operability for the profits attained in the model, the results regarding the addition of a single potential harbor location once more underline the importance of the facility locations in this case study. An increase in range of roughly 50% results in a profit increase of 24.6%, whereas the addition of a strategically located harbor increases the total profits by **236.7%**. This outcome is depicted in figure 6.8 below.

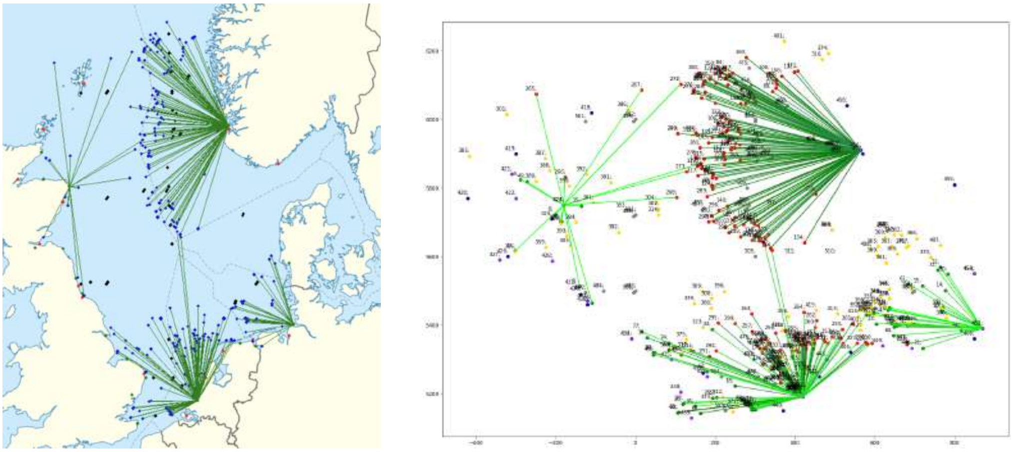

Figure 6.8: Model with harbor in Stavanger plotted on map and in standard Python representation

6.6. CONCLUSIONS

From chapter 6, some preliminary conclusions can be drawn regarding the behavior of the model and the expected outcomes of parameter alterations. These will be further tested in chapter 7. For now we will conclude chapter 6 by answering **sub question 3**: *how to develop, verify and validate a facility location problem for an initial static base scenario?*

Capturing all the complexities into a single facility location problem is a challenging task, but yields comprehensible results after the first simulations. The sensitivity analysis also pointed out some key indicators for the profitability of the system and proved to be a rather successful method to address the model outcomes for the static base scenario. The following preliminary conclusions can be drawn from the verification, validation and sensitivity analyses as conducted in this section.

6.6.1. PRELIMINARY CONCLUSIONS

VERIFICATION

- The 18-meter USVs are strongly preferred over the 12-meter USVs.
- Significant reduction in CO^2 emissions are perceived when reducing traditional vessel distances.
- Centroid throughput alterations pointed out that transits play a minor role in profit returns compared to times spent at assets during operations.

VALIDATION

- The constructed facility location problem generates intuitive results and portrays predictable behavior.
- Centroid routing anticipates reasonable representations of traditional vessel routes.

SENSITIVITY ANALYSES

- A cheaper version of the 12-meter USV could be an attractive alternative compared to the 18-meter USV for near-shore operations.
- A more confident approach towards the range of 18-meter USVs can lead to strongly increased profits.
- A risky approach that locates a robodock near the Northern inspection assets unlocks unmatched profitability.
- Peterhead, Lowestoft, Berghaven, Scheveningen and Lauwersoog are frequently recurring harbor locations throughout the different model setups.
- Extensive integration of the model complexity leads to cumbersome computations.

During the sensitivity analyses, the lack of model sparsity became apparent. This could provide serious concerns for the multi-period simulations in the following chapter.

7

ANALYSIS OF MODEL RESULTS

Analysis is the critical starting point of strategic thinking.

Kenichi Ohmae - Japanese organizational theorist

NOW that some confidence regarding the model outcomes has been established, in this chapter the giving conditions for the case study will be applied to approach the current state of activities. A thorough analysis of the results will ultimately serve as the foundation for the conclusions provided in chapter 9.

7.1. GIVING CONDITIONS

To accurately represent the current and future states of the model the following input conditions will be added to the model:

- In the current state ($t = 0$) there is one 12-meter USV.

$$\sum_{k \in K_{2,0}} \sum_{j \in H_0} z_{jk0} \leq 1 \tag{7.1}$$

- In the current state ($t = 0$) there are no 18-meter USVs.

$$\sum_{k \in K_{3,0}} \sum_{j \in H_0} z_{jk0} = 0 \tag{7.2}$$

The previous continuity constraint (5.10) ensures that the 12-meter USV that is operational in $t = 0$ will be deployed in the subsequent time indices.

MULTI-PERIOD LIMITED MODEL TRIAL

The initial results[8] meet the requirements of the model, providing the most profitable solution in which all inspection demand is met without violating any constraints regarding range, operability and travel characteristics.

The giving conditions are also met: a 12-meter USV is deployed from Peterhead in year $t = 0$, and stays there during $t = 1$, which means no robodock changes were imposed. In year $t = 1$ three 18-meter USVs were introduced while the traditional vessel fleet was scaled down from three initial vessels to a single vessel in the subsequent time index. Additionally, from these results also the decline in emissions becomes evident.

7.2. RESULTS

MULTI-PERIOD FULL MODEL

Table 7.1: Final model in year 1

Final model in year $t = 1$	Profit	Number of nodes visited	Number of vessels used	Tonnes of CO^2 emissions	USV harbor locations
Total	€129.3 M				
Traditional vessel		[141]	[5]	[15862]	
12-meter USV		[11]	[1]	[186]	Buckie [1]
18-meter USV		[266]	[15]	[1835]	Peterhead [3], Scheveningen [2], Berghaven [10]

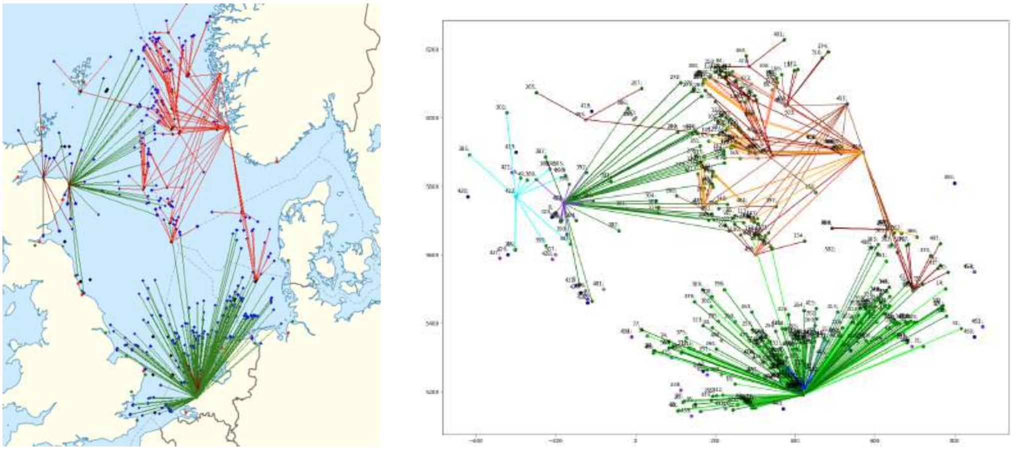

Figure 7.1: Final model in year 1, plotted on map and in standard Python representation

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[8] Appendix IX: Multi-period small model trial

The earlier conclusions drawn from the previous chapter continue their presence in the multi-period simulations. 18-meter USVs are favored over the 12-meter USV. In fact, the only reason why the 12-meter USV is in the final model is because of the giving condition in period $t = 0$ in which the acquisition of one 12-meter USV is enforced.

Focusing on the facility locations, the complete model that incorporates the construction of future wind parks recommends to harbor USVs at four distinct locations. First of all, the 12-meter USV should be deployed from Buckie to address the northern assets. Another limitation of this research is depicted in figure 7.1 by the 12-meter USV temporarily functioning as an automatic guided vehicle (AGV) covering considerable distances over land. This limitation will be further addressed in the discussion. A total of fifteen 18-meter USVs should be acquired to execute operations from Peterhead, Scheveningen and Berhaven. Apparently the development in the southern regions of the North-Sea makes the two latter harbors even more attractive locations.

In order to better comprehend the relative importance of these specific harbor locations towards the total profit, table 7.2 covers the results of a set of separate experiments.

7.2.1. IMPACT OF PRECLUDING OPTIMAL HARBORS ON TOTAL PROFIT

Table 7.2: Precluding experiments

	Total Profit	Percentage
Base run	€129.3 M	
Precluding Buckie	€118.2 M	0.91
Precluding Peterhead	€121.3 M	0.94
Precluding Scheveningen	€127.2 M	0.98
Precluding Berghaven	€128.0 M	0.99

Table 7.2 depicts the four facility locations from the simulated solution that yields the most profitable result in the multi-period model. The decisions regarding the optimal harbor locations should be understood in the light of the harbors' individual relation to one-another. In other words, even though a specific harbor might be located at a convenient place from where a vessel will be able to fulfil the most profitable asset inspections, if this same harbor can only yield poor combinations with additional harbors that will be assigned to the asset inspections that will not be covered by the specific harbor, then the overall system will not thrive with this specifically convenient harbor. Hence, in order to draw further insights from this static outcome the individual harbors are separately precluded from this optimal set of harbors. This reverse reasoning tells us what the impact of the lack of a certain harbor is. It is notable that precluding Buckie yields the largest decrease in profitability. This can be explained by looking at the remote locations of the assets that tend to be serviced from Buckie. Hence, the consideration of remote located assets for the location of facilities indicates to have a large impact on the profitability of operations. A similar conclusion was drawn from the sensitivity analysis in table 6.12

of the previous chapter. The magnitude of profit improvements as a result of the inclusion of these remote facilities is unmatched. However, the results coming forward from the inclusion of these northern harbor location do not consider the rough weather circumstances that are often attributed to these remote locations. A less substantial, but comparable result is obtained when improving the range of 18-meter USVs, albeit this improvement disregards the impact of weather conditions to an even larger extent.

