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A Spreadsheet Model for Offshore Logistics Planning with Dynamic and Activity-Based Demands

A quantitative study dedicated to improving supply-
planning efficiency

Bachelor's thesis in Logistics Engineering
Supervisor: Andreas Breivik Ormevik
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Norwegian University of Science and Technology
Faculty of Economics and Management
Dept. of Industrial Economics and Technology Management



Bachelor's Thesis at the Norwegian University of Science and Technology
Department of Industrial Economics and Technology Management (IØT)

<p>Title: A Spreadsheet Model for Offshore Logistics Planning With Dynamic and Activity-Based Demands</p> <p>Tittel: En regnearkmodell for offshore logistikk planlegging med dynamisk og aktivitetsbasert etterspørsel</p>		<p>Group number: 002</p>
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<p>Employer: Equinor ASA</p>		
<p>Employer contact persons: Marius Olsen and Fredrik Kolnes Fadnes</p>		

<p>Summary: A demonstration of Equinor's various oil field supply-needs, supplied from the depot Dusavik, and its effect on supply-planning, both in terms of route selection and number of vessels. The project team intends to apply predicted supply-needs based on future planned projects to create a method for a dynamic route selection.</p>	
<p>Keywords:</p> <ul style="list-style-type: none"> • Offshore logistics • Scheduling • Supply • Optimization • Spreadsheet modelling 	<p>Stikkord:</p> <ul style="list-style-type: none"> • Offshorelogistikk • Planlegging • Forsyning • Optimalisering • Regnearkmodellering

Preface

This bachelor's thesis culminates three years of studies in *Logistics Engineering*, conducted at the Department of Industrial Economics and Technology Management at the Norwegian University of Science and Technology (NTNU). During the course of this study, we have acquired valuable knowledge and gained useful experience which have been applied to the execution of this thesis, carried out in the spring of 2022, under the supervision of PhD fellow Andreas Breivik Ormevik, and assistant supervisor, Associate professor Alireza Ashrafian.

The foundation of this bachelor's thesis was our project assignment written in the Autumn of 2021 in collaboration with Equinor ASA. There, we gained an insight to the functioning of offshore logistics and the importance of the design of efficient transport logistics. Further investigation of the subject presented an opportunity to take a closer look at the role of ongoing projects on the oil installation, as these projects may play a more significant role in supply operations than previously assumed. This assignment has further provided us with insight into the use of optimization models to derive and analyze information from real-life processes and systems.

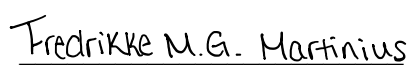
We would like to express our gratitude to our contacts at Equinor, Marius Olsen and Fredrik Kolnes Fadnes for their engagement and the opportunity they have provided us. Furthermore, we would like to thank both our supervisors, Andreas B. Ormevik and Alireza Ashrafian. We are especially grateful to our supervisor Andreas B. Ormevik who has been an essential resource to the progress of this project. His expertise, competency in the relevant field and contribution to our work through constructive feedback, good advice, and support has been crucial to the completion of this project.

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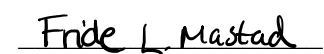
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Abstract

The petroleum industry encounters several choices in the face of a more sustainable world. Because of their production of several non-renewable products, the industry is dependent on taking measures within the various sectors to become more sustainable. Among them we find offshore logistics.

This bachelor thesis is written in collaboration with Equinor ASA, which is one of the largest actors in the Norwegian petroleum industry. Offshore logistics is essential for, among other things, the operation of the offshore installations and to ensure that supplies are delivered to the installations. This bachelor thesis will address how supply planning within offshore logistics can be improved to increase efficiency.

There are several aspects that affect how the supply operation is carried out. Each installation has a standard demand, where some installations also have ongoing projects which change their demand, leading to continuous changes in the total demand. The demand and required vessels change every week; thus, a dynamic route planning is necessary.

To be able to answer the problem statement, a case study has been carried out that specifically looks at one of Equinor's supply depots, Dusavik, and its supply to the various installations. Furthermore, Excel, which is a frequently utilized tool, was used to create a spreadsheet model that provides a dynamic solution to the planning challenges. This should optimally reduce emissions while at the same time minimizing costs associated with transport. The spreadsheet model is designed on the basis of historical data obtained from Equinor, and is based on pre-generated routes, and Equinor's future progress plan. Various supply approaches have been explored in this spreadsheet model to examine the degree to which the route planning should be dynamic in order to obtain a more optimal solution in terms of utilization.

This spreadsheet model has been developed in such a way that it provides the opportunity to adjust and modify to adapt to one's own needs and projects. Considering the model's quick answers and weekly solutions within minutes, this will not only be a useful tool for Equinor, but also provides the opportunity for the use of spreadsheet modeling as a standard tool for route planning.

Sammendrag

Petroleumsindustrien står ovenfor flere avgjørende valg i møte med en mer bærekraftig verden. Ved produksjon av flere ikke-fornybare produkter, er industrien avhengig av å gjøre tiltak innenfor de ulike sektorene i næringen for å bli mer bærekraftig. Blant dem finner vi offshore logistikk.

Denne bacheloroppgaven er skrevet i samarbeid med Equinor ASA, som er en av de største aktørene i den norske petroleumsindustrien. Offshore logistikk er blant annet essensielt for at driften av offshore installasjonene fungerer slik de skal, og at forsyninger blir levert til installasjonene. Denne bacheloroppgaven vil ta for seg hvordan man kan forbedre forsyningsplanlegging innenfor offshorelogistikk og effektivisere den mest mulig.

Det er flere aspekter som påvirker hvordan forsyningen til installasjonene burde utføres. Hver installasjon har sin ukentlige standard etterspørsel, hvor enkelte installasjoner også har pågående prosjekter som forandrer denne etterspørselen, dette fører til at den totale etterspørselen har kontinuerlig endringer. Forsyningen og behovet for fartøy endres hver uke og en dynamisk ruteplanlegging er derfor nødvendig.

For å kunne svare på problemstillingen er det gjennomført en casestudie som ser spesifikt på en av Equinors baser, Dusavik og dens forsyninger til de ulike installasjonene. Videre er Excel brukt som et hyppig verktøy for å kunne utarbeide en regnearkmodell som gir en dynamisk løsning på planleggingsutfordringen. Denne skal optimalt sett redusere utslipp og samtidig minimere kostnader knyttet til transporten. Regnearkmodellen er utformet på grunnlag av historiske data innhentet fra Equinor, samt basert på forhåndsgenererte ruter og den virkelige framtdsplanen til Equinor. Ulike forsyningstilnærminger er utforsket i denne regnearkmodellen for å undersøke hvor dynamisk ruteplanleggingen bør være for å få en mer optimal løsning med tanke på utnyttelsen.

Denne regnearkmodellen er utviklet på en slik måte at den gir muligheten til å foreta justeringer og modifikasjoner tilpasset egne behov og prosjekter. Med tanke på modellens raske svar og ukentlige løsninger innen få minutter, vil dette ikke bare være et nyttig verktøy for Equinor, men åpner også opp for bruk av regnearkmodellering som standardverktøy ved ruteplanlegging.

Explanation of Concepts and Abbreviations

Bulk	Large quantity of goods transported on the lower deck of a vessel (M3 deck, measured in m ³).
Charter vessel	A vessel rented from the spot market for a period of time.
CSR	Corporate Social Responsibility
Field	An area yielding mineral oil, on which several oil installations are often placed.
Installation	A rig/platform (stationary or mobile) where petroleum is extracted.
Jevons Paradox	By improving the efficiency of the use of a resource, its consumption tends to increase (rather than decrease). Having the opposite effect of what was originally intended.
Oil installation	A place or facility where oil is extracted, often a platform or rig.
Fleet vessel	A permanently leased vessel as part of a fleet.
Spot market	A market with “immediate delivery” products.
VBA	Visual Basic of Applications.

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1. Introduction

In the first chapter of this thesis, the background and motivation of this project will be presented, followed by an introduction of the employer to this project case. Then, the problem statement with the associated research questions will be introduced. Furthermore, the ambitions and goals regarding this project and problem statement, will be described and predetermined delimitations defined. Lastly, the remaining thesis structure will be outlined.

1.1 Background and Motivation

In recent decades, the concept of sustainable development has gained an increasing amount of attention. In the year 2000, the United Nations Organization developed the Millennium Development Goals for 2015 in a global effort to engage in indignity. In 2015, these goals were enhanced, and new goals were developed for 2030, as the initial goals lacked focus on sustainable development. Therefore, 17 sustainability goals, with 169 sub-goals, and a focus on areas within environmental, climate, social and economic conditions were developed.

The sustainability goals aim to, among other things, help fight inequality, solve climate change, and eradicate poverty (FN-sambandet, 2022). To achieve sustainability, these areas must be considered and recognized as having both positive and negative effects on one another. The advancement towards sustainability affects large parts of the industry business community, among them, the petroleum industry. Previously, companies have been inclined to exploit every resource available to run a profitable business. However, they are now forced to consider the consequences brought on by their production and consider sustainability as they strive for profitability and development. Since the mid-1960's petroleum has had an explosive development with increasing economic growth and financing of the Norwegian welfare. In fact, the Norwegian petroleum industry is now considered the most important industry in terms of the Norwegian economy, energy supply, and export industry (Regjeringen, 2021).

There are currently 37 petroleum exploration and production companies operating on the Norwegian continental shelf (Norskpetroleum, n.d.). Given its importance, the petroleum industry faces external pressure to maintain its economic contribution, while simultaneously advancing the development of renewable energy production. Considering the Norwegian petroleum industries' size, its contribution to emission reduction measures is an essential

contribution to the development of a more sustainable world. A pivotal approach towards pursuing this ambition is through reducing emissions, by facilitating more effective solutions, which may entail a fall in employment. As an incentive, these CSR goals will increase competitive advantage and maintain their economic and market position. By streamlining sustainable energy-supply, using renewable energy, and reducing CO₂ emissions companies can progress towards the set sustainable development goals.

Due to an increasing population and materialism in the developing world, transportation has become increasingly extensive. This implies a surge in cars and trains, but also ship and flight transport due to globalization. Emissions from this transport sector have immense potential for improvement. Most achievements in CO₂ reduction within transit related affairs have been accomplished through technological advancement (OECD, 2002). For instance, in the development of engine technology, reduced fuel consumption, and pollution have contributed to lower emissions. On the other hand, in conformance with Jevons Paradox, these advances have in some cases been offset by changes in behavior. For example, the progression made in engine design, leading to fuel savings have been offset by a higher engagement, higher speeds, and powerful engines, causing an increase in emission (l.c). In conclusion, technology alone cannot be the only solution to current problems; additionally, habits and behaviors need to change (l.c).

In a lack of renewable energy alternatives in the maritime segment, another method of reducing CO₂ emissions is by ensuring more efficient offshore logistics. For instance, by means of a more efficient transport and supply of goods and equipment to and from oil installations, drilling and oil production has the potential to be more efficient. Within offshore logistics, the project team still see opportunities to improve efficiency and implement more sustainable solutions. By demonstrating and anticipating the supply-need to each installation it is possible to optimize transport and develop more efficient strategies.

One of the petroleum industry's leading actors who pursue these solutions, is Equinor ASA. They are among those who recognize the challenges and possibilities following this industry. The desire for improvement within their segment was presented to us by Marius Olsen and Fredrik Kolnes Fadnes at Equinor Stavanger, and the potential of this subject is what attracted the team to the topic.

1.2 Equinor ASA

Since its establishment in 1972, Equinor ASA, formerly known as Statoil (Ryggvik, Smith-Solbakken & Tollaksen, 2021), has largely contributed to the national economy, and become Norway's most renowned oil and gas company. More recently, they have also focused on the extraction of renewable energy such as solar energy and wind power (Equinor, n.d.(a)).

Equinor's ambition is to become a climate-neutral company within 2050. Their approach to sustainability is referenced below:

“Equinor supports the Paris Assignment and a zero-emission target for society. We have already reduced CO₂ emissions in oil and gas production down to the lowest in the industry, and we will continue to do more” (Equinor, n.d.(b)).

Since Equinor is among the leading actors in this industry, it is expected that they take the lead and contribute to achieving the zero-emission target while also offering energy that keeps the wheels of society going – in production, industry, and transport (Equinor, n.d.(a)).

In Norway, Equinor has oil installations all the way from Hammerfest in the north, to Kristiansand in the south, a total of 40 installations on the Norwegian continental shelf. These installations are supplied by so-called supply depots. One of these depots is located in Dusavik, in Stavanger, Norway. The transportation of goods and equipment from depots, including Dusavik, is done by supply vessels. Equinor has around 715 of these vessels on contract at any given time.

According to Equinor, the maritime sector represents 6% of the greenhouse gas emissions in Norway, and 2-3% of the total global emissions (Equinor, n.d.(d)). As a significant participant and supplier of fuel to the global maritime sector, their ambition is to step up the production and use of low carbon fuels by 2030, as well as significantly increasing the production of zero-emission fuel by 2050 (l.c). For their own maritime business, their ambition is to halve the emissions in Norway compared with emissions in 2005, by 2030, and halve the global emissions compared to emissions in 2008, by 2050 (l.c).

Although this is an important aspiration in Equinor's work, they are aware that the future has many possible outcomes. Therefore, their approaches are evaluated against several possible scenarios to ensure profitability and sustainability before they are implemented (Equinor, n.d.(e)). To that end, these ambitions need to be tackled from several different angles, with short- and long-term perspectives.

To accomplish this, they have, among other things, put new hybrid technology battery systems to use on 19 supply vessels, and are continuously adding to this (Equinor, n.d.(d)). In collaboration with the maritime industry, they have also started the development of the world's first supply ship with emission-free ammonia (l.c). Although they plan to continue this development towards a zero-emission value chain, in an intermediate phase, this transitory technology will be used. Though, it is essential to recognize that technology alone will not be enough, and that our behavior must also change. For instance, by planning more efficient sailing routes, and optimal utilization of vessels can contribute to a more sustainable development. Therefore, impractical sailing must be optimized and reduced.

1.3 Problem Statement and Research Questions

The following section is a citation of the preliminary report for this thesis. It is an orientation of the team's preliminary project and further intentions.

“Last semester (autumn 2021), this group, in collaboration with Equinor ASA completed a project around supply vessels for offshore supply bases, more specifically those from Equinor's supply depot in Dusavik. From this base, 13 oil rigs, located in the North Sea, are supplied by both scheduled and rented vessels...” “...In that project, we rearranged the routes used to supply each rig, while keeping the same number of visits per rig, in order to accommodate for the just-in-time principle applied by Equinor. By doing this, we were able to shorten the distance travelled by the supply vessels by 31% and reduce the number of vessels needed from five to three.

Continuing this dialogue, and in cooperation with Equinor, the project team plan to continue researching this topic, but work towards being able to implement our research specifically to each field, such that it may be applied by Equinor in their offshore planning. Simultaneously, by considering each field more closely, we hope to be able to include more

factors which we were forced to exclude in our previous project.” (Gustavsen, Martinius & Mastad, 2022).

Continuing the cooperation with Equinor from last semester (Autumn 2021), the project team kept dialogue to extend the project towards a bachelor thesis. In association with the topic of offshore logistics, it was mentioned that Equinor does not have a satisfactory overview of their supply-needs during different activities at each oil installation. These supply-needs vary depending on time consumption related to, for instance rock formation or plateau size. Rock formation will impact the amount of time taken to drill, and therefore the need for new supplies, and installation size will determine the amount of supply which may be sent in advance. Other differences such as distance from the supply depot and operational service time to unload the supply vessels also need to be accounted for when determining the supply to each of these oil fields.

Equinor have mobile oil installations which may be transferred to different fields for drilling. Each of these fields have unique differences, therefore their demand, both in terms of supply and number of visits, will vary based on this. By estimating these needs, Equinor will be able to more efficiently accomplish optimal supply. The consequence of miscalculations could result in major expenses and delays, which in turn will affect other routes.

With a desire to extend the aforementioned project (Gustavsen, Martinius & Mastad, 2021), the project team plan to investigate the need of supply for various activities for each field and how this may affect the strategy of supply-need planning. This may also be applied to Equinor’s upcoming projects, and their approach to supply in the form of number of vessels and time schedule. To aid in planning, the project team aspires to create a dynamic route planner, based on estimated future demand to determine the need for supply vessels. Their routes will, to some degree, be vulnerable to season and which phase the project is in, therefore, an analysis in Excel will be used to validate the various scenarios. This will give an indication of how flexible and vulnerable the pre-established route selections are.

The team will investigate the following problem statement:

How does the demand of the various oil field activities influence the supply vessel routes and fleet size from the depot Dusavik?

To clarify the problem statement and to better answer the comprehensive problem, some research questions were formulated:

- How does the change in demand affect the route selection and number of vessels?
- In what way should the route planning be dynamic and to what extent should the routes follow the demand?
- How can Equinor adapt their approach to supply their installations?

1.4 Goalsetting and Scope

The project team has developed goals for this project, to emphasize its desired achievements and effects. These are developed as a resource to stay on schedule and ensure that the team works towards the same ambitions. These goals are formulated using the SMART acronym, which stands for specific, measurable, achievable, related, and time bound. By taking this into account, the goals will be verifiable, and the project can be evaluated against these goals (Langlo, Johansen, Olsson & Rolstadås, 2020, p. 71).

1.4.1 Result-oriented Goals

The result-oriented goals represent the end products which the project team aspires to have accomplished at the end of the completed project:

- Develop an overview of the historic supply-needs for activities on active oil fields.
- Develop a method for choosing new possible combinations of routes in the event of changes in activities at the oil installations.
- Deliver a good 60–80-page report that Equinor will benefit from.

1.4.2 Effect-oriented Goals

The effect-oriented goals represent the effect the finished project seeks to accomplish:

- Reduce Equinor's costs and time consumption related to investigating the supply-needs of the various oil fields .
- Contribute to efficiency and planning of supply to future oil installations
- Acquire knowledge we may benefit from in our future careers.

- Strengthen our understanding of how our education can be transferred and applied.

1.5 Delimitations

The duration of this bachelor thesis is limited to 4-5 months. This resulted in the need for delimitations, in an effort to restrict the extent of the project. The delimitations of this project are summarized below:

- Because of the amount of data related to the supply from every depot within Equinor, the project team only had the capacity and time to investigate one of them. Therefore, the team continued their research on the installations linked to Dusavik depot. This entails that those supplies received or sent out by these installations from and to other depots, are not included, although this does not often occur.
- The planning and development of supply routes is complicated, considering the number of variables which may affect the result. Some of these are assigned presumed values due to capacity, difficulty in quantifying, lack of knowledge, and complication in finding values, owing to their age. Therefore, the analysis will be a simplification of the actual situation.
- Lastly, due to the lack of financial resources, it has not been possible for the project team to perform own observations or primary data collection. This limits the team to perform a clean desktop survey of the case, which may have had an influence on the overall picture and the teams understanding in relation to the case, and therefore also the results.

1.6 Thesis Structure

This thesis is further broken down in these following chapters:

Chapter 2 <i>Theoretical Framework</i>	Necessary theoretical basis for this project and problem statement will be presented in this chapter. The chapter contains theory concerning inter alia Lean and Practical Management Science.
Chapter 3 <i>Methodology</i>	In this chapter, the different methods used throughout the project are introduced. Various tools and data collection are also presented.
Chapter 4 <i>Case</i>	The case-study is presented in this chapter, along with the information needed to understand it. Furthermore, a section regarding drilling will be detailed to clarify how the drilling process is pertinent to the case.
Chapter 5 <i>Spreadsheet Modelling</i>	A description of the spreadsheet modeling process is detailed for both prototypes and the full-scale model with different data inputs.
Chapter 6 <i>Analysis of Results</i>	In this chapter, the analyses performed are presented. Simultaneously, results are presented and discussed throughout the chapter.
Chapter 7 <i>Conclusion</i>	This chapter summarizes and concludes possible solutions to the problem statement and research questions.

2. Theoretical Framework

This chapter describes the relevant theory for this project. Some of the theory is derived from the subjects “*TLOG2008 – Lean Production and Quality Management*” and “*TLOG2009 – Practical Management Science and Computer Simulation in Logistics*”, both of which are compulsory subjects in the study program *Logistics Engineering* at NTNU.

2.1 Lean

Lean was originally developed by Toyota Production, to focus on eliminating waste. It has become a much more comprehensive strategy, and the Lean-way of thinking represents a significant amount of today’s business culture (Albright & Winston, 2017, p. 124). Today, Lean is being used to gain competitive advantage through efficiency, greater flexibility, less waste, and simplification of processes. One of the aspects of Lean, JIT – Just-in-Time, will be explained in more detail below.

2.1.1 Just-in-Time (JIT)

Essentially, the JIT-principle can be defined as “*right item, in the right amount, with the right quality, at the right time, in the right place*” (Pihl, 2019). It allows small batch sizes, short changeover time and minimal inventories in production. This implies a reduced need of storage space and thus may result in reduced inventory tied-up capital (Hoff & Helbæk, 2018). For Equinor, JIT can play a substantial role within the supply of oil installations since the storage space on the installations are limited. In addition, certain equipment may be leased from other suppliers. Despite a short equipment utilization time, renting it for a longer duration will lead to higher rental costs, which can be reduced with a JIT principle. On the other hand, operating with JIT can also increase the cost caused by more frequent departures.

2.2 Static and Dynamic Route Design

As previously mentioned, there are both environmental and economic motivations for improving route-efficiency. Most supply vessels within the Norwegian oil supply follows scheduled routes to the installations. In the aforementioned project (Gustavsen, Martinius & Mastad, 2021), a new weekly schedule was proposed. This schedule was based on a static route design. This design can be explained as a system of designated routes, with several nodes as transfer points, which are used on a regular basis (Woxenius, 2007).

One of the challenges of a static route design with a changing demand, is the lack of flexibility. Usually, throughout a route, a fraction of the load is transferred at every node, and the rest is transported to the next node (l.c.). With a fixed schedule, changes in demand may cause insufficient capacity, which may lead to an unsatisfied demand or the need for “emergency” solutions. In contrast, maximum flexibility is offered with the use of dynamic route design.

Generally, static route design differs from dynamic route design in the sense that a dynamic schedule continually varies depending on the circumstances. These circumstances can for instance be a change in order of nodes within the routes, or timing, departures, and arrivals (l.c.). Within dynamic route design, routes are designed and changed depending on actual demand, and evolve in real-time (l.c.). Therefore, this previously mentioned predicament around fixed routes can be avoided, as a change in demand can be responded to with possibilities around customized schedules. This suggests a potential to minimize costs associated to change in demand. Continuous modification and advancement of routes, allows for possibilities to optimize routes depending on projects, schedules, etc., and therefore also to minimize costs and emissions associated with transportation. Dynamic route design is fundamental throughout this project, much because of changing demand, and the potential to cut costs and emission.

2.3 Operation Analysis

Operation analysis is a scientific method used to analyze and provide basis for making decisions in practical problems (Lied, 2017). Within operational analysis, one is dependent on aids such as mathematical models, which give a quantitative representation of the practical problem to be solved. The purpose of operation analysis is to make decisions to support in planning and management in various businesses in addition to assessing the consequences of decisions that are made.

2.3.1 Seven-Step Modelling Process

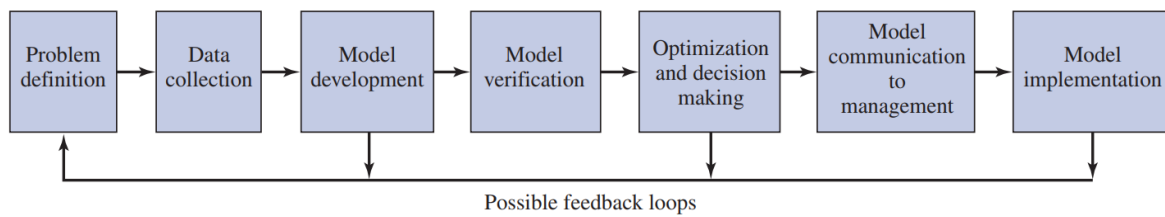


Figure 1 Albright and Winston's Seven-step Modelling Process

(Winston & Albright, p.8)

Albright and Winston, the authors of *Practical Management Science* (l.c.) present a seven-step process for modelling, illustrated in Figure 1. This process shows the seven steps of modelling and considers essential factors which should be taken into account when creating a model.