On another note, the relative importance of Scheveningen and Berghaven seems limited as depicted in table 7.2. This is because the model easily solves the absence of one of these harbors by attributing the vessels to the harbor that would still be considered in the simulations. As Berghaven and Scheveningen are in extreme close proximity to one-another, removing a single harbor does not result in significant losses. Remarkably, even when precluding both Scheveningen and Berghaven from the set of available USV harbors, the model is still able to yield a total profit of €126.3, which approximates the original model to 97.6%, by attributing 18-meter USVs to Lowestoft, Delfzijl and Lauwersoog. This is a rather confronting outcome: given the complexity of the model, and the many ways in which the different vessels can respond to precluded facilities from other neighbouring facilities, the relative importance of a specific harbor in regards to the determination of the final set of located harbor facilities is limited. Consequentially, the effective attribution of vessels to another set of harbors will be able to approach a similar profitability from the given workscope.

In conclusion, the relative importance of a facility is limited and can be effectively matched through the efficient allocation of a similar fleet to a different set of facilities. We can state that the determination of a facility location is only as good as the effective attribution of the fleet that will be located at these facilities.

7.2.2. IMPACT OF TRADITIONAL VESSELS ON EMISSIONS

In order to find an indication of the impact of USVs on the total emissions, the model was simulated while excluding USVs and only allowing traditional vessels. This results in 54.700 tonnes of CO^2 emitted while a total profit of €98.7 M was obtained.

Now running the same model for USVs only results in just 2.200 tonnes of CO^2 emitted, a reduction of over 95%. It must be noted that this result is rather trivial, considering the fact that the input parameters were set to a difference of tonnes emitted of 95 percent. Apparently the difference in routing behavior, where USVs are expected to travel significantly longer distances does not make a considerable impact on the additional tonnes of CO^2 emitted. This result can be explained from the fact that the largest contribution to the CO^2 emissions can be found during the operations, because in fact the vessel spent considerably more time in operation then in transit. The small inefficiency resulting from the additional distance that USVs travel is out weighted by the reduction in emissions during operations. Similar from the preliminary conclusions during the verification in section 6.6.1, it seems that transits play a limited role when compared to the actual operations.

After reviewing a model in which no USVs are considered, the next section will cover a situation in which no traditional vessels are considered. A closer look into the consequences of robodock mobilizations is provided in the next section.

ANNEX PART II

7.2.3. IMPACT OF ROBODOCK MOBILIZATION ON FACILITY LOCATIONS

This section shortly covers the model results from the simulations when applying a third consecutive time index. In this third time index several energy islands will have been constructed, which can be chosen as robodock locations. Furthermore, a scenario will be considered in which no more traditional vessels are operational. The other constraints will remain. Hence, the additional giving conditions consist of:

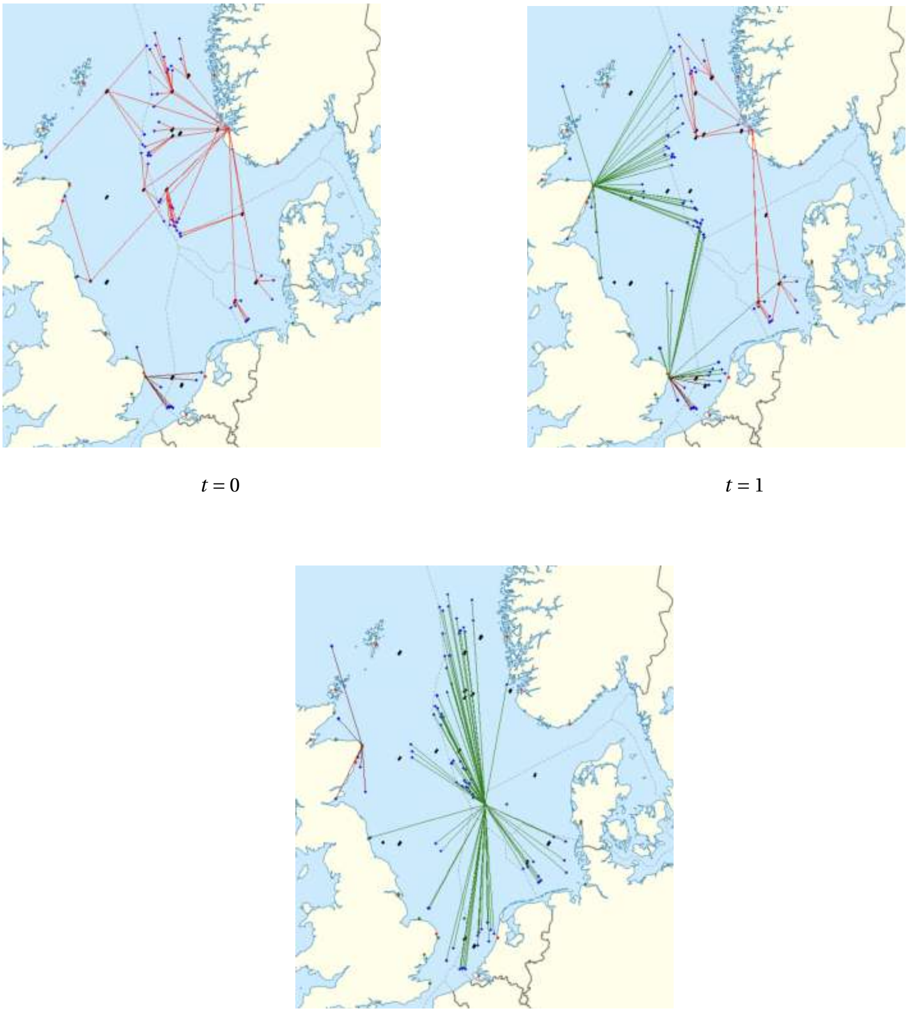
- Additional robodock harbors in the form of energy islands will be added in the future.

- There wil be no more traditional vessels in the final year.

$$\sum_{k\in K_{1,2}} \sum_{i\in H_2} z_{jk2} = 0 \tag{7.3}$$

RESULTS

The compressed run yields the expected behavior and adequately follows incorporation on the system's new giving conditions as depicted on the next page. The developing topology throughout the time indices is clearly following the newly introduced assets in $t = 1$ and from the centrally located energy island in $t = 2$. Furthermore, the model outcome commissions a robodock change a_{jkt} for transporting the robodock from Lowestoft to the energy island, while the robodock in Peterhead stays in place to cover the northern inspection jobs.


$t = 0$

$t = 1$

$t = 2$

Figure 7.2: Representations of the topology of active North-Sea assets throughout the distinct time indices.

Table 7.3: Annex part II: Robodock mobilization

Time index	$t = 0$	$t = 1$	$t = 2$
Number of traditional vessels	2	1	0
Number of 12-meter USVs	1	1	1
Number of 18m USV-meter	0	3	5
Nodes visited by traditional vessels	53	20	0
Nodes visited by 12-meter USVs	9	9	6
Nodes visited by 18-meter USVs	0	48	76

Table 7.3 tells us the 12-meter USV primarily acquired because the model enforces this in $t = 0$. No additional 12-meter USVs are acquired, while several 18-meter USVs are allocated throughout the time indices. It appears that the USVs can complete the entire workscope, departing from the set of potential harbor facilities (including energy islands) in $t = 2$, without requiring any traditional vessels.

7.3. CONCLUSIONS

From chapter 7 and Annex II, some additional conclusions can be drawn regarding the behavior of the model in the multi-period scenario. We will conclude chapter 7 by answering the final sub question, **sub question 4**: *What is the impact of further developments of the system components in future scenarios on the initial facility location model?*

In other words, how will the inclusion of a time perspective with future developments of the system components affect the strategic location decisions?

First of all, it was determined that future scenario's will not be considered when the model runs for the initial time frames were ran. The routing decisions regarding vessel investments and harbor locations are intended to have a lasting impact on decisions in following time indices. As a result, if the assumptions regarding the asset locations of hydrogen conversion platforms and energy islands were taken into account for the model, they would remain to have a considerable impact on the model outcome for initial scenarios.

Other than dealing with the same problem of sparsity, the facility location problem with multi-period time indices performed rather well. Unsurprisingly, the possibility to move a robodock towards a more conveniently located energy island is gladly commissioned. However, even despite the centrally located robodocks at the energy islands, a harbor at Buckie is still required to cover the most northern assets. In line with the previous conclusions, the geographical giving conditions substantially drive the outcomes of this case study.

Before addressing the sub questions of this research to answer the main question, the next chapter will provide a discussion of the results and outcomes that have been covered in this report.

8

DISCUSSION

Observe yourself, and you will be wary.

Latin proverb

THIS chapter addresses the model in relation to the previously presented results. The aim of this research is to determine the optimal facility locations to support vessels, ensuring that all demand nodes are fulfilled over a given planning horizon. The problem that is addressed in the model can be viewed as a *multi-period max profit facility location problem.*

The first section discusses the model's most fundamental assumptions and the limiting implications. This section concludes with a discussion regarding the research methodology that affected the outcomes. The implications of these limitations on the applicability of the model are then discussed in section 8.4.

8.1. CRITICAL ASSUMPTIONS

Considering the limited scope of this research, several assumptions are made to construct a simplified model of this complex environment.

THE SCOPE IS LIMITED TO THE OFFSHORE OPERATIONS IN THE NORTH-SEA.

The focus for this research was limited to the scope of the North-Sea. Although the model will still work when fed with other input parameters and asset locations, the question will arise whether the same relevance can be accredited to the facility location problem. The North Sea is unique in its circular shape, where an abundance of assets can be reached from a multitude of harbors from various countries. In a less complex environment with a straightforward work scope and less available harbors the application of a facility location model might not be as relevant. Furthermore, it must be noted that North-Sea is notorious for its stormy weather, excessive wave heights and strong winds. In these harsh environments, the limitations on operability per vessel is much larger than in the quiet waters in the Middle-East. Hence, the conclusions drawn from this specific case study should not be extrapolated to other geographic regions without addressing the impact of the North-Sea conditions on the model.

EACH ASSET IS EXPECTED TO REQUEST AN INSPECTION ONCE IN EVERY GIVEN TIME FRAME, MEANING NO CORRECTIVE MAINTENANCE IS TAKEN INTO ACCOUNT.
A large share of offshore inspection demand is called for as a result of the rough weather conditions. Despite considering a multi-period time frame, the model is rather static in regards to the stochastic nature of a large part of the real workscope. It should therefor be noted that the results that are obtained in this research can only predict the ideal harbor locations for the case in which all maintenance tasks can be planned by the same operator. In reality, the planning for inspection jobs is pushed by the asset owner, rather than by the inspection provider.