- Step 1 involves defining and familiarizing with the problem and what is required to solve it (ibid, p. 8-9). At this stage, the organizations goals should also be specified. For this project, this is detailed in Sections 1.3 and 1.4.
- Step 2, possibly the most crucial step in modelling processing, is data collection. Accurate data must be obtained to create realistic and valid solutions. The data may potentially not be in the correct or specified format at the time of collection; thus, this may need to be reassembled or converted to the correct format (l.c.). This was required of the project team and described further in Section 3.4.
- Step 3 involves the model development itself. A simple model design is desirable, while simultaneously accurately representing a realistic picture by including any uncertainties and delimitations (ibid. p. 10).
- Step 4 involves the verification of the modeling process. This step involves examining whether the model developed corresponds to reality, and confirming its relevance by verifying its outcomes against distinctive inputs (l.c.).
- Step 5 is optimization and decision making. In this step, the model is used to solve the actual problem. The models are often designed to achieve a purpose through optimization, such as minimizing costs, maximizing revenue etc. These results are presented in Chapter 6.
- Step 6 is to communicate the model to management. It is important to keep in mind that the organizational management may not have as good an understanding of the model as the project team, which is why the presentation of this should be as simple as

possible. Unless the solution is understood, the likelihood of its implementation and use is decreased.

- Step 7 addresses model implementation. This requires that the management is convinced that the model works and is viewed as relevant for solving the problem.

2.3.2 Spreadsheet- and Network Modeling

Spreadsheets are a significant tool for data processing and collection. Graphic visualization, diagrams, and tables in spreadsheet modeling create graphic visualizations, and may ease decision-making. Spreadsheet modelling is commonly done by entering input and decision variables and thereafter linking them correctly. This produces an output called the objective cell, which represents the answer to the suggested problem (Albright & Winston, 2017, p. 21).

In spreadsheet modelling, it is possible to develop optimization models. These models have an objective function for optimization with constraints that need to be satisfied. Only solutions within these constraints will be presented (ibid. p. 73-74). Furthermore, there are different types of optimization models, of which some can be formulated as networks. The goal of a network model is to optimize so-called “routes”, such as in Figure 2, and to receive one objective cell, such as total cost, revenue, or profit. The “Network model”, owes its name to its appearance, as the optimization model can resemble and be formulated as a network.

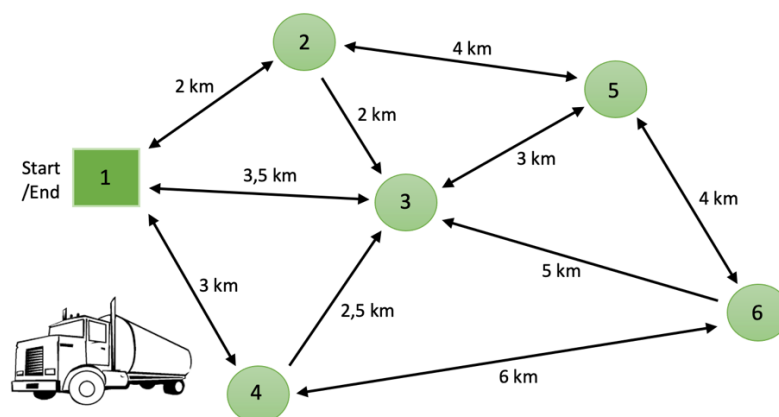


Figure 2 An Example of How a Network Model Is Constructed

Examples on network models are the related Arc-Flow and Path-Flow Models. The Arc-Flow Model is composed in such a way that every potential route is a possibility. Because of how large this model can become when solving complex problems, and how difficult it is to make

one that works with several constraints, it was not an option for this project. The model, on the other hand, was explored in the previous project (Gustavsen, Martinius & Mastad, 2021), and ended up with too many variables to run. This gave a further introduction to the Path-Flow model.

With the Path Flow model, which can be considered a slightly lighter model than the Arc-Flow, the routes are made in advance within the boundaries and constraints that have already been set. This reduces the number of constraints in the model, since most of the constraints are intertwined in the pre-made routes. Additionally, a lower route requirement lessens the variable quantity. Models of this type are more common and are a better alternative to bigger problems since they are much simpler. The problem with this type of model is that one can unknowingly exclude alternatives by omitting possible routes in the preparation of creating those routes. Typical restrictions in such a model are often: how much can be sent at each arc or the maximum capacity of each node. A deeper explanation of how the Path-Flow model is structured, and how it is used in this project is carried out in Section 5.2.

2.3.3 Solver

Solver is an add-in feature in Excel, primarily used for what-if analyses and optimization problems, in which the model tries to identify the optimal value in its objective cell. This cell is subject to formulas on the worksheet and their established constraints. By adjusting the decision variables, the model establishes an either minimized or maximized optimal solution (Microsoft, n.d.).

Within Solver, the following three algorithms or solving methods can be chosen:

- Generalized Reduced Gradient (GRG) non-linear
- LP Simplex
- Evolutionary

The non-linear GRG and Evolutionary algorithms are used to analyze non-linear problems, while LP Simplex can be used to analyze linear problems (l.c.). There is a considerable difference between the non-linear algorithms. GRG searches only for local critical points, while Evolutionary searches for a more global critical point. While this makes the GRG method significantly faster, its disadvantage is that it relies on the initial conditions, meaning that the

original numbers entered into the decision variable cells, will determine where the solver function starts looking for a solution. This entails that the solver function will present the first local minima or maxima it encounters from there, depending on its setting, as its final answer. As shown in Figure 3, if the initial conditions, or numbers entered into the model, places the objective cell on the leftmost point on the figure, the GRG method will produce the local minima below as its answer, although, in reality, it is possible to produce the most optimal solution at the global minima. The GRG non-linear method also requires smooth functions. Among other things, this means that “IF” and “LOOKUP” functions cannot be used.

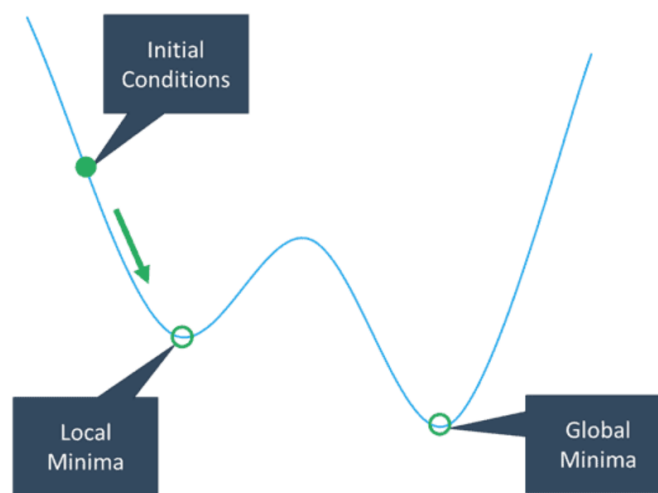


Figure 3 Example of How the GRG Non-linear Finds a Local Minima Although There Is a Better Global Solution

(EngineerExcel, n.d)

Due to these restrictions, the Evolutionary method may be a more robust algorithm than GRG non-linear. Although both GRG non-linear and Evolutionary can solve non-linear functions, the GRG non-linear method is difficult to use with discontinuous and non-smooth functions. Meanwhile Evolutionary is able to handle these functions (FrontlineSolvers, n.d.(b)). However, this method is more time-consuming, because, as it does not rely on derivatives or gradient information, it cannot determine if a given solution is optimal, therefore it does not know when to stop. Instead, it simply says that a new candidate is better than those discovered earlier (FrontlineSolvers, n.d.(a)). Therefore, even when running the Evolutionary algorithm for an extended period of time, there is still no guarantee that the best solution has been found (l.c.). Lastly, LP Simplex has the most stringent requirements to be met, because of its linearity requirement. As a result, you can be assured the solutions are always the global optimum.

Another important limitation of the standard Solver add-in is that it cannot manage an infinite number of decision-variables and has a maximum limit of 200. These premises are the that reason larger models often are made as Path-Flow models, instead of Arc-Flow models. In addition, Solver has a limitation of 100 constraints.

2.4 Flaw of Averages

“The only certainty is that nothing is certain” (Savage 2003). This quote emphasizes that every calculation and assumption will have hidden uncertainties and risks. The Flaw of Averages states that everything based on an assumption that the average will occur, is often wrong (Savage, 2003). Using averages may be misleading and lead to an unrealistic representation of the actual situation. This could result in the use of averages of averages, or a combination of these. Such outcomes could be unrealistic and counterproductive. Since this project involves a substantial amount of data collecting and processing, Flaw of Averages should be taken into consideration. An example of the Flaw of Averages is this lake, shown in Figure 4, illustrating that an average does not necessarily give an accurate representation of the actual situation.

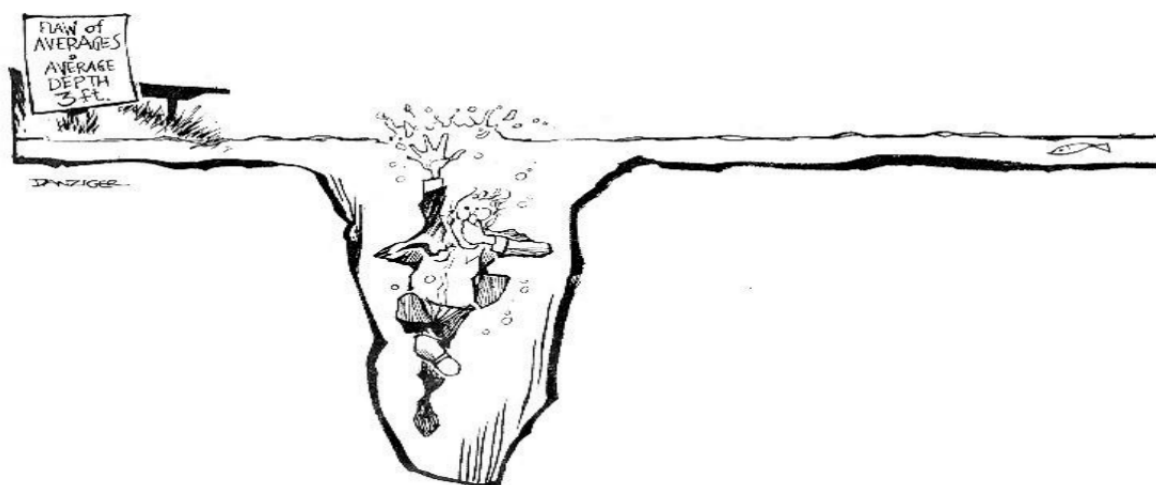


Figure 4 Example of How Flaw of Averages Can Manipulate the Outcome

(l.c.)

3. Methodology

In this chapter, the methods and approaches used by the project team to achieve the projects goals, will be presented. This chapter introduces research design and case studies as methods used for data collection. Thereafter, qualitative, and quantitative methods are presented in Section 3.2, followed by their varieties of data collection methods. Section 3.5 more specifically explains literature research for this project. A description of how Excel is used as a tool is also provided. Lastly, error processing is explained.

3.1 Research Design

Because the conditions and phenomena explored, are little known, an exploratory research design has been used. Typical results using this type of design are understandings and interpretations of the current situation, in addition to hypotheses (Sallis, 2021). As a first step in an exploratory design, it is natural to investigate whether the topic has been previously researched or written about (l.c.). Therefore, the theoretical basis intended for this project is mainly based on route planning and network-modelling detailed in Chapter 2. This theory will be transferred for use on this specific problem and geographical section, since any previous research with the use of spreadsheet modelling on this relevant area is unknown to the team. Exploratory design is appropriate when little is known about a research problem, thus it is natural to research weather data has been previously collected by others (secondary data) (l.c.). In secondary data search, we say we conduct a desktop survey.

In exploratory design, one frequently jumps back and forth between steps, rather than following a linear path. Such examples can be found in the problem statement, where the project is started with a broad and open problem statement, before it is gradually narrowed down, or when the analysis itself is conducted, theories and methods which were not previously considered may arise. Thus, it is vital for exploratory design to be flexible so that new ideas, thoughts, ways of thinking and revelations can occur.

Another research design applied, is the explanatory design. The design is used to explain the causes and consequences of a well-defined problem. In this case, explanatory design is mainly used to describe what the quantitative data collection tells us, and what significance it has for the analysis itself. Such a design makes it possible to explain the connection and meanings

between the quantitative and qualitative data (Baskerville & Pries-Heje, 2010). This results in a project with both good empirical and logical qualifications and framework. The next subsection explains the empirical case study in more detail.

3.1.1 Case Study

An empirical study, often referred to as a case study, examines a contemporary phenomenon in detail, and within real-life, especially in cases where the boundaries between context and phenomenon are not entirely clear (Yin, 2008). A case study usually consists of a single case, but sometimes also includes multiple cases, which are usually systematically compared and referred to as a comparative case study (Dahlum, Grønmo & Wæhle, 2020). The method is preferred when “why” and “how” questions are posed. These research questions seek to explain a phenomenon, and a deeper understanding may therefore be required (Yin, 2008). By use of a case study where the case is selected as a typical representation of a more comprehensive universe, the study can form the basis for a theoretical generalization (Dahlum, Grønmo & Wæhle, 2020).

There are different ways to make the decision of which case or cases to choose for the study. The decision can be made, for example, based on the data access sufficiency, or to what extent the cases can provide answers to the research questions (Yin, 2008). For this project, the decision of which case the study should apply to, was made by the employer. The employer considers this projects procedure leading up to potential solutions, or the conclusion itself, to be a good generalization to other areas within the company. The project team is also already familiar with the case, maintaining the same general case is therefore a natural choice. Admittedly, it can be demanding to derive general considerations based on a simple case study. Causation can be challenging to identify since an outcome may often be affected by several factors (Dahlum, Grønmo & Wæhle, 2020). The causation of uncertainties is therefore important to consider and should be clarified throughout the thesis. Nevertheless, the study can be an indication, and form a basis for new findings, or development of new hypotheses, to be further analyzed (l.c.).

3.2 Qualitative and Quantitative Method

It is common to distinguish between the research strategies: quantitative and qualitative methods. Traditionally, quantitative methods relate to objectivism, and qualitative methods to

social constructionism (Bryman, 2012). Most differences between the methods arise because quantitative research has usually been founded on a positivist view, in which experiential facts lead to absolute knowledge. Meanwhile qualitative research has moved from a positivist view to a hermeneutic view of knowledge, in which the individual's interpretation of the social world is emphasized (l.c.).

By using quantitative methods, it is easier to evaluate and control the work. This allows for easier comparison and delimitation of the scope, with use of numerical data, as opposed to using qualitative methods, which have a more open scope and allow for important data to be overlooked (Choy, 2014). Even though quantitative methods fit better when a significant amount of data is being processed, it does not take knowledge into account unlike qualitative methods, which gives a more holistic understanding of the problem (l.c.).

In this project it has been determined to use method triangulation (mixed methods) to answer the problem statement. This means that both quantitative and qualitative methods will be used, where in this case, qualitative methods will complement the quantitative methods in situations where the retrieved data is weak, or when a certain understanding and knowledge is needed, which quantitative methods can't provide.

3.3 Qualitative Data Collection

Qualitative data gathered is usually in the form of text (Grønmo, 2020). There are different methods for collecting this data, for example through observations, unstructured interviews, focus groups etc. (l.c.). Since qualitative methods will be used to complement the quantitative methods in this project, the qualitative methods used will be in the form of research interviews. Due to the unpredictable nature of the data required in this project, this type of research is an easily manageable approach. This approach allows for interviews at any stage in the process, where needed. Qualitative research interviews have: “...*the purpose of obtaining descriptions of the life world of the interviewee in order to interpret the meaning of the described phenomena.*” (Brinkmann & Kvale, 2015). More accurately, interviews in the semi-structured format will be applied.

The semi-structured format is a combination of structured and unstructured formats. The main questions are determined in advance with the opportunity for follow-up questions based on the

answers. These types are probably the most common format of interviews (Leavy, 2014). Unlike structured interviews, semi-structured interviews allow more leeway for following up what's important from the interviewee's perspective, as well as visualizing the interviewer as a knowledge-producing participant in the process (l.c.). Additionally, the interviewer has the opportunity to focus the interview on what they deem important in relation to the project (l.c.).

Due to unpredictability, distance, and lack of financial resources, the interviews were conducted using the digital tool Microsoft Teams. The members in the project team each had their responsibility, where one had the responsibility to interrogate, while the remaining team members took notes and made an interview summary. Keeping one team member in dialogue maintained better continuity, interaction, and flow throughout the interrogations.

3.4 Quantitative Data Collection

Data retrieved through quantitative methods are usually available in form of quantity terms, as numbers (Grønmo, 2021). This data can be collected through structured schedule, using different methods, official statistics or various databases and registers (l.c.). Because quantitative methods are mostly used throughout the project, the majority of the data will also be quantitative.

The data collected and assigned from our employer are obtained from the third-party digital platform WELS, which acts as a logistic software platform for managing the employer's cargo logistics (Equinor, n.d.(c)). Furthermore, the employer has also provided internal excel sheets which contain models that calculate quantity and volume based on the type of equipment. In addition, data obtained and analyzed from the project team's previous project, will also be utilized. Collectively, this data provides a detailed picture of the supply-needs for the various activities, and the foundation for possible shipment routes.

All quantitative data collected is secondary, meaning the data is originally collected for another primary purpose (Johnson, 2014). Since the data is secondary, it is often presented in a format used for other purposes and may therefore not be useful for its intended purpose. In cases where the data is not available in the correct format, the project team has had to convert parts of the data. For this project, all data that could not be converted directly from the platform WELS to Microsoft Excel was manually converted. During the collection and converting of data, it has

been necessary to analyze the data through a univariate analysis for better understanding and overview.

3.5 Literature Review

The project team's prior knowledge within petroleum, offshore and drilling industry was not sufficient, although the previous project has improved the team's understanding. Therefore, literature search has an important aspect in this project.

It has been necessary to conduct literature searches from the beginning of the project, which has been a time- and resource-consuming part of the preliminary phase of the analysis of this project. In a case-study, it is common for literature search to be among the first steps in a project (discussed in Subsection 3.1.1), it is therefore important for further work. Literature has been explored mainly from professional online articles, using Google Scholar and books from NTNU's libraries. Relevant and previous syllabi from subjects within the study program have also been used. The textbook *Practical Management Science (6th edition)* has been used as a basis for the theoretical framework of the project and as a tool for the conduction of the analysis. Literature search to find relevant subject matter, while also ensuring credible sources which are neither outdated nor incorrect, has been challenging in this project. In addition, by expressing the overall problem statement in form of several research questions, an efficient and helpful literature search has been made possible.

3.6 Excel as a Modeling Tool

In this project, the seven-step model, as explained in Subsection 2.3.1, was applied to the modelling. Following these basic principles ensures a structured and systematic process, which allows the project team to solve the problem statement. By following these steps, the progression of the project may also be tracked. Through the use of Excel, it will be possible to solve this thesis' problem statement and the goals this project intends to accomplish. The purpose of spreadsheet modeling is to investigate how different input affects the goal function, and which outputs provide an optimal solution for different scenarios. The development of the model itself, can be referred to as a typical Path-Flow model. To ensure a feasible model, a more easily manageable prototype with a smaller scope, was developed before extending this to the final model.

This prototype with associated delimitations will be further explained in Subsection 5.2.1 and 5.2.2. Compared with last year's assignment (Gustavsen, Martinius & Mastad, 2021), this Path-Flow model is further expanded to include some variables and limitations that were excluded last time, such as time-slack, resulting in a more complex Path-Flow model. The model was solved using Excel's add-in tool Solver. The verification of the model is further elaborated in the actual analysis of the project, in Chapter 5.

Following the development of the model and generation of routes, a systematic selection was executed to find the most optimal and valid solution for each week. In addition to Excel and the use of Solver, VBA - Microsoft Visual Basic for Applications was used to run the model. VBA allows an extension of Office applications through an event-driven programming language (Microsoft, 2021). This was applied to simplify the Solver process, as it enabled Solver to run a continuous optimization of all weeks. Appendix A4 provides the code used to run the loop.

3.7 Validity and Reliability

When conducting studies, research, or analysis, it is often beneficial to measure how well the process is performed. The terms validity and reliability encapsulate the adequacy of this process. With the use of these terms, the project team can address how well a phenomenon is measured (Sallis, 2021). Here validity is referred to as the legitimacy of measurements. It describes the extent to which results of the study, experiment or analysis are valid, and how these results can be used to make valid decisions (Dahlum, 2021). The project team distinguish between internal and external validity. Internal addresses the extent to which the results are valid for the specific survey, while external describes the extent to which the results from a survey can be transferred to other general situations. This means that the results of a survey may be valid for other situations too. In validation, it is not the actual method of measurement, which is validated, but rather an interpretation of the data that emerges using a specific procedure.

Reliability on the other hand relates to the accuracy of measurements, i.e., how stable, and consistent each measurement is. Figure 5 below demonstrates an example of the concept of the manifestation of reliability and validity on a target. The center of the target represents the intended measurement. Target 1, to the far left on the figure, shows consistency in the

measurements, hence reliability, but not validity, in the form of imprecise measurements. This is called systematic error, which may imply that the “wrong thing” was measured, or the same error was made in every trial. Target number three shows measurements spread randomly around the target, without a correct average, which makes it neither reliable nor valid. The last target represents measurements that are consistent and correctly measured. This results in a target with high reliability and validity.

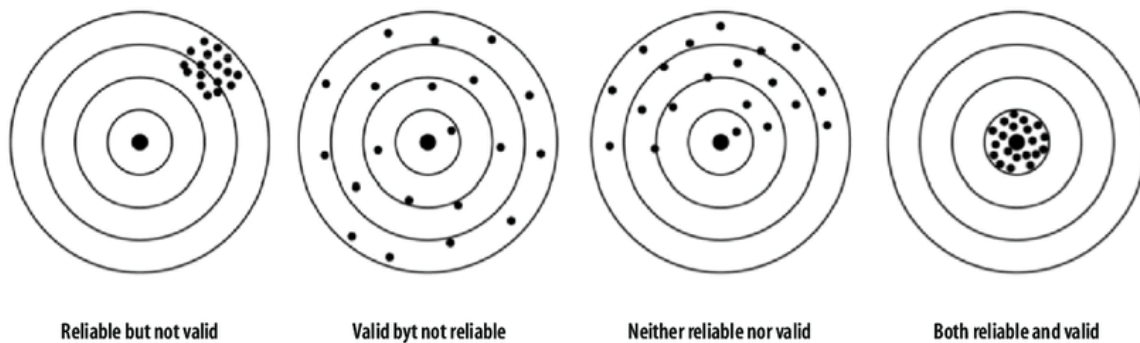


Figure 5 Possible Combinations of Validity and Reliability of Measurement Instruments

(De Souza, Neusa & de Brit Guirardello, 2017)

The underlying purpose of this project is to investigate whether it is possible to improve Equinor’s supply planning, by suggesting a method for selecting routes departing from Dusavik, and demonstrating the supply-needs of different projects at various oil fields. Thus, the project team will investigate whether the data provides a valid representation of reality, in that it can be used in other situations, by being transferred in space and time. (Johannessen, Christoffersen & Tufte, 2011). Results obtained in this analysis are primarily based on data collected from a thirteen-week period in 2021. Further data in previous periods from 2019 has also been used in regard to specific projects, in cases where recent projects were not available. Future project plans have also been collected. Data retrieved from periods affected by the Covid-19 pandemic may be somewhat unrealistic. In this case, the most important aspect is that the data collection is valid for our analysis and can give an idea of contexts and compositions with route planning. Reliability further explains how our research and analyses are trustworthy – how accurate our data is, what data is used, and why and how the data is collected and processed. By giving good and reasonable reasons for our “choices”, the requirement of the concept reliability is met.

3.8 Error Sources

Sources of errors in a survey, research experiment, etc., will always exist, as in this project. Whether it be measurements, data collection or interviews, all methods will have some error, and the errors can often be divided into random- and systematic errors (Frøslie, 2017).

3.8.1 Random Errors

Errors which arise from random causes, and errors that we cannot control, are known as random errors (l.c.). Within the retrieval of the data for example, there are errors which have occurred without being influenced by the project team. These can have occurred because of different conditions, like initial measurement conditions. Furthermore, errors can occur outside the measurement itself, for example because of weather conditions. Because of these random errors it has been important to calculate the average of multiple points throughout the project, to get a perception of the variations of the data, and therefore calculate approximated true values.

3.8.2 Systematic Errors

As opposed to random errors, systematic errors are usually caused by the incorrect use of procedures, faults within the measuring tool and faults due to capabilities (l.c). It is, however, possible to identify the cause of the errors, and narrow down their effects to some degree. For this project, some systematic errors relate directly to the retrieval of data, while others are related to the project team itself.

The data collection process from WELS was a comprehensive process. Data related to for instance the same activity or supply vessel within WELS are often available in different locations within the program. In addition, the team has a lack of knowledge of the program, therefore, it is possible that the relevant data has been misunderstood. Additionally, the back-and-forth processing caused by the fact that WELS could only be open in one tab at a time could result in data being overlooked or collected twice. This could also have occurred when the data was formatted from one format to another, since the data was not always presented in a useful format. This also caused a more time-consuming process than first assumed.

The data collected is obtained primarily from the period of January 2019 and onwards, where most of the data is from 2020-2021. Due to the COVID-19 pandemic and its effects on Equinor and the petroleum industry in general, it is possible that the data within this time-period has

been affected. The values could have deviated from normal values and further created a skewed understanding of the reality. Even without the effects of COVID-19, it is still possible that the time-period used in collection of the data does not accurately represent data from the entire population. Although the data would represent the entire population, it is possible that a few of the data points shows unrealistic high or low values, which again can influence the final average values. This has not been accounted for throughout this project.

Other systematic errors could be those related to the project team's bias. Conclusions drawn in the previous project on the same subject, or knowledge acquired during the course of the team's study program, may lead to inaccurate understanding of facts from this project. Which data is emphasized, or how the results are interpreted, may also lead to differing conclusions of the same data.

4. Case

In this chapter the project team will investigate and analyze the previously presented case. The important information of this case will be presented. Furthermore, the final section of this chapter will discuss drilling and how it relates to our project.

4.1 Case – Dusavik Depot

Dusavik supply depot is located on the northern side of Stavanger and is one of Equinor's seven supply depots in Norway. From Dusavik, the vessels supply 13 oil installations on nine oil fields. These 13 oil installations are: Deepsea Atlantic, Draupner, Gina Krog, Grane, Gudrun, Heimdal, Johan Sverdrup DP, LQ, PP & RP, Randgrid, Rowan Stavanger and Sleipner.

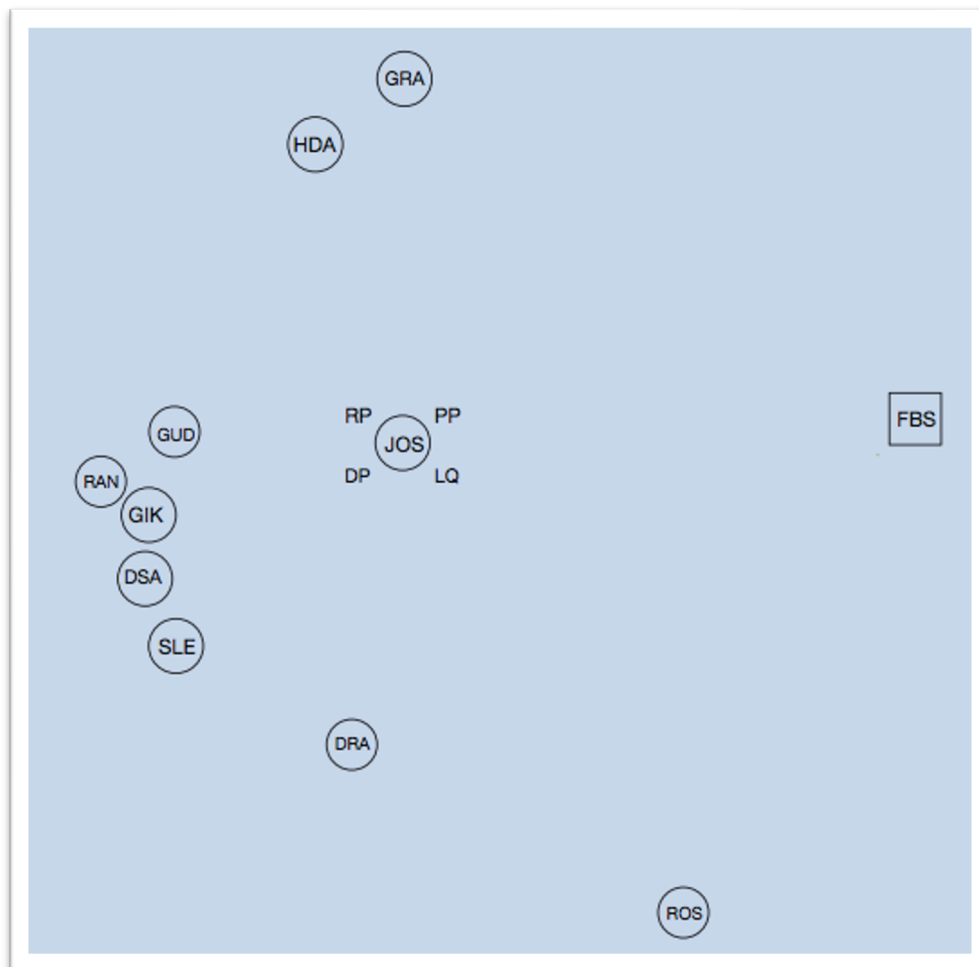


Figure 6 Position of Oil Installations with Departure from Dusavik (FBS)

Figure 6 shows a visualization of the location of these oil installations in relation to each other and the depot Dusavik. To simplify, the project team has also categorized the installations into

four zones, based on their location. With a glance at the figure, you can roughly see the zones with Johan Sverdrup field as one, and Grane and Heimdal as another. Further Draupner, and Rowan Stavanger form another zone. The last zone contains the installations Randgrid, Gina Krog, Deepsea Atlantic, Gudrun & Sleipner. Table 1 describes the various abbreviations of each installation, as well as giving an overview over both night open- and drilling installations.

Table 1 Information Regarding the Oil Installations with Their Abbreviations, Opening Hours and Type of Installation

Abbreviations	Full name	Night Open	Drilling installations
FBS	Dusavik (Depot)	-	-
DRA	Draupner	No	No
GUD	Gudrun	Yes	No
JOSPP	Johan Sverdrup PP	No	No
JOSRP	Johan Sverdrup RP	No	No
JOSLQ	Johan Sverdrup LQ	No	No
JOSDP	Johan Sverdrup DP	Yes	Yes
GRA	Grane	Yes	Yes
SLE	Sleipner	No	Yes
GIK	Gina Krog	No	Yes
RAN	Randgrid	No	No
HDA	Heimdal	No	Yes
DSA	Deepsea Atlantic	Yes	Yes
ROS	Rowan Stavanger	Yes	Yes

4.1.1 Supply Vessels

When supplying the oil installations with equipment, drilling pipes, food and other necessities, supply vessels are used. Because Equinor desires to maintain a JIT-principle, it was decided to continue using the present number of visits to each installation to sustain this capability. Therefore, the average number of visits to each installation, as calculated in the previous project (Gustavsen, Martinius & Mastad, 2021) were again used.

A supply vessel consists of two plateaus, referred to as M2- and M3-deck. The M2-deck is the uppermost deck and can be seen from the outside. This is used to store equipment such as pipes, parts for installations etc. These are usually placed in containers or baskets. A 3D-picture of the M2-deck is shown in Figure 7. The M3-deck is located underneath the M2-deck. This is where the bulk shipment is placed. The bulk consist of both goods and liquids such as drilling fluid, fresh water, and fuel. This bulk is categorized as wet (M3) and dry (MT) bulk.

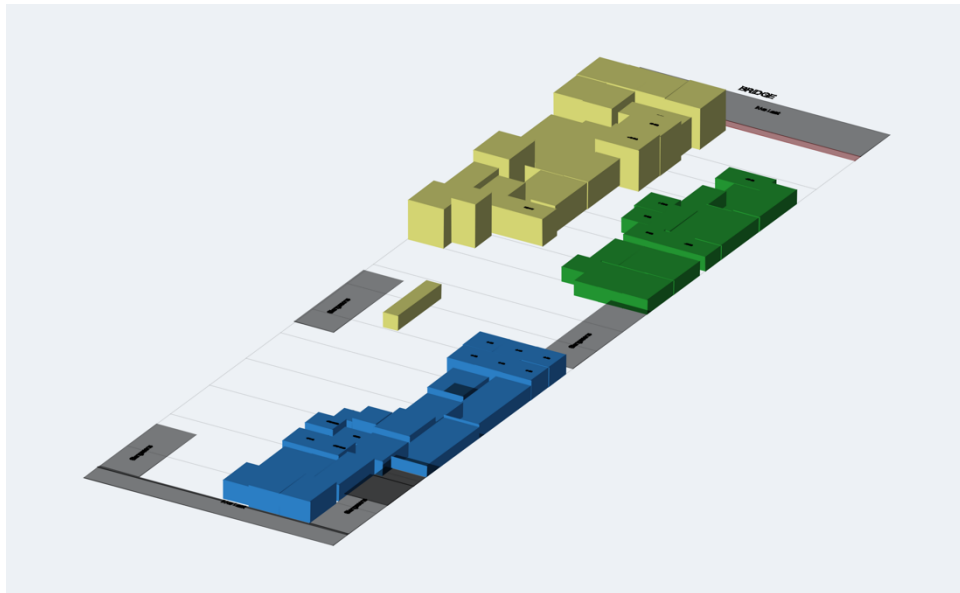


Figure 7 Vessel Cargo - M2 Deck, Example From the Logistics Platform WELS

Each deck has its own capacity and constraints. For the M2-deck, the capacity is given in square meters, whilst for the M3-deck, the cargo is given in cubic meters. Equinor operates with certain constraints on the M2 and M3 deck. This implies that the M2-deck will never be 100% utilized. 20% of the deck must be available at the first stop of each installation, although it is not a requirement for the last stop at Dusavik depot. These 20% are reserved, so that it is possible to maneuver containers and crew on deck, to be able to load backload (returned goods) onto the vessel before loading onto the installation, because their capacity is limited. In addition, parts of the deck are reserved, as dangerous goods (ADR) cannot be placed in areas above explosives. This industry also has equipment in large quantities and heavy machinery, making stacking impossible. This result in a maximum utilization of 60%. For this investigation, an average sized vessel of 1026 m² was used as the standard. Overall, this results in a total capacity of 615 m². The M3 deck carries several large containers of around 1000 m³. However, because the shipment usually contains various different cargoes, which natures are not considered in the calculations of this project, using this total, is not a realistic portrayal of

its total capacity. For example, if a total of 500 m³ of fuel and 500 m³ of drilling fluids were to be transferred, it would seem that the capacity of one tank would be enough to carry this, while, in reality, these two cannot be combined, and therefore two tanks would be needed. For this reason, it was decided to use a total capacity of 1000 m³ on the M3 deck.

The supply vessels used by Equinor to supply their oil installations can further be categorized as fleet and charter vessels. Fleet vessels includes both dedicated vessels and preplanned route vessels. The dedicated vessels are dedicated to the installations with the highest demand, and usually visit fewer installations than the preplanned route vessels. The preplanned route vessels, as the name implies, have fixed routes and fixed departure times. Charter vessels, also referred to as rented vessels, are vessels rented from the spot market. The intention is to avoid using these vessels, since this implies additional high costs.

Today, the preplanned route vessels for Equinor with departure from Dusavik, are named Normand Sun and Normand Sygna. These have regular departure on Mondays, Wednesdays and Fridays with a fixed route which return after 72 hours. This is a static approach with six standard routes per week. The dedicated vessels are currently often used for Johan Sverdrup and Deepsea Atlantic. The vessels have an approximate consumption of 10 000 L diesel per day at their standard speed of 10 knots. An increase to 12 knots per hour will double fuel consumption, causing more emissions and higher costs. Therefore, this same speed has been used in the team's calculations.

4.2 Drilling

In step with the development of technology, the petroleum industry has also significantly developed in relation to the extraction of oil. Today, there are 86 fixed installations on the Norwegian continental shelf (Norsk Oljemuseum, n.d.). One often distinguishes between a production- and drilling installation.

The production installation, of which Sleipner is an example, has equipment that makes the installation capable of operating, and maintaining wells (SNL, 2020). A drilling installation on the other hand, like Rowan Stavanger, is an installation which has facilities to drill wells such that this oil and gas may be extracted. Because not all installations are drilling installations, there is a variation in their corresponding demands based on their activities.

Drilling usually begins with a large drill bit of about 80 cm in diameter. As the well gets deeper, and more narrow, different drill bits are used. At the beginning, the drilling occurs at a high rate with penetration rates averaging 10-15 meters per hour (Gundersen & Lundberg, 2021). With increasing depth, drilling speeds decrease, but again increase as one enters deeper reservoirs. This is due to higher pore pressure (l.c.).

With the increase in speed, the reason for an increase in drill pipe demand (in m²) is twofold. Firstly, a higher speed implies a quicker increase in depth, meaning that more drill pipes are needed. Then, as the depth increases, the width of the drill pipes needed also increases. Thus, the pipes occupy more space on the supply vessel. Table 2 shows a simple overview of the different dimensions of drill pipes and the area one pipe occupies on the vessel. Due to the difference in required dimensions and depth from project to project, the demand development will also differ.

Table 2 Different m² for Various Dimensions of Drill Pipes

Differences in Drilling pipes	
Dimension	m ² per Pipe
26"	9
14"	5
10 3/4"	4
7 5/8"	3
5 1/2"	2
4 1/2"	1

Other than the common vertically downwards drilling practice, there is also a drilling technique called side-tracking. Using this technique, holes are drilled in an existing well which have already been drilled, thereby reusing the existing well slots. If this well is filled with e.g., water, it must be plugged, as it no longer contains any oil to collect. The side-tracking will thus be performed from a point above this plug. An example of this is shown in Figure 8. Sidetracking is performed on certain installations which are investigated in this project, and since the sidetrack drilling-progress is different from the usual drilling, the development of demand will also be different. This is because these measurements are included in the data collection used for calculations. Thus, because the average activity level includes these, it also affects the average speed and supply demand, because the rock formation is not the same horizontally as it is vertically. One of the installations which carries out sidetracking today is Grane.

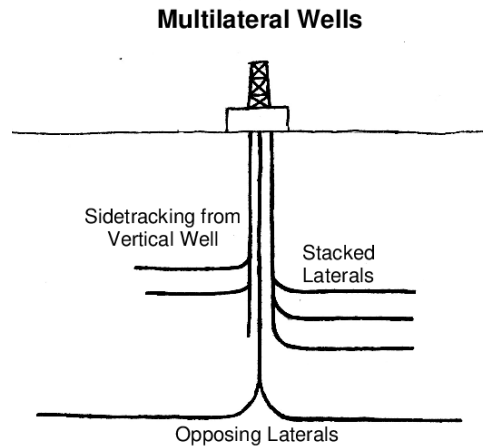


Figure 8 *Illustration of Sidetracking From an Installation*

(Molvar, 2003)

Because the drilling speed may depend on the bedrock where the drilling takes place, demand will also be influenced by the location of the drilling installation. As mobile drilling installations may be moved from one oil field to another without being permanently fixed to the seabed, this is an important distinction to make. Deepsea Atlantic for instance, is a mobile drilling installation which has recently been moved from the Sleipner field and is currently located on the oil field Johan Sverdrup. Depending on the demand, the number of supply vessels will differ. In this project, a standard supply for each installation has been determined, and used as a foundation for the minimum supply demand, where activities will add additional supply requirements to that particular installation. For further use of the model, the average supply of active drilling installations can be used as a reference for new drilling installations arriving at the same location.

5. Spreadsheet Modelling

The spreadsheet model is constructed for the purpose of determining how drilling activities can influence the supply through the change in number of vessels, and choice of supply routes, when the goal is to minimize the cost, and hence the distance. Furthermore, this chapter will address the development of this spreadsheet model in addition to explaining the collecting and preparation of the data used in the model.

5.1 Preparation of the Model-Inputs

In the process of developing a model, as mentioned in Subsection 2.3.1, data collection is a crucial step. For the model to give realistic solutions, accurate input, and reality reflection, is especially important. Therefore, accurate and precise data collection has been a significant part of the modelling process, to secure realism. Because the supply-need-related data is historical, an approach to calculate the future supply-needs was developed in order to create a model that is developed with regard to the future. Furthermore, three spreadsheets constituting historical data associated with general- and activity supply, and generic formulas, were made and assembled to build the spreadsheet model. An overview and brief description of these spreadsheets are given in Table 3.

Table 3 Spreadsheet Overview; Description of Every Spreadsheet, and Which Appendix number They Are Given

Spreadsheet	Appendix	Description
“General Supply”	A7	Basic data and information about the oil installations and supply vessels, necessary to calculate cargo and general supplies.
“Activity Supply”	A8	Data regarding projects, more specifically activities happening on several oil installations.
“Generic Project Demand”	A9	Graphic figures and generic formulas for supply-needs within the active oilfields.

5.1.1 General Supply

Throughout the previous project (Gustavsen, Martinius & Mastad, 2021), all supply within the timeframe of August 2 - October 31, 2022, collected for use in the modelling, was considered to be general supply. The general supply can be described as a fixed demand of equipment, provisions, etc. On further inspection at the start of this project, it was determined that this was not the case, and that some of the supply was in fact supply needed for temporary activities due to drilling projects. Therefore, the data collected from the previous project could not be useful without removing the activity-related supply from the total supply. This was executed by registering the activity supply in that same period of time, and subtracting it from the total supply, see Appendix A7. By doing this, the remaining supply for each installation became the grounds for estimating their actual general supply.

This process for estimating general supply was not problem-free. There were incidents where the general supply for a week gave negative values, which could indicate several different errors. Since negative values would cause unrealistic numbers, and present falsely low average values, it was determined to treat these values as zero. This was done because a larger average value is preferable to smaller values, as this provides an increase in flexibility rather than impossible expectations.

5.1.2 Activity Supply

To collect information about the volume of supply, which is to be shipped to each installation, different projects needed to be examined. Each project has various activities which are performed. The data collected from each activity is usually available in very detailed formats and specifies every object which is to be transported. It is therefore necessary to differentiate between the M2- and M3 deck on board of the vessel what is brought in containers or in fluid. Because WELS is not consistently accurate with its measurements this must be analyzed. For instance, all drilling pipes are inaccurately quantified, therefore, all drill pipes found in the list of equipment for each activity must be counted. This must then be inserted into the Excel sheet provided by Equinor, based on the size of each of these pipes, in order to accurately depict the space these would occupy on board. By considering all items for each activity and noting down the number and unit of measurement of each activity, for each project on all drilling installations, an average can be calculated to highlight the differences between drilling projects on each oil field. Below shown in Figure 9 is a mind map depicting the level of detail of the

data gathered for each project. The grey arrow illustrates the level of detail of the data collection done in this project, from the microdata retrieved from WELS, to where it was incorporated into the model.

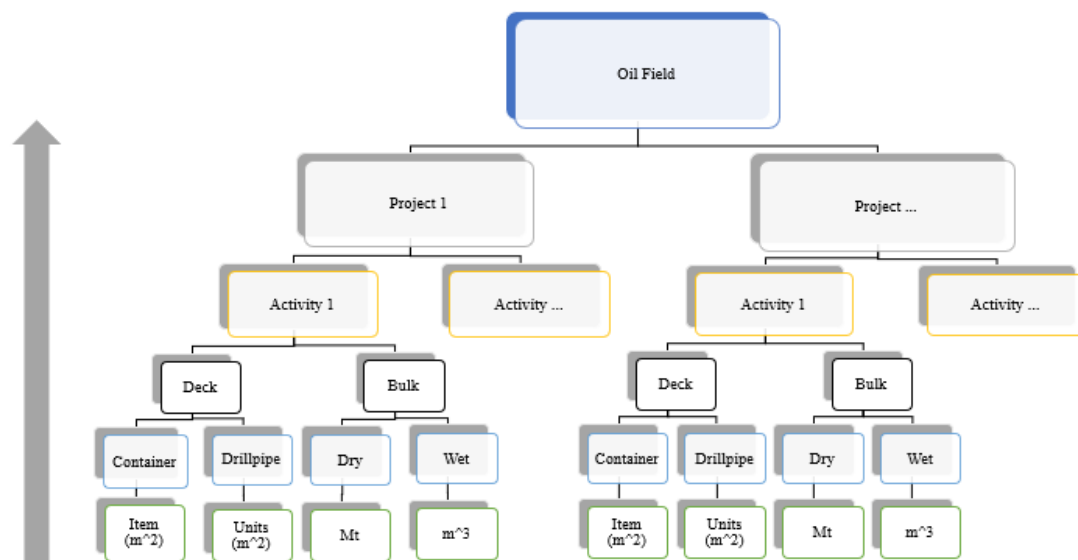


Figure 9 Mind Map of Data Collected from WELS, Pertaining to an Oil Field. The Grey Arrow Illustrates the Way From the Micro Data to the Overview of the Projects

Further, to be able to estimate future weekly project supply-need, this same information was collected from previous projects. Due to the variation in when the supply was shipped to the installation for every activity, it was decided to use a chronological approach since the activities are also performed chronologically. Therefore, the total supply-need for every activity was equally divided over the total time of the activity. Additionally, in this scenario, the supply is delivered to the installation in the same week as the project is set to begin. It is possible to modify this, such that they are instead delivered the week prior, or subsequent to each activity start.

5.1.3 Generic Project Demand

In order to determine weekly demand for projects on both the M2- and M3-deck when project lengths, and maximum supply-needs change, the project team have applied generic formulas. These have been designed by studying the supply pattern for several weeks, with different projects. Where the weekly demand $D(t)$ consists of the variables M (maximum demand), L (project's length in weeks) and t (week into the project). By designing graphical visualizations of the supply over time, as in the example shown in Figure 10, it was possible to discover

typical supply patterns. Furthermore, these patterns were studied, and designed to create generic formulas.

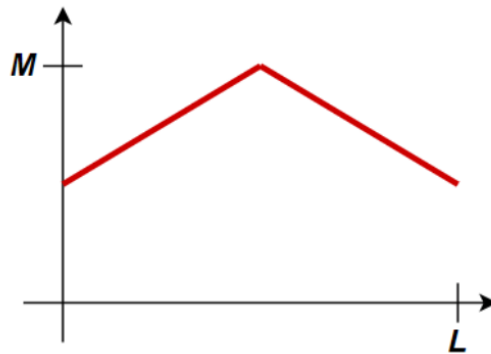


Figure 10 The Pattern of M2-demand to the Oil Installation Grane

In Figure 10, it can be seen that the demand of the first week starts at around 50% of the maximum demand. Then, the demand gradually increases to reach its peak in the middle of the project, before declining at the same rate until returning to the same 50% demand at the end of the project. Based on this, it was possible to formulate the generic formula, Formula 1. This formula presents the M2 supply development for the projects on the Grane installation. Both visualizations and generic formulas are presented in Appendix A9, where a composite visualization of both M2 and M3 supply-needs for each installation have also been presented.

$$D(t) \begin{cases} M \frac{1}{2} + \left(\frac{M - \frac{1}{2}M}{\frac{1}{2}L} \right) (t - 1), & \text{if } t \leq \frac{1}{2}L \\ M \frac{1}{2} - \left(\frac{M - \frac{1}{2}M}{\frac{1}{2}L} \right) \left(t - \frac{1}{2}L \right), & \text{if } t > \frac{1}{2}L \end{cases}$$

Formula 1 - Generic Formula for Projects on Grane Representing the Development of Demand Throughout the Projects (M2-demand)

During the research of these projects, the project team originally planned to analyze several projects on each installation. However, upon inspection, these projects were profoundly similar, thus, they were combined into one supply pattern, instead of looking at each project separately. Further the pattern of both M2 and M3 weekly demand was combined, resulting in collective graphs for each installation. This enabled a generalization based on installation

demand development, as shown in Figure 11-14. For instance, Figure 11 shows the supply demand development of a typical project at the Johan Sverdrup installation. This demand slowly rises in the beginning, peaks in the middle, and falls towards the end, a typical “Normal distribution”, therefore also the name.