ALL DEMAND IS TENDERED TO A SINGLE PARTY.
Once again, this constraint surpasses the stochastic demand of inspection jobs. In reality, the inspection jobs can be tendered to many different parties that offer similar services. This assumption therefor implies that the model outcome determines the optimal harbor locations from where the totality of the static work scope can be optimally performed. However, it also entails that either a monopolist should have the decision to construct the complete system, or alternatively, that all parties would collaboratively construct the final model outcomes. Unfortunately, the first is not the case, and the latter is unrealistic. Given the fact that multiple parties are performing the inspection jobs, and there are corrective as well as preventive inspection jobs, induces two simultaneous stochastic elements to consider that are not included in this research.

DEMAND NODES ARE SPLIT UP INTO WINDPARKS OR OIL & GAS PLATFORMS. EACH WITH A SIMILAR REVENUE AND SIMILAR WORK SCOPE RESPECTIVELY.
This is an overestimation across several aspects. First of all, there are more types of inspection jobs to consider than the two above: from pipeline, cable and vessel surveys, to environmental and coastal surveys. The routing to and from non-stationary objects or structures such as pipelines require certain simplifications in order to be represented by nodes. Furthermore, the assets that are considered in this research all generate the same revenue. Ultimately, the model decides which vessel should perform which inspection by subtracting the transportation costs and operation costs from these revenues. This means that locations further offshore will automatically result in less profit than assets closer to shore. In reality, this could be quite the opposite. Locations further offshore are out in heavier conditions, and are likely to request more frequent and more thorough inspections. The transit costs in these tenders will often be covered by the asset owners, and not by the service provider as we assume in this research.

8.2. LIMITATIONS

The model creates a visual representation of the vessel routes and harbor locations, which has proven to be helpful for the validation of the model behavior and intuitive communication of the model behavior. However, they also point out some shortcomings in relation to actual marine traffic.

THE ROUTING DECISIONS ARE NOT BASED ON REAL MARINE TRAFFIC

The model intends the vessels to navigate in a straight line through open water, like drones that do not follow a fixed network but rather fly directly through continuous space. However, in reality, the North-Sea coastlines display some curves that do not always match the straight navigation behavior of the vessels. In some instances this results in the vessels covering sizeable distances over land. In the optimal configuration of facilities a 12-meter USV is deployed from Buckie. This USV is suddenly functioning as an automatic guided vehicle (AGV) covering considerable distances over land. This obviously could never be a trip made by the 12-meter vessel. In fact, it is debatable whether the 12-meter vessel would even have the endurance to reach the northern asset that is is currently assigned if it would have to travel the full length around the northern coastline, in stead of the shortcut over land that the model currently allows it to take. Consequentially, this misconception drives the optimal outcome of the model in a direction that is fundamentally infeasible in the real world.

Additionally, some harbors are located further inland. The model takes no further level of detail into account regarding manoeuvres in and around of harbors that might include locks, nor does it require vessels to adhere to traffic rules or follow specific maritime waterways when entering international waters.

NO SPECIFIC EQUIPMENT REQUIREMENTS FOR ASSETS INSPECTIONS WILL BE CONSIDERED. EVERY VESSEL WILL BE ABLE TO EXECUTE THE SAME OPERATIONS AT EACH DEMAND NODE.

Other than oversimplifying the types of infrastructures that are inspected, the model does not take different types of inspections into account. In reality, different types of ROVs can be deployed from the different types of vessels. Each ROV has its own characteristics in terms of operability, speed of operations and vessel that is able to carry the ROV, whereas each asset inspection is defined by the type of ROV that is able to perform the inspection. Ignoring this aspect of the inspection jobs allows each vessel to execute operations at each demand node. Therefor, the relative considerations between vessel assignments are rather one-dimensional as they are only based on the operation time, the transit time and the related costs.

WEATHER CONDITIONS WILL ONLY BE TAKEN INTO ACCOUNT TO A CERTAIN EXTEND: A STRONGLY LIMITED NUMBER OF OPERABLE DAYS FOR THE SMALLER VESSELS.

As mentioned in the first assumption, the North-Sea can be a rough environment. The vessels have a distinct allowance in regards to wave heights. This means that larger traditional vessels can sometimes continue operations while a smaller USV has to come back into port. Each given vessel type has some limiting operational weather requirements. The requirements can be related to waves (wave heights, period and direction) and wind (wind speed and direction). Vessels also have safety weather requirements. These requirements are either less strict than or correspond to the operational weather requirements. When a weather parameter reaches one of the safety weather requirements for a vessel type, all vessels of this type have to return to a safe haven, in most cases the vessels' base. Some vessels need to return to their base after one operative shift, while other, larger vessels with accommodation possibilities can stay offshore and operate several shifts offshore before they need to return to their base. Consider a scenario in which there are 5 workable days, followed by one stormy day, followed by 5 workable days. In that case, during ten operable days the smaller vessels will not be leaving port for operations while the traditional vessel might be able to stay out during the rough conditions. As a consequence, the *yearly operational days* that are considered per vessel per year will not be attained.

8.3. REFLECTION ON RESEARCH APPROACH

The decision to use a simulation model was part of the research design. The research design contains several limitations as well, which are often the result of trade-offs between the inclusion of more complex additions resulting in more realistic results and more cumbersome computations, or keeping simplicity, reducing the level of detail in the representation of reality while preserving model sparsity. The choice for an MIP was made for several reasons.

The first reason followed from the gap that was identified in the literature review. This gap identified a lack of attention for facility location problems in the maritime industry, whereas these type of problems are frequently covered in other remote operation applications. However, translating the complexity of the maritime environment into a mathematical model that captures an appropriate trade-off between incorporated complexity and adequate sparsity, turned out to be challenging.

Especially when studying the choices of a heterogeneous fleet over a multi-period time interval the issue regarding computational times became apparent. In hindsight, the decisions regarding the facility costs and travel costs appear to be of lesser importance than the costs during operations. This goes to say that the implications of the reality, in which the largest amount of time is spent during operations and not during transit, were not considered to be as influential as they turned out to be. When reflecting on this approach compared to other studies regarding facility location problems, like drone deliveries or distribution centers, the activity at the demand node is significantly different. In a drone delivery, the majority of the time for the delivery is spent in transit. In other words, the delivery at the node is only a small part of the whole operation. However, in this research a disproportionately large amount of the operations are occurring *at the node*, and the transits in between have a remarkably lower impact.

8.4. IMPLICATIONS OF THE RESULTS

The simplifications and assumptions that are made in this research can lead to model results that deviate from results that would be obtained in reality. As partially discussed in the preceding sections of this chapter, various assumptions and limitations are driving the model outcomes. Nevertheless, the outcomes of the simulations can serve the validation of several hypotheses regarding vessel design, facility location determination and robodock applications in the future.

An important indicator found through the extensive analyses of the results is the significant improvement in profitability shown by the allocation of vessels at remote (Northern) locations. A less substantial, but comparable result can be obtained by improving range of vessels. These results are especially fragile when considering the larger impact of extreme weather conditions in those remote locations.

Hence, the results should always be considered in the light of its limitations. However, when understanding the underlying implications of the model components and their relative impact on the model behavior, the simulations can unquestionably provide insights to support intuitive validation regarding the strategic decision making in the studied maritime environment. By applying alterations to the input parameters, the constructed model will be able to indicate the credible inferred consequences and additionally trigger an enforced reflection of the complex system components to unlock valuable insights.

9

CONCLUSION

It is a long road from conception to completion.

Molière - French actor and poet

9.1. SUB QUESTIONS

In this final chapter, the sub questions around which this research was constructed will shortly be revisited before addressing the main research question. After, a reflection of the scientific contributions of this research will be provided. To conclude this report, several suggestion for further research will be made, as the field of logistics research in remote and autonomous operations is only just at the break of dawn.

SUB QUESTION 1

What are the critical considerations regarding the available methods to formulate a facility location problem in the maritime environment?

From the relevant literature many studies regarding vehicle routing problems in the field of maritime operations and many facility locations regarding drones and automated vehicles were found. Compared to other maritime operations studied in the literature, the USVs are characterized by several non-standard features that resemble the drones and automated vehicles to some extend. Additionally, to address the fleet heterogeneity other researches have been covered to introduce the notion of centroids for traditional vessels. To the best of my knowledge, no previous research has studied facility location problems in the maritime environment considering a heterogeneous fleets that combines the distinctive routing behavior of centroid-like hubs and drone-like one-to-one trips.

For a comprehensible understanding of all the critical considerations to formulate a facility location problem, some disadvantages must be noted regarding the application of facility location problems in the maritime environment. First of all, an FLP oversimplifies the many stochastic factors that affect the system. This also means that only recurrent and constant demand is being considered and that no corrective inspection jobs are being considered, despite representing a large share of the total work scope. Another main difficulty in solving FLPs is the huge number of variables and constraints needed to model them. For this reason, formulations with fewer variables and constraints should be preferred to reduce the computational burden. The complexity of the maritime environment will be hard to capture in a sparse facility location model.

With regards to facility location problems, the aim of this research is to determine the optimal facility locations to support vessels, ensuring that all demand nodes are fulfilled over a given planning horizon. To overcome the expected computational difficulties of the proposed complex model, this research will adopt the MIP solver Gurobi to run the model optimization. The problem that is addressed in the model can be viewed as a *multi-period max profit facility location problem*, in which the vehicles are survey vessels, the customers are offshore assets, and the depots are harbors. These components are further investigated in sub question 2.

SUB QUESTION 2

What are the unique characteristics of the system components in the offshore service industry?

In chapter 4 an extensive overview regarding the details of the case study was provided to cover the following components:

1. the set of demand nodes $i \in I$ in the North-Sea.
2. the different types of possible harbor locations $j \in J$.
3. the versatile fleet of vessels $k \in K$.

These components were included into an extensive mathematical model, covered by sub question 3.

SUB QUESTION 3

How to develop, verify and validate a facility location problem for an initial static base scenario?