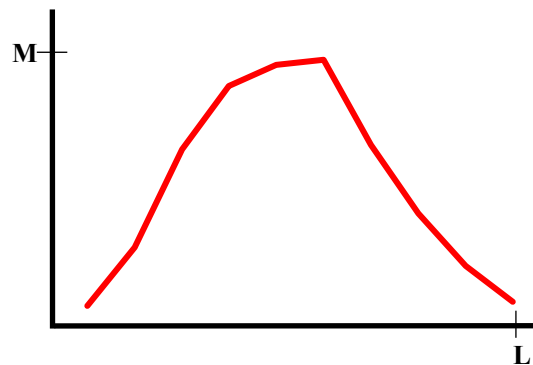


Figure 11 Collective Graph for Johan Sverdrup (Both M2- and M3-demand) Called “Normal distribution”

Sleipner’s development, as pictured in Figure 12, has a completely different development, than that of Johan Sverdrup. Its demand gradually increases, and has a late peak, which does not differ particularly much from the earlier demand in the project, hence the name “Active, late peak”. Both fields have each had several projects with the same development and classification.

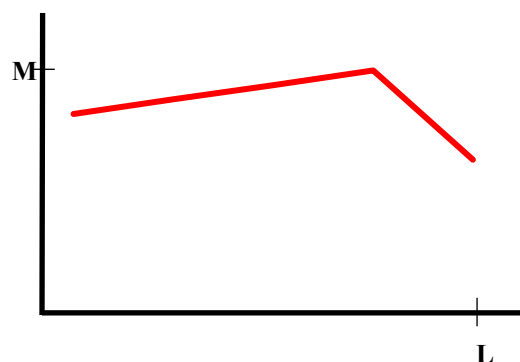


Figure 12 Collective Graph for Sleipner (Both M2- and M3-demand) Called “Active, late peak”

Figures 13 and 14 illustrate the supply demand development of the two remaining drilling installations. Gudrun has been classified as a “Two-Step” development, and Grane as “Pyramid”. Because the data for projects on these fields was very limited, each of the classifications is decided only based on one project and cannot be verified as an accurate representation of the actual demand.

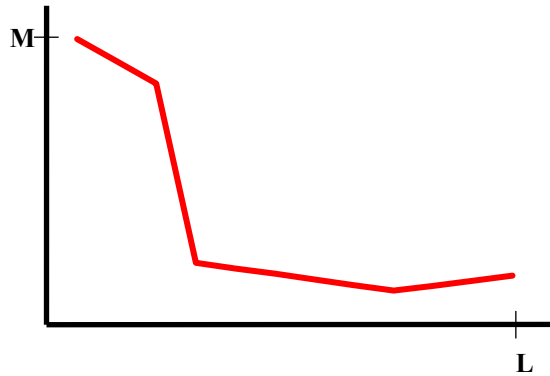


Figure 13 Collective Graph for Gudrun (Both M2- and M3-demand) Called “Two-Step”

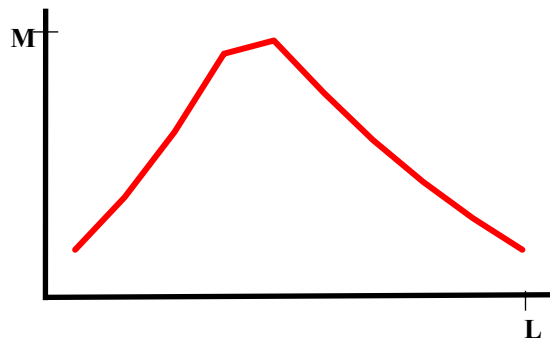


Figure 14 Collective Graph for Grane (Both M2- and M3-demand) Called “Pyramid”

5.1.4 Future Progression Plan

In order to create robust routes based on future projects, a future plan was created, appertaining to upcoming projects. To simplify, an imaginary prototype for a future progression plan pictured in Figure 15 was created in reference to the prototypes elaborated in 5.2.1 and 5.2.2.

Node	Weeks															Inputs					Outputs			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	M (M2)	M(M3)	L	Start week	End week	t	M2 D(t)	M3 D(t)	Lifts
1																0	0	0	0	0	0	0	0	0
2																400	300	10	3	12	5	333	240	56
3																500	600	15	1	15	7	125	600	21
4																700	350	8	7	14	1	350	175	58
5																0	0	0	0	0	0	0	0	0

Week 7

Figure 15 Future Progression Plan for the Prototype, Estimating the Demand for the Plotted Week

The model allows for its user to plot in the week number (of the year), which gives a dark green column that indicates which week of the project t this concurs with and provides a complete overview of all projects. For instance, the displayed week in Figure 15, is week 7, which gives

the outputs presented on the right-hand side. Variables used in the model are abbreviated as follows:

M = Maximum demand

L = Length of project

t = Project week number

D(t) = Weekly demand

To demonstrate, node two (installation 2) for example has an ongoing ten-week project, which is currently in its fifth week. The outputs also produce weekly demands for both M2 and M3 for each installation, through the use of the generic formulas explained in Subsection 5.1.3.

The future progression plan used for the final model, in contrast to the prototypes, consists of upcoming projects Equinor has planned in the future, see Appendix A11. These plans have been obtained through Equinor. Data regarding current and future projects on a variety of installations was provided by the project's contact persons at Equinor. This overview included projects happening on the installation Johan Sverdrup DP, Grane, Deepsea Atlantic and Rowan Stavanger. Projects are sometimes temporarily stopped, before restarting at a later point, thus, the actual future progression plan consists of multiple projects which are separate throughout the plan. An example of this are the sidetracks, previously described in Section 4.2. These are also split up in the plan, to portray a realistic project length. Since Equinor's plans span over two different calendar years, it was necessary to include an extra input cell to specify which year the week is in.

As described in Subsection 5.1.3 the projects on the same oil fields are relatively similar, thus, based on the planned activities, the plans can be used to predict the time and supply demand associated with the projects. By combining the simultaneously ongoing projects at each field and adding it to the general supply required to each installation, a total demand can be determined. Although this approach will be considerably more dynamic than in the previous project, it will not be completely dynamic in the sense that the routes are updated for every change made in the network demand. Instead, route selection will stem from different anticipated scenarios, the timeframe of each activity and their topology. It will, however, contrary to a fully dynamic routing, be necessary to manually determine when these different scenarios come into play, for instance by use of a threshold quantity value, or activity phase

planning. The future plan created may be used as a resource to determine how many vessels, or alternatively, which routes are best suitable for transport. Using the Solver, the potentially most efficient routes will be decided for Equinor's future projects based on the predicted scenarios.

5.1.5 Route Generation

To maintain a dynamic process, and create routes which are adaptable to varying situations, the routes were created in a different manner than last year's assignment. Instead of creating different routes by considering if they could be a possibility only based on predetermined rules, the technique to find these new routes was done with the opposite approach. This time, the process was started with all route possibilities, and then eliminated in intervals based on rules, such that the best routes remained (Appendix A5 and A2). The approach was constructed and executed by this thesis' supervisor Andreas B. Ormevik and allows for quick regeneration of routes with changing variables, making it a much more dynamic and adaptable approach. It also gives the possibility to quickly see which routes are very robust and continue to be chosen with shifting variables, and how fragile the proposed routes are. An important element of the route generation is the fact that general supply is included in the calculations of the route. Because of this, the general supply does not affect the model, but only restricts remaining slack time, and the number of nodes can be chosen on each route. Solutions of this model will therefore only be influenced by the extra demand.

Firstly, to present the extent to which the route generation has to be limited, the calculation below, Formula 2, was made to show the number of routes which are possible to generate, N , where n represents the number of installations. All possible number of visits to each installation, in this case 1-13 is represented by k . This produces a total amount of 16 926 797 485, almost 17 billion different combinations within 13 installations. This means that all route options cannot simply be tested, and an elimination process must be performed.

$$N = \sum_{k=1}^n \frac{n!}{(n-k)!}$$

Formula 2 – The Formula for the Number of Possible Routes

The process of route limitation executed in the programming platform MATLAB by Andreas B. Ormevik is described below. The first step of elimination is done through a set of rules which must be upheld. The rules which were used in this case, that resulted in a total of 162 routes, are listed below:

- A maximum of five installations may be visited on one route.
- All routes must depart from the depot at 16:00. This is when the employees at the depot are finished for the day, and everything should be loaded on the vessel.
- All vessels sail at 10 knots. This is a standard speed at which the vessels are supposed to sail, and thus cannot be changed.
- 10 containers can be lifted per hour at each installation.
- 80 m³ bulk can be unloaded per hour.
- Our calculations of an average sized container from the previous project of 6 m² is used for calculations.
- A maximum deck capacity of 600 m² is used. The reason for this is explained in Subsection 4.1.1.
- As explained in Subsection 4.1.1 a total capacity of 1000 m³ was used for the M3 deck.
- The maximum permissible slack of deck- and bulk- loads is respectively 60% and 75% of effective maximum capacity. This means that the utilization must be above 40% (deck) and 25% (bulk) of maximum capacity. Considering this, the routes have quite specific and constant capacity rates.
- Each supply vessel may only visit three zones per route.
- Each route must arrive, load and unload, within the installations opening hours. In addition, it is possible to arrive at the installation up to 4 hours before installation opening, which causes some idle time. Any extra expenses caused by this have not been considered in this project.
- Each route has a maximum duration of 72 hours.
- To maintain flexibility and adjustability, for example in cases of bad weather, each route must have at least 3,5 hours slack.
- If multiple routes are generated, which visit the exact same installations, only the shortest one of these is retained, and the rest are deleted.

Table 4 Route Generation – Original Route Pool

Installation	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of visits	162	31	70	15	16	18	69	49	88	40	44	10	87	35
%-share	100	19	43	9	10	11	43	30	54	25	27	6	54	22

The original route pool above in Table 4 displays the original number of visits to each installation. To further limit the number of routes, a heuristic approach in the following four steps, was chosen to select an appropriate number of routes:

1. Find the installation with the fewest number of visits and select all routes which visit this installation.
2. Update the table by removing the selected routes from the original route pool.
3. Repeat steps 1 and 2 until the desired number of routes are selected. Installations which have been previously chosen as the least frequently visited installations, may not be chosen again in the next iterations.
4. When a given number of routes are generated, it should be confirmed that all requirements for the selected routes are met. In this case, the project team is restricted by the number of variables and constraints the Solver extension of Excel can handle. Consequently, the model was restricted to 74 routes. In addition, a requirement of at least 5 route options to each installation was decided upon.

If the requirements are not met, steps 1 and 2 should be repeated, but the sampled route pool should be used to check the frequency of visits to each installation. This ensures that the remaining installations are visited as much as possible on the new routes generated.

The iterations performed throughout this process can be found in Appendix A2. After all iterations, the table below, Table 5, illustrates the number of visits to each installation with the use of the final decided upon routes. These routes are then checked against the requirements set for step 4. Relevant data and details for these routes are then printed, which will serve as input to the path-flow model.

Table 5 Route Generation - Final Route Pool

Installation	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of visits	74	31	26	15	16	18	34	25	39	8	17	10	45	11
%-share	100	42	35	20	22	24	46	34	53	11	23	14	61	15

5.2 Development of the Path-Flow Model

As explained in Subsection 2.3.2 a Path-Flow model is an optimization model that can be described as a network, usually a transportation-network. The decision variables within the Path-Flow model present the flow, which in this case is the decision of which route is selected and how many times they are being used. According to the definition, a “Flow” value of 0 means that the route is not chosen as part of the solution, 1 means that it is used once, etc. For the purpose of simplifying the explanation of the Path-Flow model, and testing different approaches, prototypes were developed. Prototypes are usually the first drafts of final products, which are used to test and demonstrate the product itself (Hofstad, 2019). These prototypes have been a significant element in the later explained analysis, and troubleshooting. Furthermore, two prototypes were developed before the final model. Since they are both based on the same inputs, including the same decision variables, constraints, and objective cell, their differences will be explained in the following section.

5.2.1 Initial Design of the Model

In the initial phase, and throughout the Prototype 1 (Appendix A10), in conformity with the intentions of this project, the goal function was to minimize the total distance in order to reduce emission. The objective cell could therefore be formulated as the product of the “Flow” and distance. The “Flow” in this case, represents the number of times each route is selected, as mentioned in Section 5.2 above. Furthermore, the inputs are the foundation for the constraints, where the inputs for the prototypes were based on the inputs used for the final model, only modified to fit the prototype size, and are listed below:

- The minimum number of visits in one week required at every installation
- Remaining capacity of every route
- Available time (slack time) of every route
- Route distance

- Route duration
- Additional supply linked to ongoing projects

The different elements, inputs, decision variables and the objective cell in the actual prototype, pictured in Figure 16 below, are represented in different colors, to keep a structured overview throughout the layout of the models.

Route number	Flow	Distance
1	1	200
2	1	245
3	0	250
4	0	230
5	0	180
6	0	195
7	0	300
8	1	195

Total Distance	640
----------------	-----

Decision Variables
Inputs
Objective Cells
Route numbers

Figure 16 Different Elements of the Prototype; Variables, Inputs, Objective Cell and Route Numbers Divided in Different Colors for Better Overview

Although the constraints are connected to the inputs, they are not represented in this same blue color. This is because the inputs are not directly used as constraints as they often are in other models. Instead, the product of these inputs and the flow is often used as constraints for the model. An example of this is the slack time, which is the allowed delay time for each installation on the route, without any consequences. For instance, if the route is delayed five hours, but one installation had a maximum slack time of four hours, the delay will mean that the installation closes before all supply is unloaded. Therefore, a delay to either installations, or the base itself larger than the tolerable slack is not permitted. Both remaining slack time and remaining capacity, after the extra demand, is calculated by subtracting the total change in time and capacity from the available slack on every node and route. To ensure accuracy, simplifications of calculations were avoided in the development of prototype 1.

In prototype 1, the slack time at every node must be ≥ 0 , as shown in Appendix A10. In the same manner, the remaining capacity constraints on every route must be ≥ 0 . Due to the maximum number of constraints which can be handled by Solver, these had to be collected into a smaller number of constraints. An example of this is shown below in Figure 17, which shows the change in slack time of route 1 of the prototype. To minimize the number of constraints,

the “CountIf” function was used to summarize the number of nodes (installations) with a positive “remaining time” value, in cell S6. To ensure that the solution is valid, all routes must have a positive slack time, therefore, this number must be equal to the number of nodes on the route, cell U6.

	M	N	O	P	Q	R	S	T	U	
2	Route number	Sequence								
3	1	3	5	1						
4	Time Slack	10	5	5						
5	Change in Time	-0.69	-0.69	-0.69						
6	Remaining Time	9.31	4.31	4.31			3	>=	3	
7		>=	>=	>=						
8	Constraint	0	0	0						

Figure 17 An Example of the Slack Time Constraint of a Route in Prototype 1

To calculate the available slack time and remaining capacity, the future progress plan, is used (see Figure 15 in Subsection 5.1.4). This plan is the basis for deciding the expected extra demand to each installation and provides a more dynamic approach of the model. In absence of ongoing projects, the only constraint that affects the model is the number of required visitations at every installation. However, in cases where there are ongoing projects, more constraints are required to ensure that the capacity and time constraints are not exceeded. This is because all generated routes have already taken the general supply into account. Therefore, both slack time and available capacity on each of these routes are constraints for all extra supply emanating from activities on the four active drilling installations. The first prototype assumes an equally distributed extra supply on every visit to each installation. For instance, if Johan Sverdrup DP has a weekly extra demand of 500 m², and requires five visits, each visit would contribute 100 m². This increases predictability for all active drilling installations, but also rules out routes with lesser available capacity.

After evolving Prototype 1, to a full-scale model “Path-Flow Model 1, found in Appendix A10, the simplifications made through the use of “CountIf”, “Hlookup” and “If”-sentences, made the model “non-smooth”, making the use of Solver more problematic. Due to this, the only solving method capable of solving the problem was Evolutionary. However, even with the use of the Evolutionary method, see Subsection 2.3.3, Solver could not find a feasible solution. Therefore, a troubleshooting of the model was initiated, explained in more detail in Appendix A1. This led to the conclusion that there was a need of further simplifications, to avoid complex functions in Excel, and a different approach to the development of the model.

5.2.2 Final Design of the Model

Through the troubleshooting completed on “Path-Flow Model 1” (Appendix A1), it was concluded that commands which make the model “non-smooth” are the main reason for the problems Solver faces, causing its slow computation, and unrealistic answers. Therefore, it was determined that even though the Evolutionary method could work, it would be best to make the model smooth, so that the GRG non-linear method could be applied instead. This necessitated changing the modelling approach, especially considering the constraints regarding remaining slack time and capacity.

To do so, the extra supply demand and slack time of every route was equally distributed to all active installations. This means that the demand of all drilling installations had to conform to the available area designated on the route, instead of the opposite solution, which was used in prototype 1, where the supply demand of all drilling installations was equally distributed on all routes which visited those installations. For instance, if a route, for example route 2, which visits Johan Sverdrup DP and Deepsea Atlantic, has a remaining capacity of 319 m² this capacity will be divided in two, so that each of these drilling installations have a reserved capacity of half of the remaining available area on deck (159,5 m²). If either one of those installations have a weekly demand higher than this reserved area, only the reserved amount for that installation will be accepted on the vessel, even though they collectively do not exceed the total capacity slack if the other installations do not meet their full share. Thus, the route may still be chosen, as long as the weekly demand is fulfilled with the total of all routes, contrary to the first model, where demand per visit could restrict the possibility of the use of the route, if the average demand per visit was exceeded. Therefore, the second prototype has a more conservative approach, which increases the flexibility and resilience of the chosen routes. Since demand is varying, this approach has a higher possibility of still being able to deliver all supply, if the actual demand was higher than predicted.

In order to restrict the number of constraints without the use of “non-smoothing” commands, the smallest slack time value of the route is chosen as its constraint, such that the remaining slack time at every node is \geq “Smallest Slack Time”, as shown in Appendix A10. Thus, only one, constraint was needed per route. Examination of the slack times also revealed that the smallest slack times often occurred as one of the last nodes of every route. Consequently, if

delays occur, for instance due to bad weather, the chance of further delays along the route is considerable. This collective delay increases with the duration of the route. Thus, having the smallest slack time at the end of the route prevents a higher collective delay than its smallest slack time, and sets a restriction for the entire route because it limits the slack allowed on all earlier nodes. This creates a more conservative approach, because the total slack time cannot be higher than the smallest slack time, whereas if this slack time was already reached early on the route, more delays could occur. Figures 18 and 19 are used to further illustrate and explain this concept. As shown in Figure 18 the smallest slack time is late on the route, meaning that those nodes before it, cannot have a larger accumulated time slack than, in this instance 4 hours. Because they altogether exceed this limit, this route cannot be chosen, thus all routes which are chosen must have a very small, aggregated time delay. On the other hand, in Figure 19, the same smallest slack of 4 hours is on the first installation, this route is therefore approved, although the total aggregated time delay becomes 12,5, which could affect the following route.

Sequence					
Route	13	11	4	6	7
Time Slack	24	10.5	6	4	24
Time Change	-1	-2	-1	-0.5	0
Aggregated Time	-1	-3	-4	-4.5	-4.5
Remaining Time Slack	23	7.5	2	-0.5	19.5

Figure 18 Example of the Smallest Slack Time Late on a Route

Sequence					
Route	6	11	4	7	13
Time Slack	4	10.5	6	24	24
Time Change	-0.5	-2	-3	-2	-5
Aggregated Time	-0.5	-2.5	-5.5	-7.5	-12.5
Remaining Time Slack	3.5	8	0.5	16.5	11.5

Figure 19 Example of the Smallest Slack Time Early on a Route

During the development and testing of the model, it was observed that the vessel requirement varied substantially depending on the week and selected routes, indicating that the fleet size should vary from week to week. Intermittently renting additional vessels to meet those requirements would be both expensive and demanding. Therefore, a type of “penalization” was implemented. By including costs associated with the use of additional vessels, such as charter and fuel costs, it was possible to force Solver to select more realistic routes based on how many routes are in the permanent fleet.

Costs	
Charter costs	20000 USD/day
FuelCosts	34 USD/nm
Tot charter costs	120000 USD/week
Tot. Fuel costs	115662 USD/week
Total Costs	235662 USD/week
Total Distance	3402

Hours	
Vessels in fleet	3
Hous in week	168
ChartHours	144
FleetHours	624
	<=
Available Hours	648

Charter Vessel Days	3
----------------------------	----------

Figure 20 Overview of the Use of Vessels and Hours, Along With the Costs and Distance Outputs, as Shown in the Final Model

For Solver to treat these costs as a restriction, it was necessary to cumulate the costs into the original goal function, the gray cell in Figure 20. The fuel costs force Solver to minimize the distance with a specific number of vessels. Additionally, the charter costs restrict Solver from choosing an excessive number of routes because of the extra costs associated with charter vessels, needed to sail all routes. This was made possible by implementing an extra decision variable, where Solver chose the number of days (24 hours) where charter vessels are necessary.

The prices used as inputs to this model are not real-time prices for charter vessels or fuel, but merely estimations to better understand the impact on the Solver’s route preferences. The circumstance of the actual cost is not of interest in this situation. Naturally, to ensure a realistic representation, the chosen cost inputs are based on an historical data, provided to us by our supervisor, as shown in Figure 20 under “Costs”.

The changes made to prototype 1 as explained above, created prototype 2, see Appendix A10. Figure 21 below gives a full overview and illustrates how the different elements are combined to create the operative model. The “non-smooth” commands are removed to allow the GRG Nonlinear method to be used by the Solver add-in. By using this method, a local minimum is found, and although this may not always give the most optimal solution, it also means that it will require less time to find a reasonably good solution. A full-scale model was therefore further made based on prototype 2, which became the final model for this project, see Appendix A11.