Capturing all the complexities into a single facility location problem was a challenging task, but yielded comprehensible results after the first simulations in the verification section (6.2) . The results were then validated by experts and a comparative analysis of market studies. Additionally, the sensitivity analysis also pointed out some key indicators for the profitability of the system and proved to be a successful method to address the model outcomes for the static base scenario. Several insightful conclusions were drawn from the sensitivity analyses regarding the recommendations for future vessel design:

- A cheaper version of the 12-meter USV could be an attractive alternative compared to the 18-meter USV for near-shore operations.

- A more confident approach towards the range of 18-meter USVs can lead to strongly increased profits.
- A risky approach that locates a robodock near the Northern inspection assets unlocks unmatched profitability.
- Peterhead, Lowestoft, Berghaven, Scheveningen and Lauwersoog are frequently recurring harbor locations throughout the different model setups.
- Extensive integration of the model complexity leads to cumbersome computations.

During the sensitivity analyses, the lack of model sparsity became apparent. This could provide serious concerns for the multi-period simulations in the following chapter.

SUB QUESTION 4

What is the impact of further developments of the system components in future scenarios on the initial facility location model?

In other words, how will the inclusion of a time perspective with future developments of the system components affect the strategic location decisions?

First of all, it was determined that future scenario's will not be considered when the model runs for the initial time frames were ran. The routing decisions regarding vessel investments and harbor locations are intended to have a lasting impact on decisions in following time indices. As a result, if the assumptions regarding the asset locations of hydrogen conversion platforms and energy islands were taken into account for the model, they would remain to have a considerable impact on the model outcome for initial scenarios.

Other than dealing with the same problem of sparsity, the facility location problem with multi-period time indices performed rather well. Unsurprisingly, the possibility to move a robodock towards a more conveniently located energy island is gladly commissioned. However, even despite the centrally located robodocks at the energy islands, a harbor at Buckie is still required to cover the most northern assets. In line with the previous conclusions, the geographical giving conditions substantially drive the outcomes of this case study.

9.2. MAIN QUESTION

The goal of this research is to determine the optimal harbor locations from where a fleet of USVs can serve the inspection demand of offshore assets. In order to attain this goal, an optimization model was constructed to determine harbor facility locations that will yield the maximum profit over an extended period of time. Hence, the following research question was formulated:

> *How to determine the optimal locations for harbor facilities that maximize the profit of remotely operated vessels servicing maritime infrastructures in the North Sea?*

With regard to the chosen approach, the methodology of studying the facility location problems and incorporating relevant considerations from researches in different fields worked reasonably well. An attempt was made to integrate suitable aspects from related fields of research. USVs were represented by drone-like trips from remote operations research and integrated with traditional vessels based on delivery models that make use of centroids. Capturing all these complexities into a single facility location problem was a challenging task, but proved to be successful after the first simulations in the verification and validation section. The sensitivity analysis also pointed out some key indicators for the profitability of various vessel design components. However, other findings led to conclusions that were less in favor of the applied facility location problem.

In terms of attaining the goal of this research to determine the optimal harbor locations where the fleet of USVs should be allocated some final remarks have to be made. One of the most striking conclusions from the research is the indication that transit times and facility costs play a minor role compared to the operational times at demand nodes. Whereas the facility location problem is usually applied for drone deliveries and package deliveries, in this research the delivery itself has a more profound role within the system. Looking at the bigger picture, the facility location problem oversimplifies the operations occurring at the demand nodes. All of the complexity that is at the core of the facility location problem lies within the harbor locations, transit times, transit speeds and vessel characteristics, while the complexity of the operations at the nodes is largely overlooked. This is a disproportional oversimplification in the sense that the core of the activities, and actually the majority of the time of the operations is spent *at* the demand node.

Another confronting outcome resulted from the preclusion of optimal harbors in chapter 7. Given the complexity of the model, and the many ways in which the different vessels can respond to precluded facilities from other neighbouring facilities, the relative importance of a specific harbor in regards to the determination of the final set of located harbor facilities is limited. Consequentially, the effective attribution of vessels to another set of harbors will be able to approach a similar profitability from the given workscope.

In conclusion, the relative importance of a facility is limited and can be effectively matched through the efficient allocation of a similar fleet to a different set of facilities. We can therefor state that the determination of a facility location is only as good as the effective attribution of the fleet that will be located at these facilities.

One of the biggest pain points during the simulations phase were the cumbersome run times. Translating the complexity of the maritime environment into a mathematical model that captured an appropriate trade-off between incorporated complexity and adequate sparsity turned out to be a challenging task. One of the main difficulties in solving FLPs is the huge number of variables and constraints needed to model them. For this reason, formulations with fewer variables and constraints should be preferred. This became painfully evident when the choices of a heterogeneous fleet over a multi-period time interval were studied. However, despite the long running times and heavy mathematical modeling, the simulation were able to provide intuitive results that allowed to draw several relevant conclusions from this research, including:

- A cheaper version of the 12-meter USV could be an attractive alternative compared to the 18-meter USV for near-shore operations.
- A more confident approach towards the range of 18-meter USVs can lead to strongly increased profits.
- A risky approach that locates a robodock near the Northern inspection assets unlocks unmatched profitability.
- Transit time only play a minor role in profit returns compared to the time spent at assets during operations.

The importance of range and operability should be considered in the light of the North-Sea topology. The allocation of vessels is to a large extend dependant on the inspection jobs in the northern regions of the North Sea. These are further secluded and only within reach from few harbors. Therefor, altering USV characteristics that benefit the accessibility of these isolated assets have a considerable impact on the performance of the overall system. However, in reality these secluded inspection jobs in the northern regions are subject to severe weather conditions and consequentially not as attractive for USV operations as the model suggests. When validated against real world observations, the indicated importance of said vessel characteristics turn out to be disproportionately affected by the generalization of operability assumptions in their disregard of geographically specific weather conditions.

Additionally, transits from harbors to demand nodes were found to play a minor role in profit returns compared to operations at the assets. This is a rather confronting outcome considering the limited attention paid to the actual operations of asset inspections in this research. However, this outcome is reasonably intuitive: whereas facility location problems are commonly applied for distribution centres or drone deliveries where services at the demand are largely trivial, in this research the demand nodes play a significant role throughout the entirety of operations. In stead of delivering packages or goods, a multi-day service is being performed at the demand nodes. In contrast to the facility location problem in this research, where the complexity lies within the harbor locations, transit times, transit speeds and vessel characteristics, while the operations at the nodes are largely overlooked. This is a disproportional oversimplification of the observed system in the sense that the core of the activities, and actually the longest time of the operations is not spent in transit but rather *at* the demand node.

These are some interesting notions to consider when applying a facility location problem in a comparably complex environment. Other contributions pointed out by this research will be covered in the next section.

9.3. SCIENTIFIC CONTRIBUTION

This research can be regarded as an early study for remote operations in a maritime environment. Since previous studies regarding UAV types of routing using facility location problems were unprecedented in this discipline, much research still needs to be done. This research can play a role in the considerations for future studies to come.

First of all, this research has emphasised the considerations regarding the application of a complex facility location model. In MIP problems, sparsity and compactness are values to strive for rather than extensiveness and complexity. This research has taken a first step in the apprehension of this complex environment into an MIP, with mixed results. Given the complexity of the whole system this research considers an MIP with multi-periods, a heterogeneous fleet and even heterogeneous facilities. Furthermore, throughout the multiple periods new demand nodes have entered the model, and located facilities were allowed to move from their previous destination. On the one hand, this approach encapsulates a decent amount of the complexity of the real case. On the other hand, sparsity and compactness are overlooked, as computation times were long. Furthermore, by incorporating too many variable in the model, the results tend to get less reliable. Future researchers can learn from the approach that was taken regarding the integration of factors in this research.

In short, my research has pointed out that the complexity of USV operations in the maritime industry is difficult to capture within an acceptably sparse facility location problem. Furthermore, future researchers are advised to consider the demand nodes in more detail. In fact, vessels spent most of their time performing operations at the inspection nodes, rather than in transit. Additionally, given the specific inspection requirements related to each job, their irregular inspection demand and the developments of new assets in the future, it will be interesting to address the stochasticity in the operational phase.

The most profound conclusion of this research is the interchangeability of precluded harbor facility locations. When determining the optimal harbor locations, it turns out that many different combinations of harbors and vessel fleets can approach the optimal profit. Given that all demand nodes are being serviced by a single company, a tremendous increase in the complexity of the model is perceived in the many different ways in which many different vessels can respond to precluded facilities from other neighbouring facilities. Consequentially, the effective attribution of vessels to another set of harbors will be able to approach a similar profitability from the given workscope. Hence, the determination of a facility location is only as good as the allocation of the fleet that will be located at these facilities. As a result, the relative importance of a single facility in the final set of located harbor facilities is limited when considering the exhaustive set of nodes, harbors and vessels of the entire North-Sea.

The final advise regarding the complexity of the model results from the application of traditional vessel routing via centroids. The routing via these centroids allows the model to make calculated decisions between traditional vessel and USVs, and allows the final outcomes to be validated with real world data. However, in trying to incorporate an important part of the complexity of the system, the centroid routing is an oversimplification in itself that makes the simulations extensively cumbersome and the comparing of results more ambiguous. That being said, the validity of the model as a whole was reasonably adequate. Despite long running times and heavy mathematical computations, the simulations were able to provide intuitive results that allowed this research to draw relevant conclusions regarding the future development of remote operations.

9.4. SUGGESTIONS FOR FURTHER RESEARCH

Some suggestions for further research were already made during the previous reflections on this research. This final section will conclude this research with several suggestion for further research to be done.

- Because the range of USVs indicated to have a significant impact on the profitability on the model, research regarding the efficiency of vessel design will need to prove whether this can be a reasonable expected addition in the near future.
- Subsequently, extended range allows the USVs to perform operations further offshore. This will infer some heavy consequences on the wave heights that USVs need to be able to withstand and begs the question whether the same operability can be guaranteed in these harsher conditions.
- In this research, centroids were considered to represent the behavior of traditional vessels. In previous studies, the centroid locations were determined with a separate heuristic, while in this research the centroid locations were picked manually. A future study regarding the application of centroid-like trips for traditional vessels, including the development of a heuristic for the determination of centroid locations could be conducted to validate the routing behavior for traditional vessels.
- As this research pointed out that the relative importance of facility locations for the profitability of inspections seems modest when accommodated with a properly allocated fleet, the recommendation to consider other key performance indicators than costs is introduced. For example, qualitative research regarding the importance of visibility of remote technologies for tendering processes or marketing purposes can be studied.