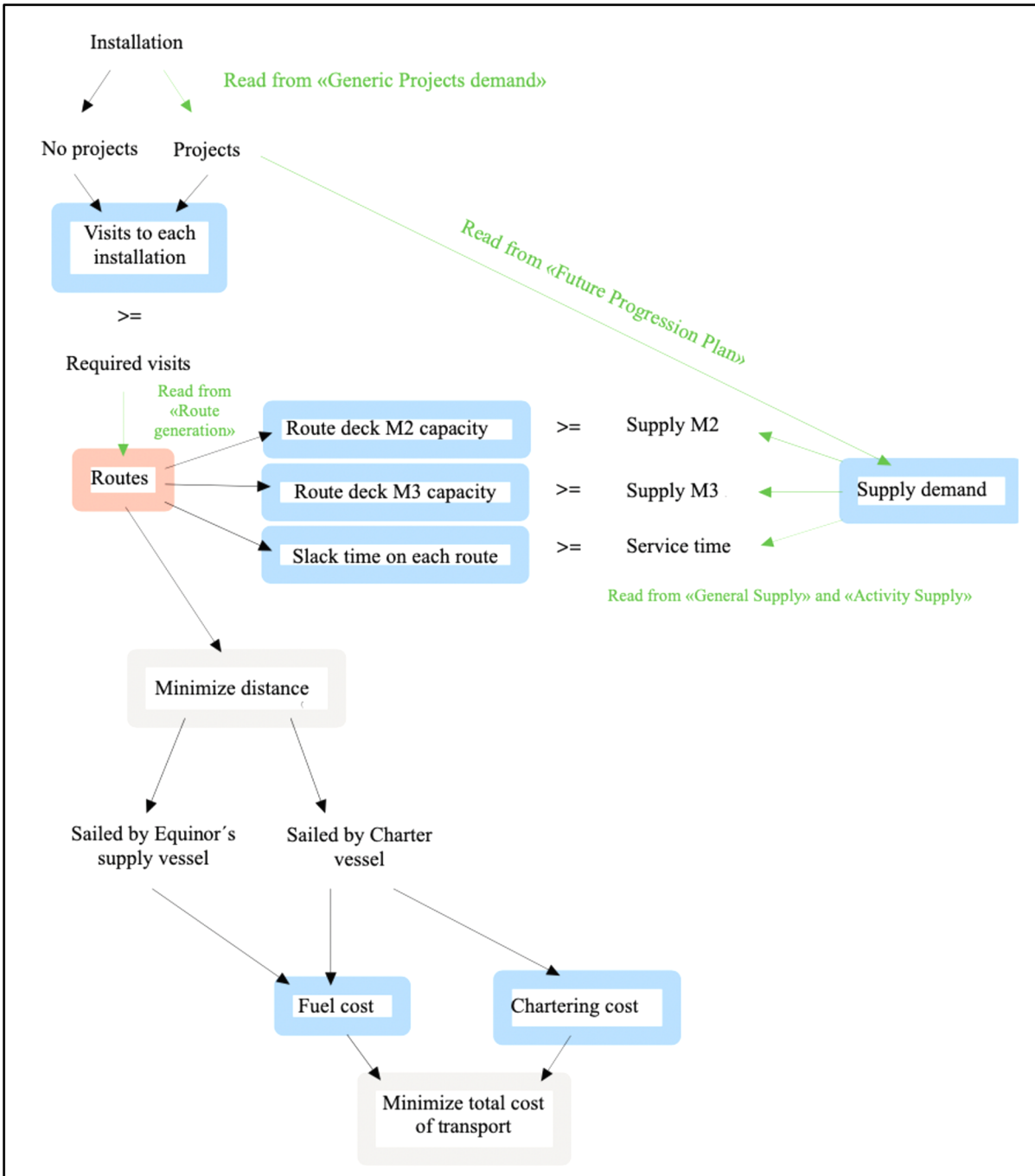


Figure 21 An Overview of How All the Elements in the Model Are Interconnected and Affect Each Other

5.2.3 Assumption Summary

To develop the final model (see Appendix A11), it was necessary to make more assumptions than for the original, more ideal idea for the model (prototype 1), so that the model would be smooth enough for Solver to handle. An overview of all assumptions made for the final model is listed below:

- The capacity of a vessel is based on the assumption that every vessel is the same size and therefore have the same beginning capacity.
- The required visits to each installation are the same as the average visits calculated for the period of August 2 – October 31, 2020.
- The time taken to complete one lift is equal for all installations.
- All vessels must have returned to the depot by 8 a.m. if departing by 4 p.m. the same day.
- All vessels move at 10 knots/hour.
- The generic formulas are created based on the projects weekly supply. This is calculated on the basis that activity supply is equally distributed over the length of the activities in the project.
- The available capacity on every route is equally divided on the number of active installations on it. Since the capacity differs from route to route, the supply arrives to the installations in unequal deliveries.
- The service time of the M2 deck always is longer than that of the M3 deck. Therefore, “change in time” in the model is calculated based on the extra supply of M2.
- The node with the least slack time is always late on, or at the end of the route
- fuel and charter prices are constant. This makes it easier to compare the differences in costs from week to week.

5.2.4 Solver Setting Analysis

Although the theory behind the models is the same, the conversion from Prototype 2 to the final Path-Flow Model caused a substantial prolonging of its solution time. Therefore, an investigation on how to reduce this time by changing the Solver settings and initial conditions was initiated. An understanding of which combinations simplified the problem enough to reduce the solution time, became crucial to making a well-functioning model. This led to the Solver setting search, which is described in detail in Appendix A1. The results from this search were the following:

- Forward Derivatives were chosen instead of Central, because although Central finds more accurate derivatives, it takes longer to calculate than Forward Derivatives since it requires twice as many calculations in each trail solution.

- Considering the results of the solver setting analysis, Appendix A1, where Multistart either gave an incumbent within the time limit or caused an error, it was decided to not use Multistart.
- The analysis showed that an Integer Optimality percentage of 0.1 and 0.001 gave the quickest results. Therefore, because Integer Optimality decides the maximum accepted difference between the objective cells, it was decided to use 0.001 due to the more precise answer.
- The initial flow conditions have an impact on Solver. When all decision variables are set to 0, the model struggles to even start its search for an optimal solution. This is caused by the fact that some constraints give an #DIV/0! error, caused by the division by 0. Therefore, the initial flow conditions can never start with all zero's and are instead set to the no activity solution.

5.2.5 The Use of VBA – Loop

Through the Solver setting search, it was found that utilizing a continuous loop to run the model would be less time consuming and consistent. As mentioned in Section 3.6, VBA was used to run this loop, producing the optimal solutions of all 58 weeks. Even with the use of this loop, finding an optimal solution for a model of this size and complexity was challenging, and therefore time consuming. For this reason, Solver was set to a maximum time limit of 300 seconds (5 minutes), due to the number of weeks. If each week uses 5 minutes ($5 \times 58 = 290$ minutes = 4,8 hours) each run of the loop would have taken 5 hours. Excluding practice runs the model was run a total of seven times. This gives a total run time of 35 hours.

Once the loop is started, it runs through all weeks in one continuous process. If Solver has not yet found the optimal solution by the time the time limit is exceeded, a window with a choice on whether the iteration should continue to run, or if the user wishes to stop and continue to the next iteration appears. If an incumbent solution has been found when the time limit is exceeded, the “Stop” option is chosen, such that Solver no longer searches for solutions on this iteration. If an incumbent solution has not yet been found by this time, “Continue” is chosen. A member of the team then has to pay attention to the solutions Solver attempts, until an incumbent is found. Once Solver has found an incumbent solution, the solver is manually stopped, such that this is chosen as the final solution for that particular week.

6. Analysis of Results

In this chapter, the project team's findings from the analysis will be presented. Following this, a discussion on the results, including their limitations regarding routes, the model itself and final approaches are presented.

6.1 The “Optimal” Solution of the Path-Flow Model

An analysis will be presented in this section that examines results from the Path-Flow model. Because there are so many aspects to discuss regarding this case, the topic of these subsections was selected based on which of these the project team found most important to point out and further discuss.

6.1.1 The Choice of Routes With the Change in Number of Fleet Vessels

Firstly, the model was run through the VBA loop to see the difference with the use of three and four fleet vessels. This resulted in two separate runs lasting around four hours each. The VBA then printed out its “optimal” solution, with the number of charter vessels, total distance and the total costs, together with the flow for each week. This made it possible to compare how the routes change with the number of fleet vessels available, and which routes are preferred. Moreover, it makes it possible to identify which routes are chosen regardless of the number of vessels.

By analyzing the total use of the routes in Appendix A13, it could be determined which routes are chosen more frequently than others. In fact, there is only a slight difference in the total routes chosen between three and four fleet vessels. In total, 23 out of 74 routes were never chosen. Thus, by keeping the model dynamic and giving Solver the option of changing the route choice every week, it would most likely only choose between those 51 common routes throughout the 58 weeks. Unlike Equinor's method, which uses fixed routes, this is an entirely different, dynamic approach.

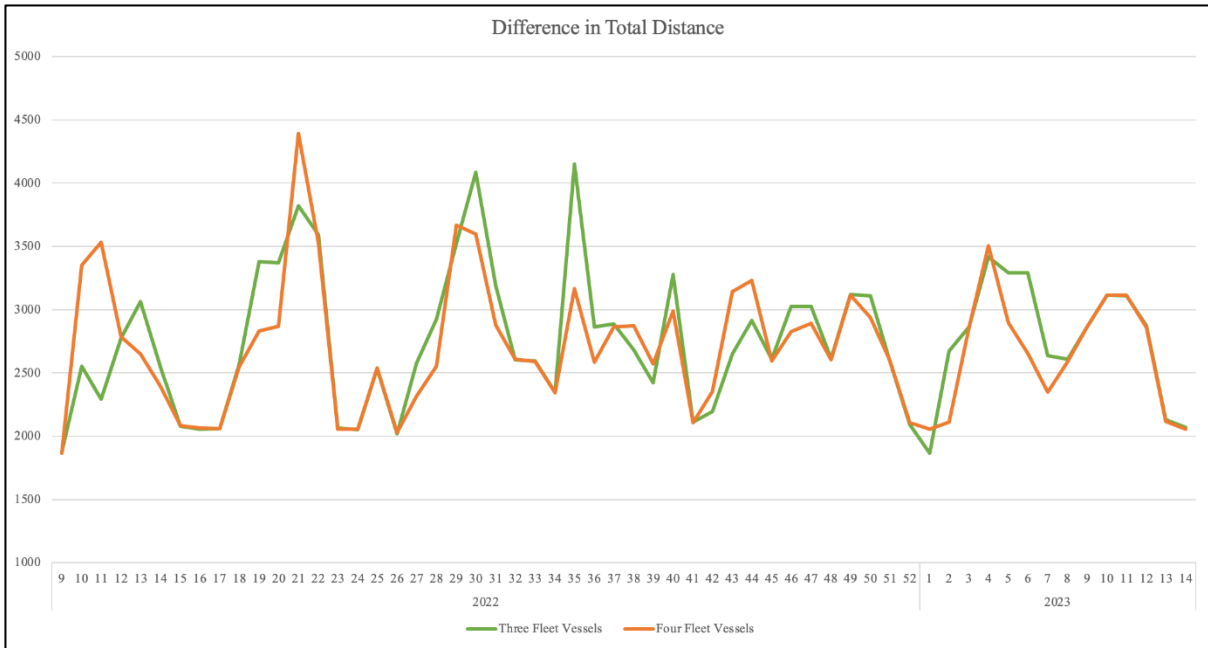


Figure 22 Difference in Total Distance With the Use of Three and Four Fleet Vessels

Figure 22 gives an overview over the weekly distances of all solutions chosen by Solver. Through this model it can be observed that it is quite varying which of the three or four fleet vessel sizes have the longest distance. When taking a closer look at the solutions, it is apparent that many of these solutions can be used for both three and four fleet vessel conditions. Therefore, some of these were to be combined, shown in Figure 23 below. This could be done for two reasons. Since most routes chosen with a three-vessel fleet had fewer than seven charter vessel days, one extra vessel (four-vessel fleet) would be able to cover these hours. The other reason this was possible, was that the solution for the use of four fleet vessels had a duration under the total duration that a three-vessel fleet could cover, since three fleet vessels can cover a total duration of 504 ($24 \cdot 7 \cdot 3$) hours, while four can cover 672 hours per week.

The reason that the same solutions were not chosen in the different runs for the same situation, where the only difference was the fleet size, could be that by reducing the fleet size, 168 hours per extra fleet vessel are lost every week. The only example of this, in this case, is week 47, where the difference is barely visible, shown in Figure 23. There, a better solution is found with the use of four fleet vessels. The cause of this is that when solver runs with four vessels, it can easily make full use of all 672 hours, however, when only three fleet vessels are allowed, those extra hours outside of the 504 available hours must be chartered instead, which comes with extra costs. The cost of achieving what four vessels have achieved is most often not worth the distance reduction. Therefore, Solver chooses other routes to avoid these extra costs.

Further, this may indicate that the total distance increases with a decrease in the number of fleet vessels, as long as the charter cost is a part of the goal function.

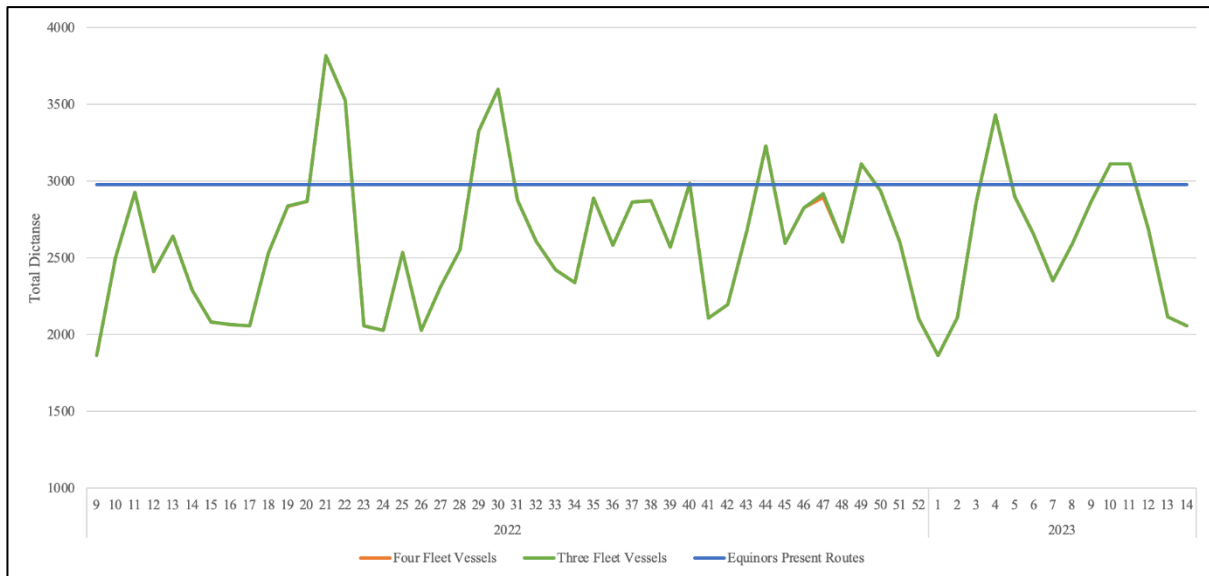


Figure 23 Difference in Total Distance Using Both Three and Four Fleet Vessels and Equinors Present Routes as the “Typical” Week and Reference Point After the Forced Fix of the Solutions

In order to further compare the forced, fixed solutions shown in Figure 23, the route schedule for week 41 (2021) was used as a reference point. This week was categorized as a “typical” week by Equinor and gave a total distance of 2977 nm with the use of five vessels. Because the exact activities on each installation for this period are not known to the team, the accuracy of the comparability cannot be determined. However, from the figure, it can be observed that most weeks, the solutions, with both three and four fleet vessels, have a smaller distance than that of week 41 (2021).

Furthermore, these forced solutions, in Figure 23, should theoretically have been chosen in both runs (with three and four fleet vessels). Because the outcomes differed, and a combination of the best solutions was created, it was necessary to confirm that Solver would actually end up choosing the same solutions with the use of both fleet vessels. To confirm and explain why the same routes were not chosen in the two runs, although one was evidently better than the other, week 30 with three fleet vessels was used to show an example of how Solver works, as shown in figure below.

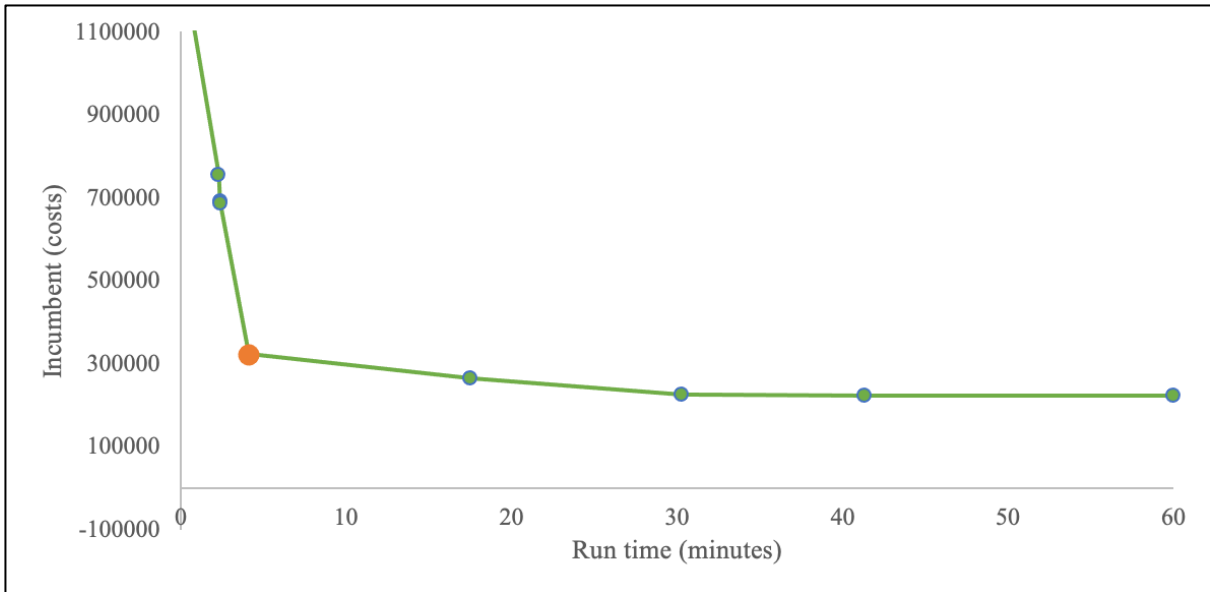


Figure 24 Incumbent Solution Throughout Different Run Time

Through Figure 24, it can be observed that although an incumbent was found before the time limit was exceeded, the solution was worse than that found with four vessels. With the use of the loop, the final solution would be the one found after 5 minutes, which was the point marked in red in this case. It took a total of 41,3 minutes for Solver to find a solution which was only 30 nm longer than the solution found with four fleet vessels. The solution for four fleet vessels was 3559 and the one found for three was 3589, although the cost was 99 639 higher due to the additional charter costs. Though, as the graph shows, the solution has its most drastic change during the first five minutes of the search. Also, during the last 20 minutes, no new solution was found. Although, if Solver was left undisturbed to search for a better solution, it should in theory have been able to get the same, or an even better solution. Thus, although the solution improves with an increase in time allowance, the changes are not so drastic that it has a great effect on the final solution. The inaccuracy caused is due to Solvers limitations and is not caused by the model itself.

6.1.2 The Differences in Costs Due to Changes in Number of Fleet Vessels

In comparison to the sailed distance elaborated in Subsection 6.1.1, the cost diagram has the same approximate pattern because only fuel and charter costs are taken into account. Only certain weeks where charter vessels are used, create a divergence in the graph. Because of this, the main difference in the total costs (fuel and charter) between the different number of fleet vessels, are the chartering cost. The peaks shown in Figure 25 below, provide an indication of

the differences in costs when chartering is needed. In light of these costs, the total- and average costs over the 58-week period are higher with three fleet vessels than with four. Though, the cost of the extra vessel in the four-vessel fleet are disregarded throughout this analysis.

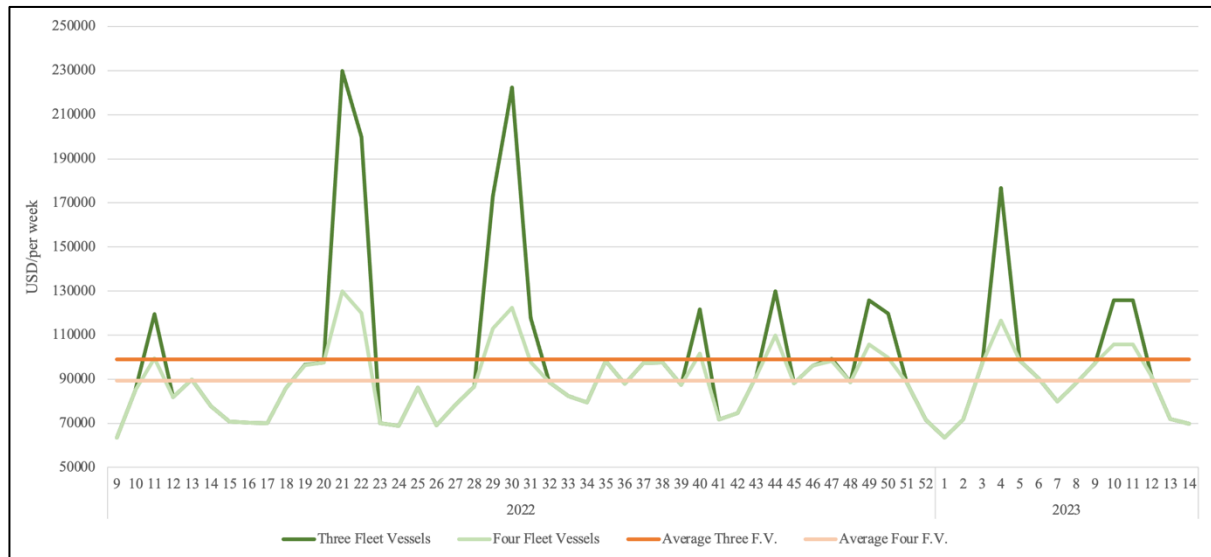


Figure 25 Comparison of Total Costs Using Both Three and Four Fleet Vessels Among With Their Average Costs

The costs in Figure 25 are not correctly represented, because it cannot be guaranteed that the cost of both fuel and chartering are the same as they were at the time that this thesis was written, since they may vary from year to year, or even day to day. The figure only shows where the potential differences in cost would occur. By calculating the costs in real time with the real time prices, it would be up to the decision maker if it is worth leasing a fourth fleet vessel, or if it is cheaper to only use three, and charter the remaining routes not covered by these.

Furthermore, as the use of fleet hours is much higher with a three-vessel fleet size, than with four, spare time is much less. In other words, the opportunity costs of using four fleet vessels would be higher than those of using three, if the vessels could be used for other purposes. In Figure 26 below, the average spare time throughout the 58-week time span for the different fleet sizes is illustrated. Since it is assumed that the fleet vessels are dedicated as supply vessels for Dusavik depot, any extra spare time could be considered lost. Thus, the more fleet-vessels are in use, the more time is lost.

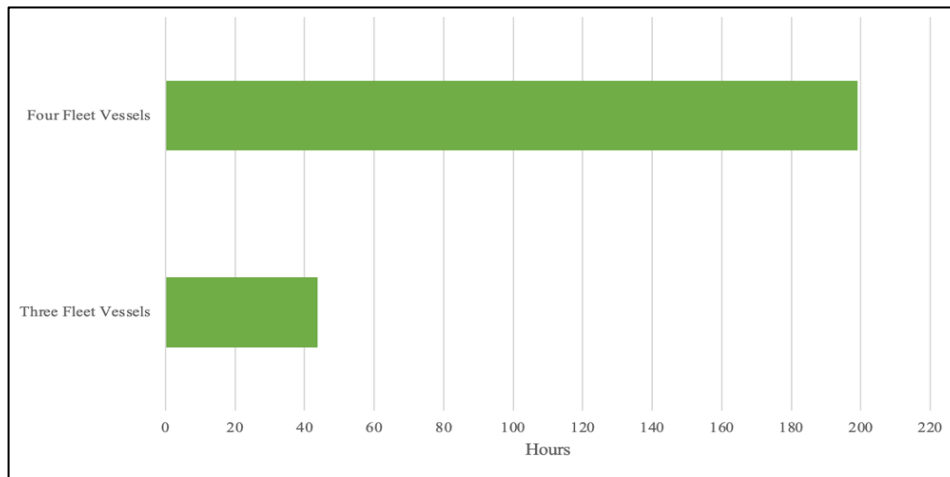


Figure 26 Weekly Average Spare Time in Hours for Both Three and Four Fleet Vessels

In Subsection 6.1.1 it is mentioned that charter vessels are not needed before reducing the fleet size to three vessels. Thus, to be able to see the changes and trends in chartering needs, the use of a three-vessel fleet was extended throughout further analysis. In doing so, the triggers and changes causing the need for charter vessels can also be more easily detected.

Leasing an extra vessel rather than regularly chartering a vessel is an alternative which was investigated; however, it was concluded that the average spare time is much higher in that case. If an extra vessel was needed, another alternative for Equinor would be to use these inactive fleet vessels for urgent shipments. Another alternative is to rent out these vessels to others, though this requires additional resources and follow up when needed.