- As efforts within the maritime industry to move towards sustainable fuels are rapidly increasing, future research regarding the effect of adopting sustainable fuels on the model outcomes and overall emissions could provide interesting insights regarding the attainment of new IMO regulations.

- Lastly, to cope with the cumbersome simulations further research into heuristics to obtain lower and upper bounds more effectively could help to efficiently solve complex MIP problems in the future.

In short, my research has pointed out that the complexity of USV operations in the maritime industry is difficult to capture within an acceptably sparse facility location problem. Furthermore, future researchers are advised to consider the demand nodes in more detail. In fact, vessels spent most of their time performing operations at the inspection nodes, rather than in transit. Additionally, given the specific inspection requirements related to each job, their irregular inspection demand and the developments of new assets in the future, it will be interesting to address the stochasticity in the operational phase.

In conclusion, this research provides a first piece of reflection regarding MIP problems for remote and autonomous operations in the maritime industry that can be addressed by future researchers studying this topic. I will conclude this report with a final reflection on the conclusions in this research regarding facility locations of uncrewed surface vessels:

A ship in harbor is safe,
but that is not what ships are for.

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LIST OF APPENDICES

APPENDIX A: SCIENTIFIC PAPER

The scientific paper is depicted on the following pages.

A facility location model for uncrewed surface vessels in the maritime survey industry

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***Abstract*—The maritime industry is preparing for a future where human presence is no longer required on board of ships. This will revolutionize the global execution of maritime operations and consequentially introduce unprecedented challenges to the corresponding logistics. This paper presents a non-standard facility location problem (FLP) that arises in the maritime survey industry. The goal is to determine a number of uncapacitated facilities and assign a heterogeneous fleet of both remotely operated vessels and traditional vessels to the located facilities in order to serve the inspection demand of offshore infrastructures such as oil platforms and wind parks. The facilities serve as sites where vessels can refuel and accommodate crew changes. Both current traditional vessels and future uncrewed surface vessels (USVs) are considered in the heterogeneous fleet that respectively combines the distinctive routing behavior of centroid-like hubs and drone-like *one-to-one* trips simultaneously. A mixed-integer linear programming (MILP) model is constructed to determine the optimal harbor locations and the associated vessel fleet size & mix to perform the inspection demand of North-Sea assets over a multi-period time interval. The simulation results are reported for a real case study commissioned by geo-data company Fugro. The results of the model suggest that the effective establishment of facility locations and corresponding fleet allocation can reduce the total costs and environmental footprint of the survey operations in the North-Sea. This research provides a first piece of reflection regarding MIP problems for remote and autonomous operations in the maritime industry. The research pointed out that the complexity of USV operations in combination with traditional vessels is difficult to capture within an acceptably sparse facility location problem. Finally, this study identifies the stochasticity of inspection operations to be the most promising future contribution to automation research in the maritime industry.**

***Index Terms*—Facility location problem, mixed-integer linear programming, centroid-based routing, uncrewed surface vessels, robodocks, maritime survey industry.**

I. INTRODUCTION

The latest technologies in the maritime industry include uncrewed vessels and automated refueling stations, so called *robodocks*. These technological innovations involving autonomy and remote control are considered to be critical to achieve the industry's ambitions to realise carbon footprint reduction, faster decision making and increased workforce well-being. However, the incorporation of autonomous vessels into the existing logistical models is a challenging process as the smaller vessels have particular characteristics in terms of size, operability and endurance. As a result of their smaller size, uncrewed surface vessels carry less fuel and have an approximated endurance of mere days instead of months. In line with the industry's vision on autonomy, automated docking platforms are designed to effectively cope with the frequent refueling needs of USVs. An offshore environment consisting of uncrewed vessels and autonomous docking platforms will fundamentally change the maritime industry and consequentially introduce unprecedented logistical challenges.

Evidently, the locations of robodocks are crucial for efficient operations. From the selected harbor locations, the USVs must be able to reach the asset locations of potential clients at the occurrence of an inspection request. Momentarily, for its piloting project, harbor locations are identified pragmatically; project based with high mobilization costs, uncertainty about available facilities and inefficient staff use as a consequence. To overcome these deficiencies, USVs need to be harbored across strategically located ports from where they must be able to swiftly respond to inspection requests.

The remainder of the paper is structured as follows: The model will be validated numerically using real data provided by geo-data company Fugro. Several analyses are performed to determine critical vessel attributes and strategic harbor locations. Such insights are key considerations for Fugro in the ongoing development of its USV fleet.

II. LITERATURE REVIEW

This section provides a brief review of the relevant literature regarding logistical studies that are related to this research.

A. Logistics in Maritime Operations

Transportation models in the field of maritime operations have mostly been studied for scheduling and routing optimization of offshore activities. These activities range from supply vessel routing for offshore oil & gas (O&G) installations to technician scheduling for wind park maintenance. Mardaneh et al. [6] introduced a non-standard vehicle routing problem (VRP) in the oil & gas industry to schedule a series of round trips for a heterogeneous fleet of vessels.

Alternatively, offshore wind turbines are among the fastest growing electrical generation systems worldwide [7]. Nevertheless, offshore wind is still dependent on governmental subsidies and far more costly than conventional energy sources [8]. This is largely due to high operation and maintenance costs, which include transportation costs, technician salaries and costs of spare parts, accounting for up to a third of the overall lifetime costs [9]. In the future, wind farms will be located further offshore where rough weather and greater distances from shore make the turbines more difficult and expensive to access [[10]; [11]]. Extensive research has been conducted in O&M to make offshore wind a competitive alternative by reducing costs through efficient use of maintenance vessel fleets and maximum utilization of good weather periods. [12].

O&M is currently only performed by heavy-duty vessels that are capable of conducting offshore operations for long consecutive periods with significantly more endurance than USVs. Determining efficient harbors that will only occasionally be used, results in marginal profits at best. Hence, in O&M, finding strategic harbor locations is not yet considered to be a relevant issue that is worthwhile studying. On a different note, some similarities can be drawn between logistics research in the offshore sector and the onshore sector. The following section discusses the relevant logistics research in remote operations outside of the maritime environment.

B. Logistics in Remote Operations

Self-driving intralogistics vehicles, automated guided vehicles and other autonomous systems are state-of-the-art in many transport modes in closed environments on land. The near future requires solutions based on electric vehicles (EVs) [13]. EVs are considered a premium solution in land transportation systems because they can significantly reduce the dependency on oil and minimize transportation-related CO^2 emissions [14]. However, unlike traditional fossil fueled vehicles, EV technology has a limited range and needs regular recharging [15]. Consequentially, EV charging station planning has become an emerging research problem. Similar facilities, like warehouses, distribution centers or other types of depots are often constructed for long time spans and require substantial financial investments [4]. In order to address these long-term commitments, facility location problems are commonly applied to strategically determine the optimal location for such facilities [5].

Drones are on the verge of becoming a proven commercial technology for civil applications in many public and private sectors [16]. Lynskey et al. [17] proposed an algorithm to optimally place drone ports to minimize the average distance drones must travel based on a set of potential drone port locations and tasks generated in a given area.

A typical shortcoming of the research regarding facility location problems for drones when applied in a maritime environment is the homogeneity of the similar drones on which these models are based. In contrast, the studied vehicles in this research consist of nonidentical vessels with distinct designs that follow particular rules. Whereas USVs follow drone-like *one-to-one* trips, traditional vessels are represented by centroid-based routing.

Fisher et al. [18] describe a common variant of the vehicle routing problem in which a vehicle fleet delivers products stored at a central depot to satisfy customer orders. In their research a generalized assignment heuristic for vehicle routing is proposed that makes use of a set of ‘seed customers’ which ‘seed points’ are used to initialize the heuristic partitioning the plane into n small cones for each customer. This concept of creating centroids is further developed by Agatz [19] as a heuristic to determine home delivery time slots.

III. CONTRIBUTION OF THIS PAPER

Integrating a heterogeneous fleet of traditional vessels based on routing via centroids, in combination with a fleet of USVs that follow the drone-like behavior of *one-to-one* trips will provide a simultaneous assignment of vessels to demand nodes To the best of my knowledge, no previous research has studied facility location problems in the maritime environment considering a heterogeneous fleets that combines the distinctive routing behavior of centroid-like hubs and drone-like *one-to-one trips*.

In this paper, a new variant of the FLP is introduced, based on a real harbor locating problem faced by geo-data company Fugro in the development of its future USV fleet and robodock assembly. The problem setting is described as follows.

Each remotely operated vessel makes several *one-to-one* trips from a facility location to a demand point and back until the operability limits are met. Each traditional vessel visits demand nodes via centroids from which various inspections can be performed before having to return to harbors for crew changes. The problem involves multiple offshore assets, each of which requires regular service from survey vessels. The goal is to determine the desired harbor locations for the vessels so that all services are fulfilled and the total profit is maximized. Other constraints that must be considered include vessel operability constraints, range constraints and constraints related to the routing behavior of the various vessel types. The planning period is yearly and regarded in multiple non-consecutive time indices.

Compared to other maritime operations studied in the literature, this model is characterized by several non-standard features:

1) the vessel fleet is heterogeneous.
2) vessel performing *one-to-one* trips and vessels traveling through centroids are compared simultaneously.
3) a multi-period timeframe is considered.
4) demand nodes develop over time.
5) possible locations for facilities develop over time.

Although some of these non-standard features have already been covered separately in the available literature, to the best of my knowledge, no previous research has studied facility location problems in the maritime environment considering a heterogeneous fleets that combines the distinctive routing behavior of centroid-like hubs and drone-like *one-to-one* trips simultaneously.

IV. SCOPE

This research assumes that all demand nodes have a predictable recurring and constant demand with a fixed profit that can be collected by each of the vessel types. Furthermore, the model assumes all inspection requests are tendered to a single company. The influence of weather conditions is limited to an approximated number of workable days per vessel type per year and does not affect the travel speed, operability or range of the vessels. Perfect weather conditions are assumed during these operable days.

V. PROPOSED MODEL

A mixed-integer linear programming (MILP) model is formulated with the objective of maximizing profits through the allocation of various vessel types at possible harbor locations while explicitly incorporating operability and range constraints. Based on the model for this *multi-period max profit facility location problem*, several recommendations will be made regarding the locations of robodocks, the according fleet size & mix and the design of future vessels. Therefor, the following decision variables are incorporated in the model:

- x_{ijkt} $\begin{cases} 1, & \text{if demand node } i \text{ is served by vessel } k \text{ from facility } j \text{ in year } t \\ 0, & \text{otherwise} \end{cases}$
- y_{jt} $\begin{cases} 1, & \text{if a facility is located at } j \text{ in year } t \\ 0, & \text{otherwise} \end{cases}$
- z_{jkt} $\begin{cases} 1, & \text{if vessel } k \text{ is assigned to facility } j \text{ in year } t \\ 0, & \text{otherwise} \end{cases}$
- a_{jkt} $\begin{cases} 1, & \text{if a robodock at } j \text{ and attributed vessel } k \text{ are relocated in year } t \\ 0, & \text{otherwise} \end{cases}$

The parameters in the model are defined below:

Sets	
T	Set of time indices t,
I_t	Set of active demand locations (wind and O&G nodes) in year t
J_t	Set of active potential facility locations in year t
U_t	Subset of all potential USV facility locations in year t
H_t	Subset of all potential traditional harbor facility locations
Q	Set of centroids
V	Set of vessel types with $V = 1, 2, 3$
$K_{V,t}$	Set of all vessels
$K_{1,t}$	Set of traditional vessels in year t
$K_{2,t}$	Set of 12-meter USVs in year t
$K_{3,t}$	Set of 18-meter USVs in year t

Parameters	
p_t	Maximum number of facilities at time t
d_{ij}	Distance in knots between node $i \in I$ and $j \in J$
w_{it}	Demand at demand location $i \in I$ at time t
f_j	Facility costs at harbor $j \in J$
r_k	Range capacity of vessel $k \in K$
s_k	Travel speed of vessel $k \in K$
v_k	Vessel operating costs per day of vessel $k \in K$
s_k	Travel speed in knots of vessel $k \in K$
o_k	Maximum yearly operational days of vessel $k \in K$
l_i	Duration of performing an operation for vessel $k \in K$
$G_{k,t}$	Constant for double transits of 12m-USVs, 2 for $k \in K_{2,t}$, 1 for $k \notin K_{2,t}$
dc_V	Depreciation costs of vessel type V per year
rc	Costs to mobilize and transport robodock pontoon
M	Arbitrarily large number

The goal of this research is to maximize the profit of the inspection of all demand locations. Therefor, the objective function below, is represented by the total revenues in the first term, and the total costs in the remaining terms. Considering the assumption that traditional vessels visit demand nodes via centroids, while uncrewed surface vessels visit demand nodes directly from the harbors, in the first line, j is represented by both harbors J and centroids Q. All the following terms are representing a part of the cost. The second line invokes the specific vessel costs to perform operations at a demand node. The third term represents the travel costs. Note that the summations over I and J are complemented by centroids Q since both the trips from the traditional harbors to the centroids as well as the trips from the centroids to the demand nodes must be considered. The travel costs are defined as a function of both the speed s_k and vessel operating costs v_k of vessel k. Dividing twice the distance (round trip from harbor to demand node) over the travel speed per day and multiplying by the vessel operating costs per day results in the travel costs between nodes. $G_{k,t}$ denotes an additional factor for 12-meter USVs that doubles the trip length (and according travel costs). This is a result of the intermediate refueling that is required halfway through each 12-meter USV operation. The fourth term registers the port dues for crew changes. These are invoked each time a traditional vessel departs to a centroid. The fifth term represents the port dues for robodocks. Contrarily to crew changes, these are paid for per harbor J per year, instead of per vessel K per harbor visit. Hence, here $y_{U_t t}$ is used in stead of $x_{ijk_{1t}t}$. The next term accounts for the depreciation costs of the selected vessels (this is calculated per vessel per year, contrarily to the operation costs which are based on the days of operation) and the final term charges a penalty in the form of mobilization and transportation costs if a robodock is relocated to another harbor.

$$
\begin{aligned}
max \quad & \sum_{i \in I_t} \sum_{j \in \{J_t, Q\}} \sum_{k \in K_{V,t}} \sum_{t \in T} w_{it} x_{ijkt} \\
& - \sum_{i \in I_t} \sum_{j \in \{J_t, Q\}} \sum_{k \in K_{V,t}} \sum_{t \in T} v_k l_k x_{ijkt} \\
& - \sum_{i \in \{I_t, Q\}} \sum_{j \in \{J_t, Q\}} \sum_{k \in K_{V,t}} \sum_{t \in T} \left(\frac{2G_{kt} v_k d_{ij} x_{ijkt}}{24 s_k} \right) \\
& - \sum_{i \in I_t} \sum_{j \in Q} \sum_{k \in K_{1t}} \sum_{t \in T} f_j x_{ijkt} \\
& - \sum_{i \in U_t} \sum_{j \in J_t} \sum_{t \in T} f_j y_{U_t t} \\
& - \sum_{i \in I_t} \sum_{j \in H_t} \sum_{t \in T} dc_V z_{jvt} \\
& - \sum_{i \in U_t} \sum_{k \in K_{\{2,3\}t}} \sum_{t \in T} rc * a_{jvt}
\end{aligned}
$$

The following constraints are proposed in the model:

Subject to:

$$\sum_{j\in J_t}\sum_{k\in K_{V,t}} x_{ijkt} + \sum_{j\in Q}\sum_{k\in K_{V,t}} x_{ijkt} = 1 \; \forall i \in I_t, t \in T \quad (1)$$

$$\sum_{j\in J_t} y_{jt} \le p_t \quad \forall t \in T \quad (2)$$

$$z_{jkt} \le y_{jt} \quad \forall j \in J_t, k \in K_{V,t}, t \in T \quad (3)$$

$$\sum_{j\in J_t} z_{jkt} \le 1 \quad \forall k \in K_{V,t}, t \in T \quad (4)$$

$$\sum_{i\in I_t} x_{ijkt} \le 4 \quad \forall j \in C, k \in K_{V,t}, t \in T \quad (5)$$

$$d_{ij}x_{ijkt} \le r_k z_{jkt} \quad \forall i \in I_t, j \in J_t, k \in K_{V,t}, t \in T \quad (6)$$

$$\sum_{i\in I_t}\sum_{j\in J_t} l_k x_{ijkt} + \left(\frac{2G_{kt}d_{ij}x_{ijkt}}{24s_k}\right) \le o_k \; \forall k \in K_{V,t}, t \in T \quad (7)$$

$$\sum_{j\in U_t} z_{jk(t-1)} \le z_{jk(t)} \quad \forall k \in K_{\{2,3\},t}, t \in T > 0 \quad (8)$$

$$z_{jk(t-1)} \le z_{jkt} + a_{jkt} \quad \forall k \in K_{\{2,3\},t}, t \in T > 0 \quad (9)$$

$$x_{ijkt}, y_{jt}, z_{jkt}, a_{jkt} \in \mathbb{B}, \; \forall i \in I_t, j \in J_t, k \in K_{V,t}, t \in T \quad (10)$$

The constraints ensure that each demand location is covered by a vessel from a centroid *or* a facility (1). The total of facilities is limited by p_t (2). (3) assures that vehicles can only be assigned to located facilities and (4) assures that vehicles can only be assigned to one facility. (5) orders the traditional vessel to return to the traditional harbor for crew changes after executing at most 4 projects from a single centroid. The range constraints of the vessels are enforced by (6), while (7) limits the days of operations to stay within maximum yearly operational days. Similar to the second term in the objective function, the days of operation is calculated using distance and speed. Dividing the distance in knots by the speed in knots per hour and multiplying by 24 hours results in the number of days that are spent in transit. Once again, $G_{k,t}$ is noted to account for 12-meter USVs having to travel twice to complete a single job. Adding this with the days spent on operations should be less or equal to the maximum yearly operational days of a vessel. Additionally, several constraints are introduced to enforce consistency regarding the vessel fleet throughout the time indices. (8) ensures that the decisions to acquire additional USVs in previous time indices will be preserved as giving conditions in the subsequent time indices. Similarly, (9) enforces a penalty when a robodock is moved in between consecutive time indices. Finally, (10) assigns binary dimensions to the domain of the decision variables.

Considering the introduced heterogeneity of the vessel fleet in combination with the centroid-like routing, some additional giving conditions were defined in order to properly find results for the case study. The following giving conditions therefor had to be included in the form of additional constraints:

- Traditional vessels only visit demand nodes via centroids:

$$x_{ijkt} = 0 \quad \forall i \in H_t, j \in J_t, k \in K_{1t}, t \in T \quad (11)$$

- If a traditional vessel goes from a centroid to demand node, the vessel has to go from a harbor to a centroid:

$$\sum_{j\in J_t} x_{ijkt} \le M * \sum_{j\in H_t} x_{jikt} \; \forall i \in C, j \in Q, k \in K_{1t}, t \in T \quad (12)$$

- USVs do not travel through centroids but go directly to demand nodes:

$$x_{ijkt} = 0 \quad \forall i \in U_t, j \in Q, k \in K_{\{2,3\}t}, t \in T \quad (13)$$

VI. PROBLEM SETTING

In this research, the scope is limited to the offshore operations in the North-Sea as depicted in figure 1. Each asset is expected to request an inspection once in every given time frame and all demand is tendered to a single party. Demand nodes are split up into windparks or oil & gas platforms. Each with a relative revenue and similar work scope for the operations. No specific equipment requirements for assets inspections will be considered. Every vessel will be able to execute the same operations at each demand node.

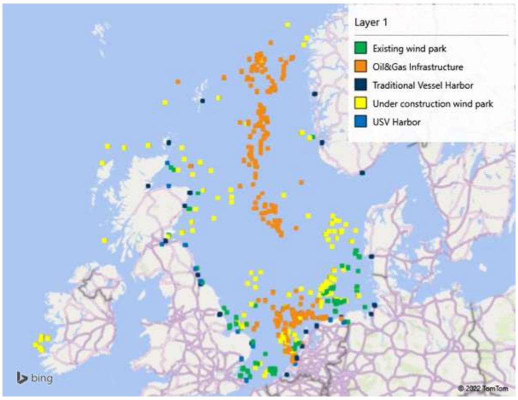

Fig. 1: Scattered nodes of the North-Sea assets

Furthermore, weather conditions will only be taken into account by differentiating between the number of operable days for the different types of vessels. The exact number of days is defined by the speed of the vessels that execute the operations.