6.1.3 Activity Change and Use of Charter Vessels

As previously explained, fleet size and the use of charter vessels, change corresponding to demand, and changes in demand are further affected by activities happening on active installations. By looking at Figure 27, which shows the extra demand from active installations along with the charter vessel days required (using three fleet vessels), it can be observed that when demand is high, the chance of extra chartering vessels being necessary, is higher. More specifically, one can distinguish between the demand for m^2 and m^3 , where charter vessel days necessary are mostly affected by m^2 . This is because the amount of m^2 and m^3 is very similar from week to week, but there is always more capacity available for m^3 on the vessels. Additionally, the extra service time on the active installations is only affected by m^2 , so if the m^2 is high, there is a greater chance that more available hours and therefore charter vessels are needed.

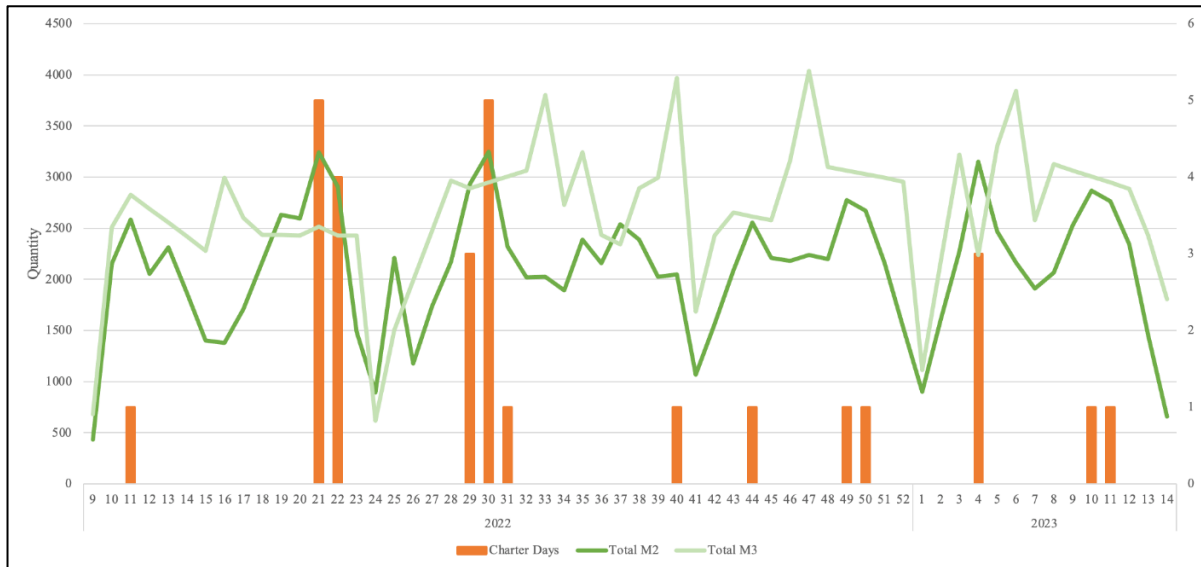


Figure 27 Comparison of the Demand and Its Effects on the Amount of Charter Vessel Days

As explained in Subsection 5.1.3, the total demand for each week was calculated using generic formulas formulated by the team. Seasonal differences were not taken into account when these formulas were used in the model, meaning that the variables M (maximum demand) and L (length of the project) are unaffected by this. Because it is known that drilling installations are more active during the summer months, these values were changed to simulate these circumstances by changing the M and L variables. Although this was not done with realistic numbers, the overall effect of this is what is of importance. Doing so makes it possible to see a different pattern of when chartering is necessary. As Figure 28 shows, the charter vessels are used more frequently for a shorter period of time of higher demand. This introduces the possibility of permanently adding an extra vessel to the fleet for this period of time, instead of sporadically chartering from the spot market, which is most likely a cheaper solution. For instance, if Figure 28 depicted an actual scenario, renting an extra vessel from week 21 to 30 may be a more profitable solution.

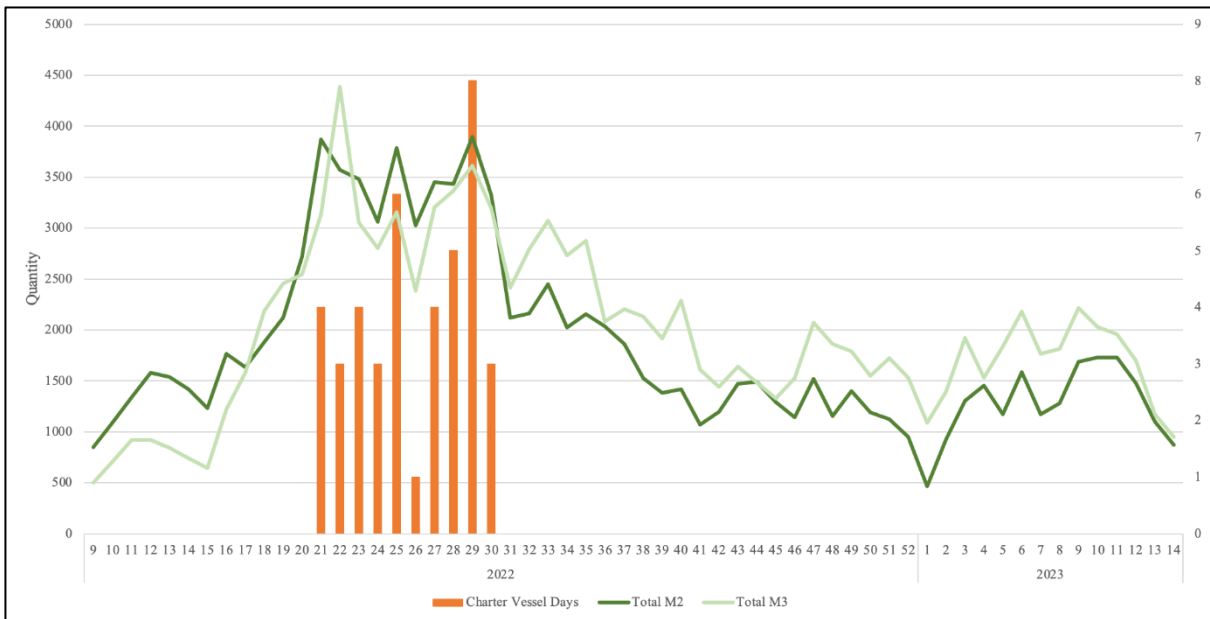


Figure 28 Comparison of a Seasonal Demand and Its Effect on the Amount of Charter Vessel Days

By comparing week 21 and 29 in Figure 28, it can be observed that their demand is very similar. However, their need for charter vessel days is quite different. The cause of this is the location of the installations where the extra activity demand is needed. In week 29 a project was started on an extra installation, meaning that the distance to provide all extra demand required at that installation may increase. When distance is increased, so does the time taken to complete the route, since the speed is constant. An extra vessel would be necessary to cover this extra time. Because of the way the final model is designed, where all available capacity of each route is divided equally to each active installation on the route, the extra active installation in week 29 leads to less capacity for all active installations. This forces the model to look for other, or extra routes, consequently, more charter days may be needed.

Furthermore, an additional examination of the need for chartering in the two scenarios could be carried out. By knowing what triggers the need for chartering, it is possible to prepare and avoid undesirable situations when unusual differences in demand occurs. However, with the use of the model, this is not necessary, because the model can give the answers to these scenarios.

6.1.4 The Use of Fixed Routes and a More Static Approach

As previously mentioned, when Solver has free rein, it chooses a total of 51 different routes. Since the uncertainty caused by the constant change in routes is undesirable for Equinor, it was determined to decide upon a few routes which are to stay constant throughout all weeks (Flow 1) and make an additional flow of extra routes which need to be sailed in order to fulfill all constraints (Flow 2), see Appendix A12. This will most likely lead to extra costs, both in economic and environmental terms, but the analysis is interesting to perform to find possible solutions that ensure more stable conditions.

To achieve the best possible results, three different approaches were evaluated. Three route combinations were used as the constant routes, and additional routes were used to supplement according to the needs of each week. The first approach uses the routes designed for weeks where there is no extra activity as its base (i.e., Flow 1). This concerned the routes: 2, 19, 24, 35, 47 and 60, which each are sailed once a week. Since routes meant for no activity will most likely not include many extra visits to those installations which will need them, the routes chosen in Flow 2 will most likely be those which visit many of the active installations.

The second approach is called “Optimal Solution for the Average week”. A week that corresponded to the average demand (both m^2 and m^3) was chosen and used as the base. Routes picked for this approach were: 2 (sailed 3 times in one week), 23 (2 times), 24 (1), 30 (1) and 64 (2). Several of these routes were also selected in the first approach. This may indicate that these routes are fairly stable and therefore a good foundation

By taking the fact that many of the routes were selected for both approaches into account, the third approach was created. The most common routes during the runs with both three and four fleet vessels, were chosen as the new basis. In total, nine routes were needed to fulfill all required visits and constraints. Table 6 summarizes which nine most common routes were chosen, and the total number of visits to each installation with the use of these routes.

Table 6 Possible Fixed Routes – 9 Most Common Routes

Sequence	Route	Duration	Installation	Visits	Required visits
1-12-8-3-13-7-1	2	72	2	1	1
1-7-12-1	4	48	3	3	2
1-13-10-6-7-8-1	19	48	4	1	1
1-13-11-5-6-7-1	23	48	5	3	3
1-13-11-4-7-8-1	31	48	6	2	2
1-9-5-7-8-1	42	48	7	9	4
1-13-9-5-7-8-1	47	48	8	5	4
1-14-2-9-3-7-1	60	48	9	4	2
1-14-2-9-13-7-1	64	48	10	1	1
			11	2	1
			12	1	1
			13	6	5
			14	2	2
Total		456			

All three approaches were run through the model, in order to find out how many extra routes were needed to meet all requirements. Preliminary studies showed that the third approach with the nine most common routes offered the best solution, because the least amount of charter-vessel days was needed, and therefore gave the lowest cost and total distance. The first and second approach had quite similar results when it came to these aspects. The third however, had a significant improvement in both total cost and charter days, as shown in Table 7, summarizing the results from Appendix A13.

Table 7 Comparisons of the Three First Approaches

Approaches			
Type of approach	Total Costs	Total Distance	Charter Vessel Days
"Optimal" Solution for Non-activity week	9606970	179617	175
"Optimal" Solution for Average week	9456318	176951	172
Most Common Routes	886937	185409	128

This led further to a comparison between this third approach of fixed routes and the no fixed routes method. Figure 29 below shows a comparison of the need for charter vessel days. The significant increase in chartering frequency with fixed routes, signifies that the approach of nine fixed routes is not entirely ideal. The goal would be to fix as many routes as possible while

still minimizing cost, distance, and chartering days. This led to an investigation of the number of fixed routes, to see which combination of fixed and non-fixed routes is desirable.

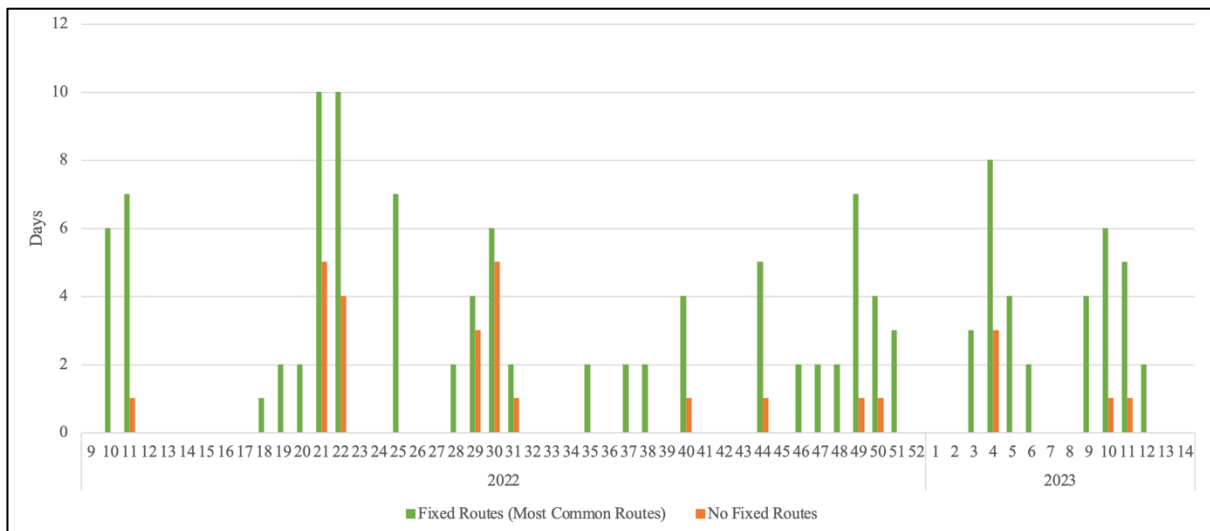


Figure 29 Comparison of Charter Vessel Days Within All 58 Weeks, Both Fixed Routes and Non-fixed Routes

In line with the third approach, further investigation of fixed routes was done with the six and three most commonly selected routes. With the use of six fixed routes, routes 2, 19, 23, 31, 60 and 64 were chosen, all of which were again only used once per week. With the use of three fixed routes, routes 2, 23 and 31 were selected, also only once per week. As predicted, the need for charter vessels and distance decreased as the number of fixed routes decreased, as shown in Figure 30. It is evident that the need for charter vessels decreases, and that the curve flattens as it approaches the no-fixed route solution. Because there is no point where the use of any number of fixed routes gives a better result than with a completely dynamic approach, other indicators are needed to determine which combination of fixed and non-fixed routes would be most beneficial.

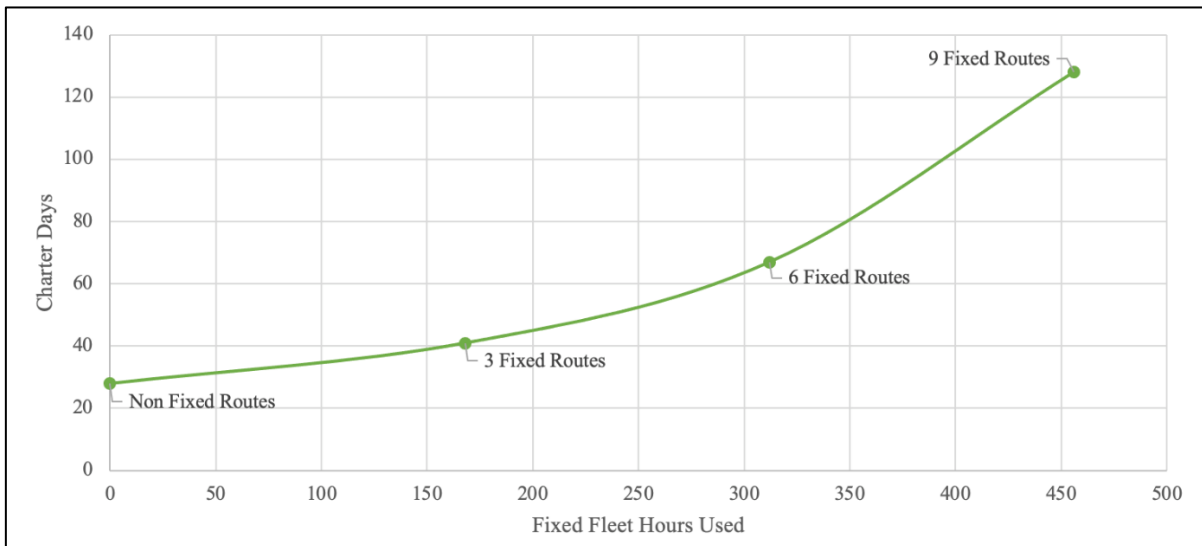


Figure 30 *The Relation Between Charter Days and Fixed Fleet Hours Used, Through Various Number of Fixed Routes*

One way of determining which combination of fixed routes is most ideal, is to examine the utilization rate of the fixed routes. Because of the vast number of combinations of routes, the goal was not to find the “optimal” combination, but rather a method of determining which is preferred. Thus, the ratio between chartering days and fixed fleet hours per week was investigated. This was done with Formula 3 below.

$$\text{Ratio} = \frac{\text{Total charter days}}{\text{Fixed hours per week}}$$

Formula 3 – *Utilization ratio of different numbers of fixed routes*

The smaller the ratio between chartering days and fixed hours per week, the larger the utilization rate of the fixed routes, and consequently, the less the utilization of chartering is needed. Since the goal is to minimize the need for chartering, while simultaneously maximizing the number of fixed routes, finding the best utilization can aid in finding the most “optimal” combination, as shown in the figure below.

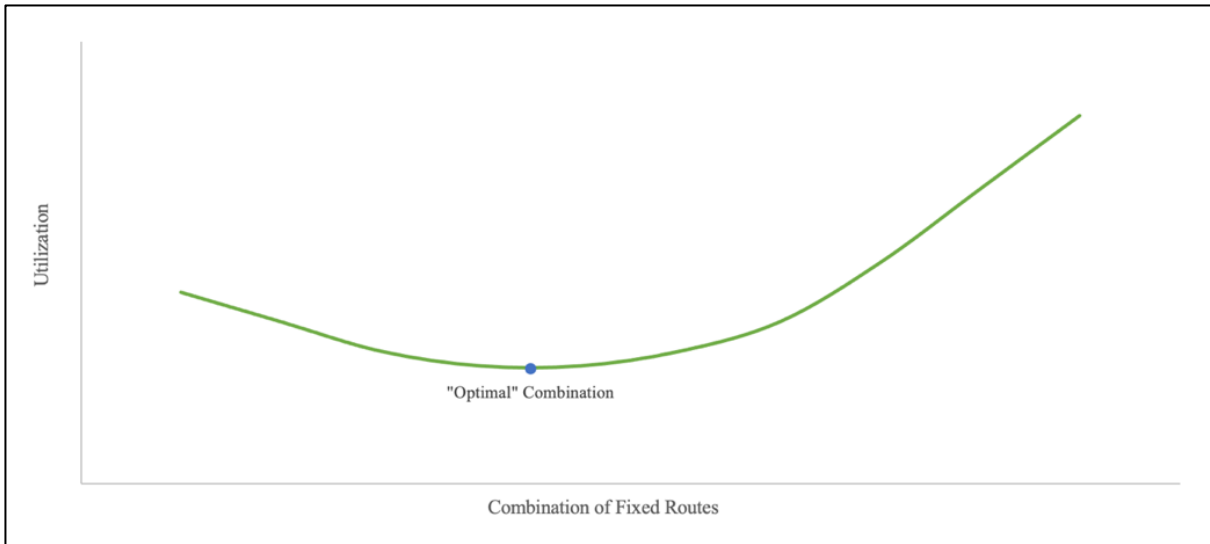


Figure 31 The “Optimal” Combination Point with the lowest utilization and a combination of Fixed routes

The utilization ratio of the methods with three, six and nine fixed routes were plotted in Figure 32. Although Figure 30 suggests that three fixed routes is the best of these options, Figure 32 shows that six fixed routes have the smallest ratio, and therefore the best utilization rate of these options, and is therefore closer to the best combination. Of course, this does not mean that the actual cost and distance are minimized, but rather suggests a compromise of fixed and non-fixed routes for Equinor. Though, the actual “optimal” combination cannot be determined without the examining of all consecutive numbers of fixed vessels.

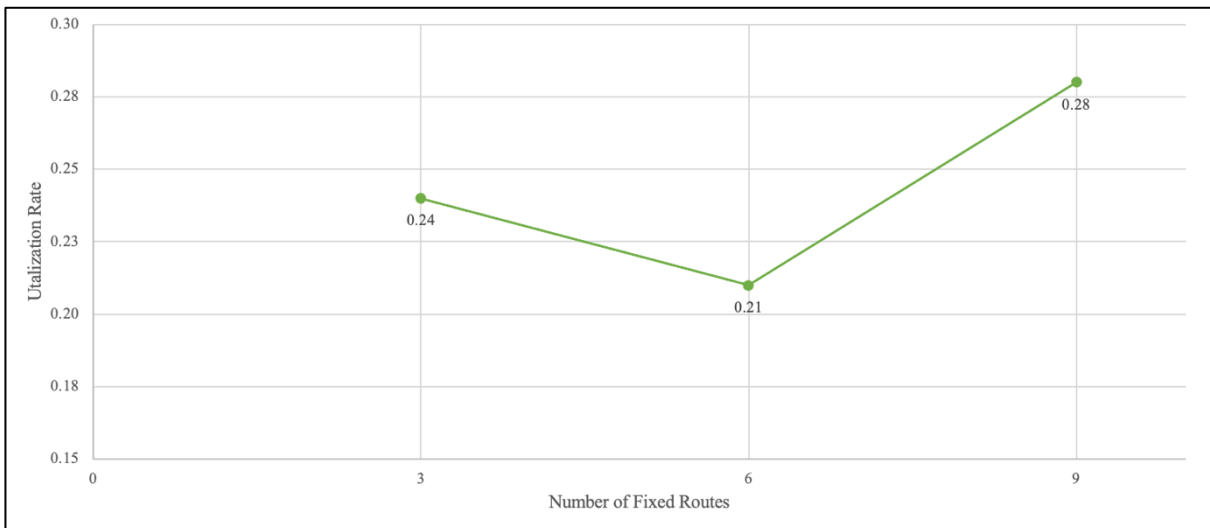


Figure 32 Comparison of Utilization Rate with a Various Number of Fixed Routes

6.2 Limitations

Multiple limitations have been encountered during this project, which each have left their mark on it. Even if the ideal model (prototype 1) had been feasible, it is not guaranteed that a better solution would have been produced. While the constraints and limitations put on the project will save the team the strain of checking the “whole” mathematical space for solutions, it does not prevent the team from finding the best solution since the best solution may actually be part of that space. As a result, these limitations do not necessarily have to be considered weaknesses since the project team is unsure whether they have affected the final results. However, the limitations will be discussed in greater depth to present their possible effects.

As previously discussed, Solvers limitations, and the additional stress of the constraints put on it by the team, could have caused consequences to the final result. The time limit set for Solver to find a solution for each week was set to 300 seconds (5 minutes). As explained in Subsection 6.1.1, this may have affected the accuracy of the solution. In addition, the use of GRG non-linear, gives local minima- and maxima points, as mentioned in Subsection 2.3.3. It is not certain that the solution found for all weeks is the most optimal solution, although they are still valid, because an incumbent solution was found. In essence, this means that the incumbent found could be a local minima and be chosen without further search for a better, global minima.

Another inconsistency is the fact that when running the loop, the selected routes from previous week are used as the starting point for next week, causing it to find a local minimum based on the previous solution, which may also be the reason for the fact that the same routes are chosen so many times. It was also observed that Solver spends more of its available time limit, and thus utilizes its available resources better when searching for solutions with four fleet vessels than it does for three, because it has more options available. Further, chartered vessel days are calculated based on days, meaning 24-hour route equals one day of chartering. Since none of the routes have a duration of 24 hours, 1 charter vessel day is not ideal, as some of the solutions suggested.

The selected routes for each week often allow for more visits to each installation than necessary. Although it is possible to skip installations on these routes which have extra visits, creating a more flexible time schedule, it also implies a less optimal route. It is also important to recognize that with an upgraded version of Solver, which the project team did not have

access to, it is possible to introduce more decision variables and constraints, which was the limiting factor in this project. With this option, the requirement of the process of elimination done in Appendix A2 is either greatly reduced, or even unnecessary. Increasing the viable routes which may be engaged will enhance the optimality of the routes.

In terms of the routes, as stated in Subsection 5.1.5, the route generation selected 74 routes out of 17 billion, which is just 0,000000435 %. There is no guarantee that these 74 routes are the best when so many options are available, and certainly not when they also have to combine in the best possible manner. In concretization of the routes of this project, the team made decisions on how to limit the number of routes based on their understanding, however, Equinor has more experience on the subject, and may better know how to prioritize the criteria; focus may therefore differ. Though, the criteria seem reasonable, and most likely won't be completely amiss, thus, the team consider the given solutions to be quite reasonable.