Given this problem setting, we try to understand the consequences of the model behavior by verifying the outcomes of experiments when imposing alterations to the input parameters. After, to validate the model, the outcomes of the base case simulations will be compared to the available real-world data. In addition, a sensitivity analysis will provide recommendations regarding the critical characteristics to consider in future vessel designs. First, a sensitivity analysis comparing the 12-meter and 18-meter vessel characteristics will be conducted, followed by an in-depth analysis of the 18-meter vessel specifically. In addition, a thorough analysis of the multi-period model will conclude with suggestions for the optimal harbor locations and the corresponding optimal fleet size & mix.

VII. RESULTS

The analysis of the model results leads to a threefold of conclusions. First of all, this section provides the recommendations regarding the vessel design. Secondly, the optimal harbor facility locations will be discussed, and finally, the findings regarding the corresponding optimal fleet size & mix will be addressed.

A. *Vessel design recommendations*

The model outcomes show a strong preference for 18-meter USVs. Therefor, a sensitivity analysis of 12-meter USVs regarding the characteristics *speed*, *operability* and *operation costs* was performed, in which the aforementioned 12-meter USVs characteristics will be incrementally adjusted towards their 18-meter counterpart. These characteristics will be considered for the following reasons:

1) Speed influences transit time, range limitations and the service time of vessels. Therefor they are adjusted simultaneously.
2) Operability relates to the days that USVs will be able to operate at sea. More operational days means more potential demand nodes can be visited to recoup vessel expenses. In reality the number of operational days is subject to weather conditions. The number of days with good weather conditions can change from year to year, thereby emphasising the importance of understanding the impact of alterations to operable days on the model.
3) Operational costs are a driver of remote and autonomous operations. Through remote operations, crew can be simultaneously assigned to multiple operations, significantly bringing down operational costs.

Concluding from the first sensitivity analysis, the 12-meter USV cannot be deemed a worthy opponent of the 18-meter USV. In fact, the 18-meter USV outperforms his smaller counterpart in the performance of almost every characteristic. The only part where the 12-meter USV might have an edge can be found in the cost component. Turning this aspect into its strength might have some interesting consequences for the whole system, leading to higher profits and a more diverse fleet. The operational costs are considered to this large extent because USVs are aimed to strongly reduce the costs during operations. Without requiring personnel to be on-site, no crew will be wasted on transits and experts can be assigned to multiple projects simultaneously. In an ideal case, this could imply that a single crew can be assigned to two (or more) projects at the same time. Which would cut the wages of the operational cost in half. However, the same conclusion holds for the 18-meter USV. Hence, this feeds the discussion in which regard the 12-meter USV would make an interesting case compared to the 18-meter USV. Given the influence costs seem to have, one suggestion would be to discover the possibilities for a cheaper 12-meter USV, that could perform near shore projects such as waterway surveys or coastal protection inspections. These projects are expected to surge in the coming years. The question would then be, first of all, where these inspections will likely be performed, and secondly, what the profitability of these types of projects will be. This notion will be further addressed in the discussion.

As it occurs to be more interesting to uncover the impact of the characteristics of the 18-meter USV, a new experimental setup is constructed. The second sensitivity analysis is based on the model configuration without allowing the allocation of traditional vessels and 12-meter USVs. Because the 18-meter USV will not be able to complete the full workscope in this case, the constraint that enforces all demand to be covered will be lifted. This sensitivity analysis yields to the results depicted in table I from which the following conclusions can be drawn:

TABLE I: Sensitivity analysis for 18-meter USV

18-meter USV	Parameter value	Total profit	Percentage change	Number of nodes visited	Number of vessels
Range	192	€66.3 M		238	14
+50%	288	€82.7 M	+25	300	18
+100%	380	€82.7 M	+25	300	18
Operational costs	6000	€66.3 M		238	14
-25%	4500	€73.4 M	+11	253	15
-50%	3000	€85.0 M	+28	253	15
Operability	200	€66.3 M		238	14
+20%	240	€78.6 M	+18	246	12
+40%	280	€85.1 M	+29	253	11
-20%	160	€52.0 M	-22	247	18
Norway port	0	€66.3 M		238	14
	1	€157.0 M	+237	300	18

1) Increasing range is an available but risky way to improve profits:

First of all, a potential gain can be attained rather easily in the field of USV range. As assumed in the model, inspection jobs that are over one day of sailing will not be assigned to 18-meter USVs. Though, with more confidence in the range of the 18-meter USV will potentially lead to a large gain in profits. Currently, this is a substantially limit constraint on the model output as can be inferred by the number of nodes visited with 192 knots of range compared to 288 knots of range. This range is in fact already available given the large fuel capacity and endurance of the 18-meter vessel. Though, it must be noted, this is also a risky approach. Applying the larger range will mean that the USV will be way further out at sea. Not only will it then be further away from the safety of ports, also the conditions further out at sea will be substantially rougher.

2) Operability is a potential opportunity and potential vulnerability:

Another design characteristic to take into consideration is the operability. As depicted by the red row in table I, if the intended operability of 200 operable days per year will not be achieved, this will result in significant losses. The model now assigns more vessels to make up for the limited number of nodes each that can be visited with each vessel. This results in a much lower profit per vessel and a much lower profit overall.

3) Strategically locating facilities is an important consideration:

Apart from indicating the relative importance of range and operability for the profits attained in the model, the results regarding the addition of a single harbor location once more underline the importance of the facility locations in this research.

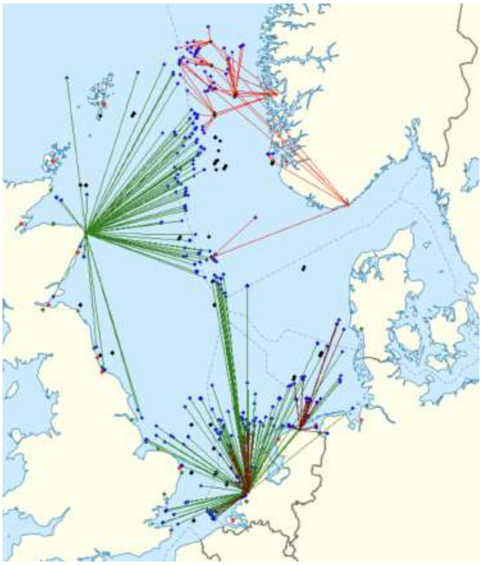

Fig. 2: Base run for sensitivity analysis 12-meter USV

When compared to the initial outcome of the base run as depicted in 2, it occurs that the model in which an additional harbor in Stavanger is introduced, as depicted in 3, yields a significantly different outcome. Compared to the scenario in which only 18-meter USVs are considered, an increase of the range of roughly 50% results in a profit increase of 25%, whereas the addition of a strategically located harbor increases the total profits by 237%.

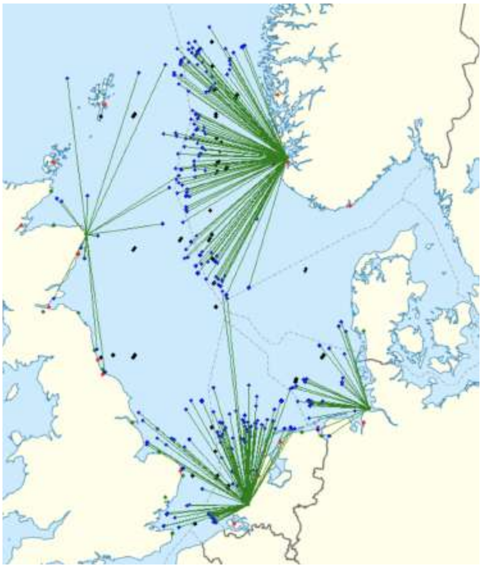

Fig. 3: Sensitivity analysis 18-meter USV with harbor in Stavanger

B. *Optimal harbor facility locations, and optimal fleet size & mix*

To determine the optimal current and future states of the model the following input conditions were added to the model:

- In the current state ($t = 0$) there is one 12-meter USV.

$$\sum_{k \in K_{2,0}} \sum_{j \in H_0} z_{jk0} \leq 1 \tag{14}$$

- In the current state ($t = 0$) there are no 18-meter USVs.

$$\sum_{k \in K_{3,0}} \sum_{j \in H_0} z_{jk0} = 0 \tag{15}$$

Applying the constructed *multi period max profit facility location model* on the full problem setting yields the following optimal harbor locations and according fleet size & mix as depicted in table II and illustrated in figure 4.

TABLE II: Final model in year 1

Final model in year $t = 1$	Profit	Number of nodes visited	Number of vessels used	Tonnes of CO^2 emissions	USV harbor locations
Total	€129.3 M				
Traditional vessel		141	5	15862	
12-meter USV		11	1	186	Buckie [1]
18-meter USV		266	15	1835	Peterhead [3], Scheveningen [2], Berghaven [10]

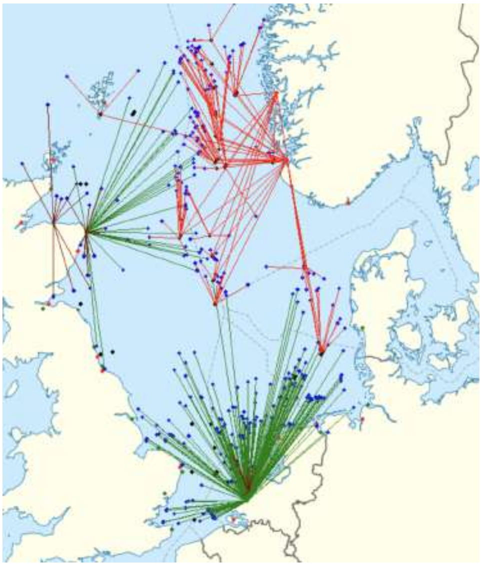

Fig. 4: Optimal harbor locations

The earlier conclusions drawn from the sensitivity analyses still uphold in the multi-period simulations. 18-meter USVs are favored over the 12-meter USV. In fact, the only reason why the 12-meter USV is even in the final model is because of the giving condition in period $t = 0$ in which the acquisition of 1 12-meter USV is enforced.