The route composition also suffers from the fact that the project team did not complete the last step as in the previous project for every solution. There, a detailed plan of which routes were sailed, and when they were sailed by which vessel was created. In other words, it is not given that the selected routes will give a feasible solution, where installations are not visited at the same time, or where visits are spread evenly throughout the week, which are both crucial to creating a well-functioning arrangement. This leads to a limitation in the route selection as not knowing if these routes can combine in a satisfactory manner in a weekly route plan.

Lastly, in Section 2.4 the importance of Flaw of Averages is mentioned. The use of averages has certainly had an impact on this project, as many of the inputs are based on averages, among these are the supply demands and the required visits per week. Because fluctuations may occur, these averages are not always realistic, and cannot be taken as a given. A larger amount of data increases the likelihood of the average representing the reality; however, it also includes the larger fluctuations, which can skew the picture.

6.3 Sustainability

Given Equinor's ambition to halve the Norwegian maritime segment emissions of 2005 within 2030, and their focus on sustainability, this component remains an important addition to the thesis. Their simultaneous strive towards competitiveness and profitability motivated the

objective to minimize the total cost, which also takes the distance sailed into account. To pursue these ambitions, in lack of the ability to use a fully zero-emission supply fleet, an approach to reduce the distance sailed facilitates finding more effective solutions and reducing emissions from transport.

This case focuses its disposition on the emissions caused by the current use of supply vessels. The maximum utilization of all vessels is crucial to reduce unnecessary sailing, thus, an increase in charter vessels, and last-minute leasing of vessels from the spot market, which increase these distances substantially, is undesirable. The solutions found in this thesis primarily focus on the benefits of a three-vessel fleet, where charter vessels are needed. Since the cost of renting a last-minute vessel are often less than the cost of operational stops on installations caused by suddenly damaged or worn-out components, these vessels can also be used to deliver these components, often causing a very low utilization of the vessels. However, since the solutions found, often involve a considerable number of extra visits to each installation, the use of these charter vessels may not be needed as often as they currently are, because the visit interval to each installation is shortened. This makes it possible to add crucial shipments to other scheduled routes, with a greater possibility of a quick delivery. When the unpredicted use of charter vessels with a low utilization rate is required less often, unnecessary emissions can also be reduced. In most cases, when the distance is reduced, the total cost is also reduced, depending on the use of chartering. The reduction of costs could instead finance research dedicated to finding more sustainable solutions.

7. Conclusion

Equinors desire to contribute to a more sustainable development encouraged the development of this bachelor thesis. Introducing the complication relating to the supply from Dusavik depot to the oil installations, to this desire, presented the problem of how to improve the current conditions. By creating an overview of the supply-need, both with and without ongoing projects at each installation, creates the potential to optimize and therefore the ability to decrease emissions. The development of a dynamic route planner and estimate of demand can be applied to establish the need for supply vessels. This led to the fundamental problem statement for this thesis:

How do the supply-needs of the various oil fields' activities influence the supply routes and the use of supply vessels from the depot Dusavik?

Throughout the analysis of this problem statement, and the accompanying research questions, it was detected that the routes choice and changes in number of vessels are sensitive to changes in installation demand and their location. The demand development varies based on the activity level at each installation. To avoid the need for constant adjustments to the route planning caused by these variations, a conservative model is necessary, although the benefits of a radical model should also be acknowledged. Therefore, the final model was composed of a combination of these two, and had the features of a radical model which could adjust routes and chartering need, while also keeping some elements of a conservative model, such as the constant routes and goal function. A dynamic approach which is capable of combining each of their most desirable traits will most likely be more beneficial than Equinors current fully static route planning.

Because the constant change in routes is undesirable, the combination of fixed and non-fixed routes enables a more stable environment while also improving the performance. Therefore, the model was modified such that a set of fixed routes could be repeated uninterrupted, while others were continuously altered based on the needs of each installation. Which approach should be chosen to accomplish a more static concept, is dependent on the preferred company strategy. This project has explored three different approaches. The first approach is the “optimal solution” given for a week with no extra activities, and consequently no demand, at any installations. The second approach conducted was the “optimal solution” for a week with

average demand. The third approach which was investigated was the use of the most commonly selected routes of a fully dynamic model. No matter which approach is chosen, the best results are always achieved with a fully dynamic model, with no fixed routes. For this reason, utilization ratio has been considered, to investigate which combination of fixed and non-fixed routes to use.

Regardless of the choice between fixed and non-fixed routes, the need for charter vessels may arise depending on the number of fleet vessels in use. The need for chartering originates from the extra demand, which triggers the need to sail more routes, necessitating chartering. By use of the model, it is possible to predict the need for chartering. This can further be used to make decisions on when to, and the duration of, chartering extra vessels.

The importance of this project is that its method can be used to improve the offshore logistics while remaining competitive and contributing to a more sustainable industry. The model is developed in such a way that it is simple to implement changes and improvements tailored to its users' needs. Moreover, it is possible to make changes to both the future progress plan, and the model itself, to change which nodes have the most substantial demands, and where they are located. Because it is possible to change both the time and space aspects of the model, it is an adaptable model which can be generally used and produces solutions relatively fast. Thus, this spreadsheet model can be useful not only to Equinor, but can also be modified to be used as a route planner for others.

7.1 Further Research

It has become apparent during the course of this project that offshore logistics is a complex professional field. Many topics within this field have been examined, but usually in a mathematical manner, and little with the use of spreadsheet modelling and tools such as the Solver add-in. Examples of these mathematical research approaches which address the offshore supply operations and services are articles such as “*Vendor managed inventory in tramp shipping*” (Andersson, H., Christiansen, M., Fagerholt, K. & Stålhane, M.) and “*Optimal policies for maintaining a supply service in the Norwegian sea*” (Fagerholt, K. & Lindstad, H.). Because of the broad extent of research within this field, these, this thesis included, only cover a fraction of the topics arising from the offshore supply operations.

The main focus on the sustainable components of the problem statement, has led to a disregard of several other aspects. An example of this are the extra costs arising from the use of an extra fleet vessel. Although some general costs are taken into consideration, they are not realistic, both in terms of all scenarios, and validity of their values. Thus, it is possible to further investigate the costs to accurately discern which approach is most profitable. Subsequently, the effect of this cost on the choice and combinations of routes can be researched more thoroughly. Also, because the fully dynamic approach with no fixed routes is the most sustainable approach a deeper investigation into the combination of fixed and non-fixed routes was not executed. If a desire to find a better combination of these arises, other approaches could be further examined.

The design of the routes, and which routes are selected depend on the users' conditions. The model created for this thesis is based on the knowledge and perception of the project team. Since the team's knowledge of this field is limited, the consultation and cooperation with specialists could lead to the design of a better approach. It is also possible to further investigate different approaches to both generating and selecting routes, to work towards a better selection of routes for the model. To be able to expand, and add more routes to the model itself, an upgraded version of Solver can be utilized. This may open the opportunity for further development and use of Path-Flow Model 1.

From a more forward-looking perspective, it can be further examined whether supply vessels with zero-emission fuel, would contribute to the reduction of emissions while still being able to handle such time- and distance- consuming routes with the same number of visits as currently provided to each installation.

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9. Appendix

A1: Troubleshooting

A2: Route generation iterations

A3: Solver Setting Analysis

A4: Microsoft Visual Basic for Applications Loop

A5: The coding for route generation performed in MATLAB

A6: Preliminary project (doc. file)

A7: Spreadsheet “General Supply” (xlsx. file)

A8: Spreadsheet “Activity Supply” (xlsx. file)

A9: Spreadsheet “Generic Project Demand” (xlsx. file)

A10: Spreadsheet “Prototypes and Path-Flow model 1” (xlsx. file)

A11: Spreadsheet “Path-Flow Model (Final)” (xlsx. file)

A12: Spreadsheet “Path-Flow Model (Final) with loop-run” (xslm. file)

A13: Spreadsheet “Comparisons and Summary of Results” (xlsx. file)

A1: Troubleshooting - Prototype 1

During the troubleshooting of Prototype 1, the following tests were carried out:

- Test 1 – Without any changes, with high capacity and slack time, **the model ran smoothly**. However, because of problems with the full-scale model, Path-Flow Model 1, this was not an accepted condition.
- Test 2 – With extra capacity (especially on the M3 deck), caused by activities, **Solver got stuck**. Problems at high demand may indicate trouble with finding routes with enough capacity and slack time.
- Test 3 – Locked M2 and M3 so that the model would not go in a loop between supply per visit, and the number of visits. Thereafter, “Time Extra” per visit was also locked with a certain quantity (especially M3) which is difficult to satisfy but should be possible (checked manually). **Solver still got stuck**. Because of this, there is a possibility that the loop the model is usually forced to run is a problem, but this is not certain without ruling out other possible problems and errors.
- Test 4 – Retained locked M2 and M3 and “Time Extra” from Test 3 and changed formulas, calculating the “Capacity Slack” as $=(\text{Route Capacity} * \text{Flow})$ instead of $=(\text{Route Capacity} * \text{COUNTIF}(\text{Flow}, >0))$ and “Capacity Change” as $=(\text{Capacity} * \text{in } m^2 \text{ (or } m^3) \text{ per visit} * \text{Flow})$ instead of $=(m^2 \text{ (or } m^3) \text{ per visit} * \text{COUNTIF}(\text{Flow}, >0))$. **Solver still got stuck**. With no difference in outcome, there is no foundation that the use of *COUNTIF() is the problem, although it could still be a part of the problem.
- Test 5 – The locked cells from Test 3 remains locked, except for the fact that $=(\text{SUMPRODUCT}(\text{Route}, \text{M2 or M3 per visit}) * \text{Flow})$ is no longer used in the formula for “Change in Capacity” to find the total supply per visit to the specific route. Instead, all M2- and M3 supply got manually summed together per visit for every route and multiplied with the Flow. **Still could not find a solution**. Because there was no change in the result from the last test, the use of “Sumproduct” also cannot be the only problem, but also still be a part of it.
- Test 6 – Retained all changes from test 5 but entered each line of “Remaining Capacity” ≥ 0 of M2 and M3, instead of the total “Countif” in the constraints of the Solver. **Solver found a solution**. This indicates that Solver reacts to the use of “Countif” in the constraints, and that the “collection” of constraints can be a problem.

- Test 7 – Reversed the changes made in test 3 back to the original, but kept the change made on Solver in test 6. **Solver could no longer find a solution.** Now the model goes in the loop, thus, it is possible that the loop is a part of the problem.
- Test 8 – Retained the changes made in test 7, but divides M2 per week on “Required visits” and set the week to week 4, where it should be possible to find a solution (checked manually, and the solution cannot be the solution to test 1). **Solver found a solution.** This confirms that Solver struggles when the model goes in the loop between the supply per visit and the number of actual visits.
- Test 9 – Reversed the changes made in test 5, so that “Sumproduct” was included. **Solver found the same solution as in test 8.** Therefore, it seems that Solver accepts the use of “Sumproduct”.
- Test 10 – Reversed changes made in test 4, so that “CountIf” was included. **Solver did not find a solution.** Thus, it is possible that “Countif” is part of the problem.
- Test 11 – Applied the changes made in test 4 again, i.e. the same starting point as test 9. Used the total “CountIf” for “Remaining capacity” and used “Sum” of “CountIf” as it is done for the constraint of “Remaining time” in Solver. Now **Solver could no longer find a solution.** This confirms that “Countif” in the constraints is a possible problem for Solver.
- Test 12 – Used the starting point of test 9, and changed the constraint of “Remaining time” for each “CountIf” to each route instead of a total “Sum”. In addition, M2 and M3 per visit was changed back to being based on the actual number of visits. Progression plan was set to week 7 to force solver to choose a solution other than the solution to test 1. **Solver did not find a solution.** Because of lack of change in the results, there is nothing to confirm or rule out.
- Test 13 – Same start values as in test 12, but each “Remaining time”>0 is separately entered into solver. **Found a “solution”, only a not usable one,** and uses much longer time. “Countif” is still used, but in a much smaller quantity.
- Test 14 – Retained the changes made in test 13 but replaces “CountIf” in the formula of “Change in Time” with “Flow” instead. **Still could not find a solution.** With all “Countif” gone, it should not be a problem to find a solution, but it still is, which indicates that there are more problems. There might possibly be a problem with the use of the loop in the model.

- Test 15 – Retained the changes made in test 14, but entered all values found in formulas with “Hlookup” manually. **No solution**. This either confirms or rules out that “Hlookup” is part of the problem.
- Test 16 – Entered “If error” where needed based on the values from test 15 and week 4. **Solver now found a solution**, but it was worse than the solution in test 8 and 9.
- Test 17 – Retained values from test 16 and week 4, but removed all “Sumproduct”, and instead multiply separately. Also removed “If error” since Solver, according to some online surveys, responds poorly to If-statements. **Same solution as with test 8 and 9**. Because of the improvement of the solution, it does not seem like “Sumproduct” and “If error” is a problem for Solver.
- Test 18 – Further testing like Test 17, only the week is changed to week 7. **Non-valid solution**. After this there is no more simplifications or formulas to remove, which may indicate that the problem is a bigger than just the commandoes used.

Final Conclusion from these tests:

- “Countif” cannot be used in the model.
- “Hlookup” can be used in simple solutions, but according to research, it is a known problem that it doesn’t work very well with Solver.
- “If”-statements should be avoided, including “iferror”, but in this case, #DIV/ 0! is even more problematic for the model, and is therefore included.
- It seems that the model struggles with the M2 and M3 being distributed on actual trips, especially when the extra supply requires that more trips **MUST** be run to reduce the supply per trip. We see this in the difference between weeks 4 and 7, where Solver manages to find a solution for week 4 but not 7, because it is not forced to run several trips to reduce the supply per trip in week 4.
- It does not seem like “Sumproduct” influences whether Solver manages to find a solution or not.
- Where Solver gets stuck or comes up with a non-usable solution, it gives unrealistic large numbers. It can be seen during solving, that solver only runs these unrealistically large numbers as possible outcomes. This led to the development of a new prototype which aims to avoid problematic loops and formulas.

A2: Route generation iterations

First, all generated routes derived from the process described in 5.2.1 are determined, and illustrated below:

Installation	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of visits	162	31	70	15	16	18	69	49	88	40	44	10	87	35
%-share	100	19	43	9	10	11	43	30	54	25	27	6	54	22

The heuristic degeneration method of routes is performed in the following manner:

First Iteration:

Installation 12 (Heimdal) is visited the fewest number of times in the left-over routes. Therefore, all these routes are chosen. (10 pcs). Consequently, the first 10 routes of the new “sampled route pool” are “sampled”:

Installation	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of visits	10	0	4	0	1	3	6	3	5	2	0	10	6	0
%-share	100	0	40	0	10	30	60	30	50	20	0	100	60	0

The original “route pool”, is updated by removing the chosen routes, with the following visit statistics:

Installation	1	2	3	4	5	6	7	8	9	10	11	13	14	1
Number of visits	152	31	66	15	15	15	63	46	83	38	44	81	35	152
%-share	100	20	43	10	10	10	41	30	55	25	29	53	23	100

Second Iteration:

Installation 4 (Johan Sverdrup PP), 5 (Johan Sverdrup RP) and 6 (Johan Sverdrup LQ) are now visited on the fewest occasions, with the same amount of visits. Therefore, one of these is selected at random. In this case, installation 6 is chosen. These 15 routes are then sampled. The “sampled route pool” then consists of 25 routes in total, with the following statistics:

Installation	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of visits	25	1	7	3	3	18	12	8	11	3	5	10	17	2
%-share	100	4	28	12	12	72	48	32	44	12	20	40	68	8

The original route pool is again updated:

Installation	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of visits	137	30	63	12	13	0	57	41	77	37	39	0	70	33
%-share	100	22	46	9	9	0	42	30	56	27	28	0	51	24

Third Iteration:

The next of the two remaining installations with the fewest visits which is chosen at random is installation 4 (Johan Sverdrup PP). Therefore, these routes (12 pcs) are chosen. We have then “sampled” the next 17 routes to the new “sampled route pool”, which now consists of 37 routes.

Installation	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of visits	37	3	9	15	6	18	16	14	13	5	10	10	26	4
%-share	100	8	24	41	16	49	43	38	35	14	27	27	70	11

The original route pool is then left with these numbers:

Installation	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of visits	125	28	61	0	10	0	53	35	75	35	34	0	61	31
%-share	100	22	49	0	8	0	42	28	60	28	27	0	49	25

Fourth Iteration:

Congruent with the previous iterations, installation 5 (Johan Sverdrup PP) is visited the fewest number of times of the remaining routes. Therefore these 10 routes are selected, and added to the “sampled route pool”, which now consists of 47 routes, with the following visit statistics:

Installation	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of visits	47	4	12	15	16	18	21	17	20	5	10	10	31	5
%-share	100	9	26	32	34	38	45	36	43	11	21	21	66	11

Removing these 10 routes leaves the following statistics from the original “route pool”:

Installation	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of visits	115	27	58	0	0	0	48	32	68	35	34	0	56	30
%-share	100	23	50	0	0	0	42	28	59	30	30	0	49	26

Fifth Iteration:

Installation 2 (Draupner) is visited the fewest time of the remaining routes. These 27 routes are then selected. The “sampled route pool” now consists of 74 routes, which is the maximum limit caused by solvers constraints. This leaves the following visitor statistics:

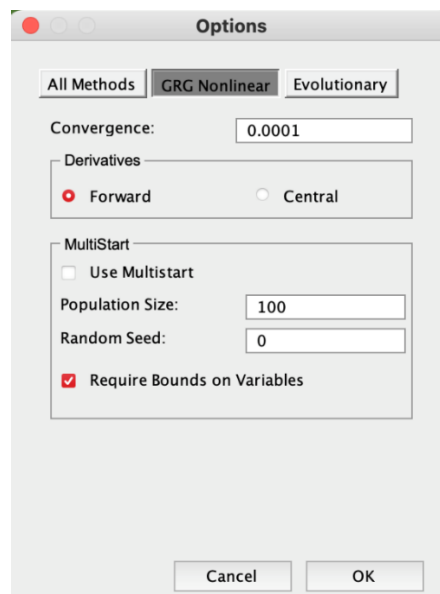
Installation	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of visits	74	31	26	15	16	18	34	25	39	8	17	10	45	11
%-share	100	42	35	20	22	24	46	34	53	11	23	14	61	15

Installation	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of visits	88	0	44	0	0	0	35	24	49	32	27	0	42	24
%-share	100	0	50	0	0	0	40	27	56	36	31	0	48	27

The original route pool is then left with these statistics of routes that are not chosen, after the removal of these 27 routes:

A3: Solver Setting Analysis

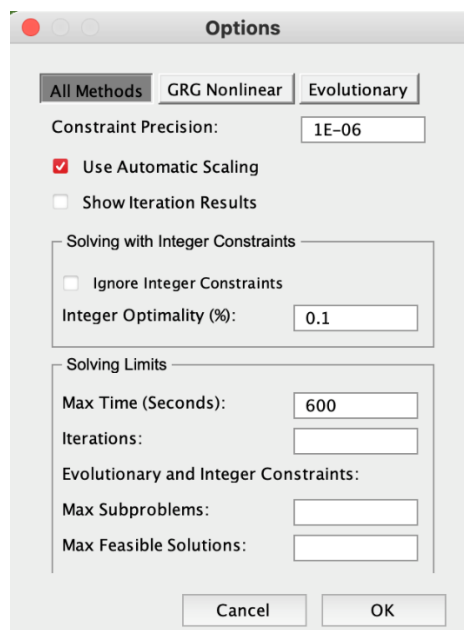
The Solver add-in has settings which may be changed as desired based on user preferences. The figure below shows the window where these changes can be made. The settings are divided into “All Methods”, “GRG Nonlinear” and “Evolutionary”. It was decided to do an analysis of which combination of settings would provide the quickest and best results, since the model is quite large and any changes to the input are time consuming. Throughout this analysis, the main focus has been on searching for well-functioning settings for the GRG Nonlinear method. This was decided because this was the previously determined best method for finding solutions for this model. The “Integer Optimality (%)” setting, which includes all methods was also considered. The settings which were investigated throughout this search were “Integer Optimality (%)”, “Derivatives”, use of “MultiStart” and with it, the “Population Size”.



Solver Options for GRG Nonlinear

Since the “Convergence”, see figure above, stops closer to the optimal solution with smaller values, even though the time taken to find a solution is longer than it would be with bigger values (FrontlineSolvers, n.d.(c)), it was determined to keep the original setting of 0,0001. Further, the “Derivatives” setting has two options, “Forward” and “Central”, where “Forward” usually is the “standard” setting even though “Central” often yields more accurate derivatives. “Central” on the other hand, uses more time than “Forward” because it requires twice as many calculations within each trail solution (l.c.). Considering these factors, an interest to find out if “Central” would be more effective than “Forward” developed, both in regard to time, but also its output.

Without “MultiStart”, Solver starts its searching from the initial conditions given (flow). By using the “Multistart” option, Solver can start its search from a variety of points of entry (l.c.). This gives makes it more likely that Solver is able to find better solutions, although the timespan will be longer than without “MultiStart” (l.c.). The number of starting points can be specified by changing the population size. The “population size” cell may contain numbers from 10 to 200 (l.c.). To create a comprehensive overview, it was decided to vary the population size between 50, 150 and 200 throughout the search. The “Random Seed” value is used as a fixed seed for the random number generator, which solver uses as its starting point. Leaving this box blank will cause a new seed every time solver is run, while entering a number will result in the same starting point (l.c.). Given the responses Solver has had during testing of both prototypes, it was determined to not set a “Random Seed”.



Solver Options for All Methods

Furthermore, the precisions of constraints, shown in the figure above, is kept as the default value. This indicates the degree of precision that the constraints should have and says something about how much the relationship between the constraint and the cell reference can be violated (FrontlineSolvers, n.d.(d)). The “automatic Scaling” is used to make Solver rescale values to similar sizes, and therefore reduce the influence of unusually large or small values on the accuracy of the solution (l.c.), therefore, this is also used as default. Additionally, the “Integer Optimality (%)” is important to determine the maximum difference Solver should

accept between the objective cells (goal functions) of the “*best known, bound on the true optimal objective value*” and the “*best integer solution found*” before giving a solution (l.c.). In addition to this, the impact of different percentages on the integer optimality has on the solution and runtime, was observed.

To prevent bias, the search for the best solver settings to use for the full-scale model, was done with other routes than the final model would contain. Thus, the routes used, were the routes first designed by the route generator before all inputs were correct. This was decided so that the routes would be as realistic as possible, without being too similar to the final routes. This allowed for testing without being influenced by our preconceived ideas, such as the ones formed by having set up routes in our previous project.

Because the runtime is very long for certain weeks when using the full-scale test model, it was decided to set the maximum runtime to 10 minutes (600 seconds), throughout the search. Throughout the process, it was noted when Solver found “incumbents”, or possible solutions. This incumbent, coherent with the test-runs of the prototype models, often ends up being the “optimal solution”. Because of this, there was no need to continue the Solver any longer, as the result most likely will stay the same. I was also determined to use only one week throughout the Solver analysis of the full model, because of the time-consuming process conducting each search. The week chosen was week 30, which has a large amount of extra demand.

In parallel with the search using the full model, another search was performed using prototype 2. In this manner, the settings can easily be changed to run the model for different weeks and scenarios, using less time. This way, differences and patterns become more apparent. The smaller-scale model also has no need for a maximum run-time limit; therefore, the total solution time could be properly measured. The prototype used week 8 to do its runs, which also has a large amount of extra demand.