Focusing on the facility locations, the complete model that incorporates the construction of future wind parks recommends to harbor USV at 4 distinct locations. First of all, the 12-meter USV should be deployed from Buckie to address the northern assets. The 12-meter USV temporarily functioning as an automatic guided vehicle (AGV) covering considerable distances over land, will be addressed in the discussion. A total of 18-meter USVs should be acquired to execute operations from Peterhead, Scheveningen and Berhaven. Apparently the development in the southern regions of the North-Sea makes the latter two harbors even more attractive locations.

Table III depicts the four facility locations that yield the most profitable result from the multi-period model. These results are always bound to the simultaneous assignment of vessel to other facilities and the resulting fleet size & mix. In order to draw some more insights from this static outcome the individual harbors are separately precluded from this optimal set of harbors. Applying reserve reasoning, tells us what the impact of the lack of a certain harbor is. It is notable that precluding Buckie yields the largest decrease in profitability. This can be explained from the remote locations of the assets that tend to be serviced from Buckie. Hence, the consideration of remote located assets for the location of facilities indicates to have the largest impact on the profitability of operations. A similar conclusion was previously drawn from the sensitivity analysis in table I. The significance in profit improvements as a result of the inclusion of these remote facilities is unmatched. However, this does not consider the rough weather circumstances that are often attributed to these remote locations. A less substantial, but comparable result can be obtained by improving the range of 18-meter USVs, although this disregards the impact of weather conditions to an even larger extent.

TABLE III: Precluding experiments

	Total Profit	Percentage
Base run	€129.3 M	
Precluding Buckie	€118.2 M	0.91
Precluding Peterhead	€121.3 M	0.94
Precluding Scheveningen	€127.2 M	0.98
Precluding Berghaven	€128.0 M	0.99

On another note, the relative importance of Scheveningen and Berghaven seems limited. This is because the model easily solves the lack of one of these harbors by attributing the vessels to the harbor that would still be considered in the simulations. As Berghaven and Scheveningen are in extreme close proximity of another this does not result in significant losses. Remarkably, even when precluding both Scheveningen and Berghaven from the set of available USV harbors, the model is still able to yield a total of €126.3, which approximates the original model to 98% by attributing 18-meter USVs to Lowestoft, Delfzijl and Lauwersoog. This is a rather confronting outcome: given the complexity of the model, and the many ways in which the different vessels can respond to precluded facilities from other neighbouring facilities, the relative importance of a specific harbor in regards to the determination of the final set of located harbor facilities is limited. Consequentially, the effective attribution of vessels to another set of harbors will be able to approach a similar profitability from the given workscope.

In conclusion, the relative importance of a facility is limited and can be effectively matched through the efficient allocation of a similar fleet to a different set of facilities. We can state that the determination of a facility location is only as good as the effective attribution of the fleet that will be located at these facilities.

VIII. CONCLUSIONS

The most significant vessel characteristics are *range* and *operability* as well as *operational costs*. Operational costs are likely to reduce when multiple USVs are deployed and remote crews can oversee several inspection jobs simultaneously. The importance of range and operability should be considered in the light of the North-Sea topology: the allocation of vessels is to a large extend dependant on the inspection jobs in the northern regions of the North Sea. These are further secluded and only within reach from few harbors. Therefor, altering USV characteristics that benefit the accessibility of these isolated assets have a considerable impact on the performance of the overall system. However, in reality these secluded inspection jobs in the northern regions are subject to severe weather conditions and consequentially not as attractive for USV operations as the model suggests. When validated against real world observations, the indicated importance of said vessel characteristics turn out to be disproportionately affected by the generalization of operability assumptions in their disregard of geographically specific weather conditions.

The most profound conclusion of this research is the interchangeability of precluded harbor facility locations. When determining the optimal harbor locations, it turns out that many different combinations of harbors and vessel fleets can approach the optimal profit. Given that all demand nodes are being serviced by a single company, a tremendous increase in the complexity of the model is perceived in the many different ways in which many different vessels can respond to precluded facilities from other neighbouring facilities. Consequentially, the effective attribution of vessels to another set of harbors approaches a similar profitability to the optimal set of harbors. Hence, the determination of a facility location is only as good as the allocation of the fleet that will be located at these facilities. As a result, the relative importance of a single facility in the final set of located harbor facilities is only minor when considering the exhaustive set of nodes, harbors and vessels of the entire North-Sea.

Additionally, transits from harbors to demand nodes were found to play a minor role in profit returns compared to operations at the assets. This is a rather confronting outcome considering the limited attention paid to the actual operations of asset inspections in this research. However, this outcome is reasonably intuitive: whereas facility location problems are commonly applied for distribution centres or drone deliveries where services at the demand are largely trivial, in this research the demand nodes play a significant role throughout the entirety of operations. In stead of delivering packages or goods, a multi-day service is being performed at the demand nodes. In contrast to the facility location problem in this research, where the complexity lies within the harbor locations, transit times, transit speeds and vessel characteristics, while the operations at the nodes are largely overlooked. This is a disproportional oversimplification of the observed system in the sense that the core of the activities, and actually the longest time of the operations is not spent in transit but rather **at** the demand node.

IX. DISCUSSION

The model creates a visual representation of the vessel routes and harbor locations, which has proven to be helpful for the validation of the model behavior and intuitively communicating the model behavior. However, they also point out some shortcomings in relation to actual marine traffic.

1) The routing decisions are not based on real marine traffic.

The model considers the vessels to navigate in a straight line through open water, like drones that do not follow a fixed network but rather fly directly through continuous space. However, in reality, the North-Sea coastlines display some curves that do not always match the straight navigation behavior of the vessels. In some instances this results in the vessels covering sizeable distances over land. In the optimal configuration of facilities a 12-meter USV is deployed from Buckie. However, it is suddenly functioning as an automatic guided vehicle (AGV) covering considerable distances over land. This obviously could never be a trip made by the 12-meter vessel. In fact, it is debatable whether the 12-meter vessel would even have the endurance to reach the northern asset that is is currently assigned if it would have to travel all around the northern coastline. Consequentially, this oversimplification drives the optimal outcome of the model in a direction that is fundamentally infeasible in the real world.

2) No specific equipment requirements for assets inspections will be considered. Every vessel will be able to execute the same operations at each demand node.

Other than oversimplifying the types of infrastructures that are inspected, neither does the model does not take different types of inspections into account. Different types of vessels can deploy different types of inspection equipment. Each having its own characteristics in terms of operability, speed of operations. Ignoring the fact that not every vessel is able to carry the same types of equipment allows each vessel to execute operations at each demand node. Therefor, the relative considerations between vessel assignments are only based on operation time, transit time and related costs.

3) Weather conditions will only be taken into account to a certain extend: a strongly limited number of operable days for the smaller vessels.

As mentioned in the first assumption, the North-Sea can be a rough environment. The vessels have a distinct allowance in regards to wave heights. This means that larger traditional vessels can sometimes continue operations while a smaller USV has to come back into port. This means in bad weather circumstances the smaller vessels will not be leaving port for inspections while the traditional vessel might. The attainment of the *yearly operational days* that are considered per vessel per year therefor heavily depend on the timing of extreme weather events.

Other critical limitations resulting from the assumptions are:

4) The scope is limited to the offshore operations in the North-Sea.
5) No corrective maintenance is taken into account.
6) All demand is tendered to a single party.
7) Demand nodes are split up into windparks or oil & gas platforms. Each with a respectively similar revenue and respectively similar work scope for the operations

The decision to use a simulation model was part of the research design. The research design contains several limitations as well, which are often the result of trade-offs between more complex additions resulting in more realistic results, and more cumbersome computations. The choice for an MIP was made for several reasons. The first reason followed from the gap that was identified in the literature review. This gap identified a lack of attention for facility location problems in the maritime industry, whereas these type of problems are frequently covered in remote operation applications. However, translating the complexity of the maritime environment into a mathematical model that captured an appropriate trade-off between incorporated complexity and adequate sparsity, turned out to be rather challenging. Especially when studying the choices of a heterogeneous fleet over a multi-period time interval the issue regarding computational times became apparent. In hindsight, the decisions regarding the facility costs and travel costs appear to be of lesser importance than the costs during operations. This goes to say that the implications of the reality, in which the largest amount of time is spent during operations and not during transit, were not considered to be as influential as they turned out to be. When reflecting on this approach compared to other studies regarding facility location problems, like drone deliveries or distribution centers, the activity at the demand node is significantly different. In a drone delivery, the bulk of the delivery is spent in transit. The delivery *at the node* is only a small part of the whole operation. However, in this research a disproportionately large amount of the operations are occurring *at the node*, and the transits in between have a remarkably lower impact.

The simplifications and assumptions that are made in this research can lead to model results that deviate from results that would be obtained in reality. As partially discussed in the preceding sections of this paper, various assumptions and limitations are driving the model outcomes. Nevertheless, the outcomes of the simulations can serve the validation of several hypotheses regarding vessel design, facility location determination and robodock applications in the future.

All in all, this research provides a first piece of reflection regarding MIP problems for autonomous operations in the maritime industry that can be addressed by future researchers. In short, my research has pointed out that the complexity of USV operations in the maritime industry is difficult to capture within an acceptably sparse facility location problem. Furthermore, future researchers are advised to consider the demand nodes in more detail. In fact, vessels spent most of their time performing operations at the inspection nodes, rather than in transit. Additionally, given the specific inspection requirements related to each job, their irregular inspection demand and the developments of new assets in the future, it will be interesting to address the stochasticity in the operational phase.

X. RECOMMENDATIONS

The final advise regarding the complexity of the model results from the application of traditional vessel routing via centroids. The routing via these centroids allows the model to make calculated decisions between traditional vessel and USVs, and allows the final outcomes to be validated with real world data. However, in trying to incorporate an important part of the complexity of the system, the centroid routing is an oversimplification in itself that makes the simulations extensively cumbersome and the comparing of results more ambiguous. That being said, the validity of the model as a whole was reasonably adequate. Despite long running times and heavy mathematical computations, the simulations were able to provide intuitive results that allowed this research to draw relevant conclusions regarding the future development of remote operations.

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