Test week 30	Solution Time	Incumbent Time	Sub- problems	Solution	Derivatives		Multistart		Population Size			Integer optimality			
					Forward	Central	Yes	No	50	100	150	0.1	0.01	0.001	
1	-	00:08:03	117	334656	x			x					x		
2	-	00:08:29	117	334656	x			x						x	
3	-	00:08:08	117	334656	x			x							x
4	-	-	53	-		x		x					x		
5	-	-	58	-		x		x						x	
6	-	-	55	-		x		x							x
7	Error				x			x		x			x		
8	-	-	6	-	x			x			x		x		
9	-	-	4	-	x			x				x			
10	-	-	3	-	x			x		x				x	
11	Error				x			x			x			x	
12	-	-	3	-	x			x			x			x	
13	-	-	3	-	x			x		x					x
14	-	-	3	-	x			x			x				x
15	-	-	4	-	x			x				x			x

Results of Solver Setting Search – Full Model

Throughout the search with the full model which was limited to a maximum runtime of 10 minutes, Solver could only find “Incumbent” solutions on 3 out of 15 runs, as shown in the figure above. The search with the prototype on the other hand found solutions on 6 of 15 runs, shown in the figure below, which includes the same three runs from the search with the full-scale model. This could possibly be related to the fact that a limited runtime was set for the full-scale model, but not for the prototype, meaning that Solver possibly did not have enough time to find an “incumbent” solution for the three runs that the full-scale model did not have a solution on. Additionally, these three runs that gave “Error” in the prototype, showed that it searched through invalid objective cell values throughout almost the entire run in the full-scale model, and would probably end up with an “Error” or an invalid solution.

Tests for Week 8	Solution Time	Incumbent Time	Sub- problems	Solution	Derivatives		Multistart		Population Size			Integer optimality			
					Forward	Central	Yes	No	50	100	150	0.1	0.01	0.001	
1	00:00:28	00:00:27	11	33490	x			x					x		
2	00:00:29	00:00:28	11	33490	x			x						x	
3	00:00:28	00:00:27	11	33490	x			x							x
4	00:01:10	00:00:44	33	38930		x		x					x		
5	00:01:13	00:00:46	33	38930		x		x						x	
6	00:01:12	00:00:44	33	38930		x		x							x
7	Error				x			x		x			x		
8	Error				x			x			x		x		
9	Error				x			x				x			
10	Error				x			x		x				x	
11	Error				x			x			x			x	
12	Error				x			x				x		x	
13	Error				x			x		x					x
14	Error				x			x			x				x
15	Error				x			x				x			x

Results of Solver Setting Search – Prototype 2

Further examinations of the initial Solver settings which were confirmed to work for the prototype were performed. The analysis was extended to include week 4, 10 and 14 in addition to week 8. These weeks were evenly spread throughout the prototypes future progress plan and had different demands. Another extension which was done was the testing of “Derivatives”

and “Integer Optimality”. Multistart was not further tested as this either didn’t give an incumbent within the maximum runtime, or an “Error” in previous tests. The figure below shows the differences between the use of “Forward” or “Central” derivatives. These changes conclude that “Forward” is the preferred setting for further runs. Furthermore, the change in “Integer Optimality” only made small differences. It is worth mentioning that an integer optimality percentage of 0.1 and 0.001, gave quicker results. To accomplish an as small as possible maximum difference between “best objective cells”, without the need for a significantly longer run-time, it was determined to use 0.001 as the integer optimality percentage for further runs.

Tests for Week 4	Solution Time	Incumbent Time	Sub-problems	Solution	Derivatives		Multistart		Integer optimality		
					Forward	Central	Yes	No	0.1	0.01	0.001
1	00:00:15	00:00:15	4	23120	x			x	x		
2	00:00:15	00:00:15	4	23120	x			x		x	
3	00:00:18	00:00:18	4	23120	x			x			x
4	00:00:24	00:00:24	4	23120		x		x	x		
5	00:00:37	00:00:37	4	23120		x		x		x	
6	00:00:24	00:00:24	4	23120		x		x			x
Tests for Week 10	Solution Time	Incumbent Time	Sub-problems	Solution	Derivatives		Multistart		Integer optimality		
1	00:00:39	00:00:35	17	36210	x			x	x		
2	00:00:39	00:00:38	18	36210	x			x		x	
3	00:00:39	00:00:36	18	36210	x			x			x
4	00:00:17	00:00:16	4	47940		x		x	x		
5	00:00:17	00:00:16	6	47940		x		x		x	
6	00:00:17	00:00:17	4	47940		x		x			x
Tests for Week 14	Solution Time	Incumbent Time	Sub-problems	Solution	Derivatives		Multistart		Integer optimality		
1	00:00:37	00:00:36	14	26520	x			x	x		
2	00:00:37	00:00:35	19	26520	x			x		x	
3	00:00:35	00:00:35	16	26520	x			x			x
4	00:00:47	00:00:39	17	25500		x		x	x		
5	00:00:47	00:00:39	17	25500		x		x		x	
6	00:00:48	00:00:38	18	25500		x		x			x

Results of further examinations with no “MultiStart”

The effect of the initial conditions of model on its solution were also analyzed. The results of week 4,8,10 and 14 of the prototype are shown in the figure down under. The figure clearly shows that Solver cannot find a solution when all “Flow” values start with 0. The same would then be true for the full-sized model, since they are designed the same. Moreover, it does not seem that there is a clear pattern on if it is better to start the “Flow” values with all ones, or with a previously found solution for another scenario (non-activity in this case). Because of this, it was decided that the initial conditions of the “Flow”, should be a previously chosen route.

Test for Week 4	Solution Time	Solution	Initial Condition		
			All zero	All ones	Non activity (635 Dist.)
1	Error		x		
2	00:00:26	23120		x	
3	00:00:15	23120			x
Test for Week 8	Solution Time	Solution	Initial Condition		
1	Error		x		
2	00:00:46	36210		x	
3	00:00:55	35190			x
Test for Week 10	Solution Time	Solution	Initial Condition		
1	Error		x		
2	00:01:03	36210		x	
3	00:00:47	42160			x
Test for Week 14	Solution Time	Solution	Initial Condition		
1	Error		x		
2	00:00:08	25500		x	
3	00:00:20	29240			x

A4: Microsoft Visual Basic for Applications Loop

This coding has been slightly modified based on which cells were used, but the basic approach remained the same.

```
Sub test()  
Dim i As Long  
Range("C100:CA157").ClearContents  
For i = 9 To 66 ' start first few, like: 1 to 3  
    Range("I4").Value = i  
    SolverSolve True  
    Cells(91 + i, "C").Value = Range("B9").Value  
    Cells(91 + i, "D").Value = Range("C11").Value  
    Cells(91 + i, "E").Value = Range("B88").Value  
    Cells(91 + i, "F").Value = Range("B14").Value  
    Cells(91 + i, "G").Value = Range("B15").Value  
    Cells(91 + i, "H").Value = Range("B16").Value  
    Cells(91 + i, "I").Value = Range("B17").Value  
    Cells(91 + i, "J").Value = Range("B18").Value  
    Cells(91 + i, "K").Value = Range("B19").Value  
    Cells(91 + i, "L").Value = Range("B20").Value  
    Cells(91 + i, "M").Value = Range("B21").Value  
    Cells(91 + i, "N").Value = Range("B22").Value  
    Cells(91 + i, "O").Value = Range("B23").Value  
    Cells(91 + i, "P").Value = Range("B24").Value  
    Cells(91 + i, "Q").Value = Range("B25").Value  
    Cells(91 + i, "R").Value = Range("B26").Value  
    Cells(91 + i, "S").Value = Range("B27").Value  
    Cells(91 + i, "T").Value = Range("B28").Value  
    Cells(91 + i, "U").Value = Range("B29").Value  
    Cells(91 + i, "V").Value = Range("B30").Value  
    Cells(91 + i, "W").Value = Range("B31").Value  
    Cells(91 + i, "X").Value = Range("B32").Value  
    Cells(91 + i, "Y").Value = Range("B33").Value  
    Cells(91 + i, "Z").Value = Range("B34").Value  
    Cells(91 + i, "AA").Value = Range("B35").Value  
    Cells(91 + i, "AB").Value = Range("B36").Value  
    Cells(91 + i, "AC").Value = Range("B37").Value  
    Cells(91 + i, "AD").Value = Range("B38").Value  
    Cells(91 + i, "AE").Value = Range("B39").Value  
    Cells(91 + i, "AF").Value = Range("B40").Value  
    Cells(91 + i, "AG").Value = Range("B41").Value  
    Cells(91 + i, "AH").Value = Range("B42").Value  
    Cells(91 + i, "AI").Value = Range("B43").Value  
    Cells(91 + i, "AJ").Value = Range("B44").Value  
    Cells(91 + i, "AK").Value = Range("B45").Value  
    Cells(91 + i, "AL").Value = Range("B46").Value  
    Cells(91 + i, "AM").Value = Range("B47").Value  
    Cells(91 + i, "AN").Value = Range("B48").Value  
    Cells(91 + i, "AO").Value = Range("B49").Value  
    Cells(91 + i, "AP").Value = Range("B50").Value  
    Cells(91 + i, "AQ").Value = Range("B51").Value  
    Cells(91 + i, "AR").Value = Range("B52").Value  
    Cells(91 + i, "AS").Value = Range("B53").Value  
    Cells(91 + i, "AT").Value = Range("B54").Value  
    Cells(91 + i, "AU").Value = Range("B55").Value  
    Cells(91 + i, "AV").Value = Range("B56").Value  
    Cells(91 + i, "AW").Value = Range("B57").Value  
    Cells(91 + i, "AX").Value = Range("B58").Value  
    Cells(91 + i, "AY").Value = Range("B59").Value  
    Cells(91 + i, "AZ").Value = Range("B60").Value  
    Cells(91 + i, "BA").Value = Range("B61").Value  
    Cells(91 + i, "BB").Value = Range("B62").Value
```

```
Cells(91 + i, "BC").Value = Range("B63").Value
Cells(91 + i, "BD").Value = Range("B64").Value
Cells(91 + i, "BE").Value = Range("B65").Value
Cells(91 + i, "BF").Value = Range("B66").Value
Cells(91 + i, "BG").Value = Range("B67").Value
Cells(91 + i, "BH").Value = Range("B68").Value
Cells(91 + i, "BI").Value = Range("B69").Value
Cells(91 + i, "BJ").Value = Range("B70").Value
Cells(91 + i, "BK").Value = Range("B71").Value
Cells(91 + i, "BL").Value = Range("B72").Value
Cells(91 + i, "BM").Value = Range("B73").Value
Cells(91 + i, "BN").Value = Range("B74").Value
Cells(91 + i, "BO").Value = Range("B75").Value
Cells(91 + i, "BP").Value = Range("B76").Value
Cells(91 + i, "BQ").Value = Range("B77").Value
Cells(91 + i, "BR").Value = Range("B78").Value
Cells(91 + i, "BS").Value = Range("B79").Value
Cells(91 + i, "BT").Value = Range("B80").Value
Cells(91 + i, "BU").Value = Range("B81").Value
Cells(91 + i, "BV").Value = Range("B82").Value
Cells(91 + i, "BW").Value = Range("B83").Value
Cells(91 + i, "BX").Value = Range("B84").Value
Cells(91 + i, "BY").Value = Range("B85").Value
Cells(91 + i, "BZ").Value = Range("B86").Value
Cells(91 + i, "CA").Value = Range("B87").Value
Next i
End Sub
```

A5: The code for route generation performed in MATLAB

```
function [RoutePool, CargoSlack, TW_SlackMat, DurDistMat] = RouteGenerationProcedure()

filename = 'InstData_FINAL.xlsx';
ZoneTransitMatrix = readmatrix('ZoneTransitMatrix.xlsx');

VoyGenInput = readcell(filename);

%Reads the numerical values in installation data input file
InstNames = VoyGenInput(1,2:end);
InstNos = cell2mat(VoyGenInput(2,2:end));
InstZones = cell2mat(VoyGenInput(3,2:end));
DeckDemand = cell2mat(VoyGenInput(6,2:end));
BulkDemand = cell2mat(VoyGenInput(7,2:end));

ReqFreq = cell2mat(VoyGenInput(9,2:end));
OpHrs = cell2mat(VoyGenInput(11,2:end));
ClHrs = cell2mat(VoyGenInput(13,2:end));

Lat = cell2mat(VoyGenInput(15,2:end));
Lons = cell2mat(VoyGenInput(17,2:end));

%Specifies parameter settings for the route generation procedure
maxStops = 5;

CommonStartTime = 16; %Hours after midnight
CommonSailingSpeed = 10; %Knots

AcceptableIdle = 4; %MaxHours that can be waited for TW to open

CommonDeckUnitSize = 6; %m2 per unit

CommonHeaveRateDeck = 10; %Heaves per hour
CommonBulkRate = 80; %m3 per hour
CommonDeckCapacity = 600; %m2
CommonBulkCapacity = 1000; %m3

%Initializes the four output variables
RoutePool = [];
TW_SlackMat = [];
CargoSlack = [];
DurDistMat = [];

rCount = 0; %Counter for generated routes
RouteInProgress = []; %Initializes the visit sequence for route being generated

%In this specific case, all route combinations with 1 to 5 stops are
%checked during this loop for L52-L581 (MAIN LOOP)
for s = 1:maxStops

    CurrTime = CommonStartTime;
    AvInsts = InstNos(2:end); %Initializes set of available installations

    nInt = 0; %Counter for stops on the intermediate route

    for i = 1:length(AvInsts)

        RouteInProgress(1) = AvInsts(i); %All installations are selected as the first stop of a route
        nInt = 1; %The intermediate route now have 1 visit

        if nInt >= s %If enough stops are added to the route, the route is evaluated in terms of feasibility

            FullRoute = [1 RouteInProgress 1]; %creates complete route to return to base
```

```

CurrTime = CommonStartTime;
ArrTime = [];
DeckCargo = 0;
BulkCargo = 0;
TW_sat = []; %Time window satisfied array
TW_LegSlack = [];

%L76-L148: Checks time windows and aggregates cargo amounts for
%the route
for leg = 1:length(FullRoute)-1
startLeg = FullRoute(leg);
endLeg = FullRoute(leg+1);

startIdx = find(InstNos==startLeg);
endIdx = find(InstNos==endLeg);

Lat1 = Lats(startIdx);
Lon1 = Lons(startIdx);
Lat2 = Lats(endIdx);
Lon2 = Lons(endIdx);

Dist = LegDistCalculator(Lat1,Lon1,Lat2,Lon2);

LegDur = round((Dist/CommonSailingSpeed)/5,1)*5;

if LegDur == 0
LegDur = 0.5; %I.e. to sail between JOS-installations
end

LegDists(leg) = Dist; %Finds all leg distances

CurrTime = CurrTime + LegDur;
ArrTime(leg) = mod(CurrTime,24);

if InstNos(endIdx) == 1
ServTime = 0;

else

NextDeckDemand = ceil(DeckDemand(endIdx)/ReqFreq(endIdx));
NextBulkDemand = ceil(BulkDemand(endIdx)/ReqFreq(endIdx));

DeckCargo = DeckCargo + NextDeckDemand;
BulkCargo = BulkCargo + NextBulkDemand;

ServTimeDeck = round((NextDeckDemand/(CommonDeckUnitSize*CommonHeaveRateDeck))/5,1)*5;
ServTimeBulk = round((NextBulkDemand/CommonBulkRate)/5,1)*5;

ServTime = max(ServTimeDeck,ServTimeBulk);

end

if ArrTime(leg) <= 24 && ArrTime(leg) > CIHrs(endIdx) - ServTime || ArrTime(leg) < OpHrs(endIdx) -
AcceptableIdle
TW_sat(leg) = 0;
else
TW_sat(leg) = 1;

if ArrTime(leg) < OpHrs(endIdx)
ActualIdle = OpHrs(endIdx) - ArrTime(leg);

else
ActualIdle = 0;
end

if CIHrs(endIdx) == 24
TW_LegSlack(leg) = 24; %There are no time windows and hence no slack considerations to make

```

```

else
TW_LegSlack(leg) = ClHrs(endIdx) - ServTime - ArrTime(leg);

if TW_LegSlack(leg) > 12
TW_LegSlack(leg) = 12 - ServTime; %There can't be more than 12 hours of idling
%when the opening window at all installations is 12 hours.
end

end

end

CurrTime = CurrTime + ServTime + ActualIdle;

end

CapUtilDeck = DeckCargo/CommonDeckCapacity;
CapUtilBulk = BulkCargo/CommonBulkCapacity;

%Check if ALL feasible requirements are satisfied

if CapUtilDeck < 1 && CapUtilBulk < 1 && mean(TW_sat) == 1

rCount = rCount + 1;

RoutePool(rCount,1) = rCount;
RoutePool(rCount,2:1+length(RouteInProgress)) = RouteInProgress;
TW_SlackMat(rCount,1) = rCount;
TW_LegSlack(end) = []; %Does not need to know slack at the depot, deletes this array element
TW_SlackMat(rCount,2:1+length(TW_LegSlack)) = TW_LegSlack;
TW_LegSlack = [];

DeckSlack = CommonDeckCapacity-DeckCargo;
BulkSlack = CommonBulkCapacity-BulkCargo;

CargoSlack(rCount,1) = rCount;
CargoSlack(rCount,2:3) = [DeckSlack BulkSlack];

TotDur = CurrTime - CommonStartTime;
TotDist = sum(LegDists);

DurDistMat(rCount,1) = rCount;
DurDistMat(rCount,2:3) = [TotDur TotDist];

nInt = nInt - 1; %The current extension has been checked, nInt is reset
end

continue %Pass on to next iteration
else %Routes are extended as nInt < s

AvInsts = AvInsts(AvInsts~=RouteInProgress(1));
%All routes with >1 stops needs a second stop, selected from
%the set of available installations except the one already
%selected

for i = 1:length(AvInsts)

RouteInProgress(s) = AvInsts(i);
nInt = 2;

if nInt >= s %The if-statement from L195-L573 is similar to the statement in lines L94-L576

intLeg = RouteInProgress(1:2);
startLeg = intLeg(1);
zoneInd = find(InstNos==startLeg);
zone1 = InstZones(zoneInd);
endLeg = intLeg(2);
zoneInd = find(InstNos==endLeg);

```



```

zone2 = InstZones(zoneInd);

if ZoneTransitMatrix(zone1+2,zone2+2)==0
continue

else

if rCount == 41
Stop = 1;
end

FullRoute = [1 RouteInProgress 1];
CurrTime = CommonStartTime;
ArrTime = [];
DeckCargo = 0;
BulkCargo = 0;
TW_sat = []; %Time window satisfied array
TW_LegSlack = [];
MemberZones = []; %Initializes zone movements
for leg = 1:length(FullRoute)-1
startLeg = FullRoute(leg);
endLeg = FullRoute(leg+1);

startIdx = find(InstNos==startLeg);
endIdx = find(InstNos==endLeg);

Lat1 = Lats(startIdx);
Lon1 = Lons(startIdx);
Lat2 = Lats(endIdx);
Lon2 = Lons(endIdx);

Dist = LegDistCalculator(Lat1,Lon1,Lat2,Lon2);

LegDur = round((Dist/CommonSailingSpeed)/5,1)*5;

if LegDur == 0
LegDur = 0.5; %I.e. to sail between JOSnn-installations and other neighbours
end

LegDists(leg) = Dist;

CurrTime = CurrTime + LegDur;
ArrTime(leg) = mod(CurrTime,24);

if InstNos(endIdx) == 1
ServTime = 0;
else

NextDeckDemand = ceil(DeckDemand(endIdx)/ReqFreq(endIdx));
NextBulkDemand = ceil(BulkDemand(endIdx)/ReqFreq(endIdx));

DeckCargo = DeckCargo + NextDeckDemand;
BulkCargo = BulkCargo + NextBulkDemand;

ServTimeDeck = round((NextDeckDemand/(CommonDeckUnitSize*CommonHeaveRateDeck))/5,1)*5;
ServTimeBulk = round((NextBulkDemand/CommonBulkRate)/5,1)*5;

ServTime = max(ServTimeDeck,ServTimeBulk);

end

if ArrTime(leg) <= 24 && ArrTime(leg) > CIHrs(endIdx) - ServTime || ArrTime(leg) < OpHrs(endIdx)
TW_sat(leg) = 0;
else
TW_sat(leg) = 1;

if CIHrs(endIdx) == 24

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```

TW_LegSlack(leg) = 24;
else
TW_LegSlack(leg) = CIHrs(endIdx) - ServTime - ArrTime(leg);

if TW_LegSlack(leg) > 12
TW_LegSlack(leg) = 12 - ServTime;
end

end
end

CurrTime = CurrTime + ServTime;
end

CapUtilDeck = DeckCargo/CommonDeckCapacity;
CapUtilBulk = BulkCargo/CommonBulkCapacity;

%Check if ALL feasible requirements are satisfied

if sum(ismember(FullRoute,9)) == 0 && CapUtilDeck < 1 && CapUtilBulk < 1 && mean(TW_sat) == 1

rCount = rCount + 1;

RoutePool(rCount,1) = rCount;
RoutePool(rCount,2:1+length(RouteInProgress)) = RouteInProgress;

TW_LegSlack(end) = []; %Does not need to know slack at the depot
TW_SlackMat(rCount,1) = rCount;
TW_SlackMat(rCount,2:1+length(TW_LegSlack)) = TW_LegSlack;
TW_LegSlack = [];

DeckSlack = CommonDeckCapacity-DeckCargo;
BulkSlack = CommonBulkCapacity-BulkCargo;

CargoSlack(rCount,1) = rCount;
CargoSlack(rCount,2:3) = [DeckSlack BulkSlack];

TotDur = CurrTime - CommonStartTime;
TotDist = sum(LegDists);

DurDistMat(rCount,1) = rCount;
DurDistMat(rCount,2:3) = [TotDur TotDist];

nInt = nInt - 1;

if TotDur > 72 || min(TW_SlackMat(rCount,:)) <= 3.5
%Route is deleted if duration or time
%slack requirements are not met

RoutePool(rCount,:) = [];
TW_SlackMat(rCount,:) = [];
CargoSlack(rCount,:) = [];
DurDistMat(rCount,:) = [];
rCount = rCount - 1;
end
end

continue
end

else %If nInt is not equal to s yet, then continue extending routes

AvInstsReduced = AvInsts(AvInsts~=RouteInProgress(s));
nPoss = nchoosek(AvInstsReduced,s-2); %Creates the possible combinations of remaining routes, given the
number of stops yet to make on the route

```

```

nPossOrdered = [];
NewPoss = [];
for permChk = 1:size(nPoss,1) %Scan through all permutations
    subSet = nPoss(permChk,:);
    NewPoss = perms(subSet);
    nPossOrdered = [nPossOrdered;NewPoss]; %Adds all new combinations
    NewPoss = [];
end

nPossOrdered = sortrows(nPossOrdered,1); %Possible permutations are sorted based on the first extra stop

for combis = 1:size(nPossOrdered,1)
    IntStops = nPossOrdered(combis,:); %Selects systematically all permutations as the next sequence of
stops
    Trial = [RouteInProgress(1) IntStops RouteInProgress(s)]; %Creates a trial "full route" for feasibility
check

    MemberZones = [];
    nCrossings = 0;
    legAllowed = [];
    for leg = 1:length(Trial)-1

        intLeg = Trial(leg:leg+1);
        startLeg = intLeg(1);
        zoneInd = find(InstNos==startLeg);
        zone1 = InstZones(zoneInd);
        endLeg = intLeg(2);
        zoneInd = find(InstNos==endLeg);
        zone2 = InstZones(zoneInd);

        legAllowed(leg) = ZoneTransitMatrix(zone1+2,zone2+2); %Checks if the zone transit is allowed
according to zone transit matrix given as input

        if zone2 ~= zone1 && isempty(MemberZones) == 1
            MemberZones(1:2) = [zone1 zone2];
            nCrossings = nCrossings + 1; %Adds to the number of zone transits made
        elseif zone2==zone1 && isempty(MemberZones) == 0
            MemberZones(end+1) = zone2;
            nCrossings = nCrossings + 1; %Adds to the number of zone transits made
        end

    end

    if mean(legAllowed) < 1 %Checks if there are any crossings not allowed
        continue %Skips to next iteration (checks next combination)
    else

        if length(Trial) > size(RoutePool,2)-1
            RoutePool(:,end+1) = 0; %If this is the first route with an extra stop compared to previously made
routes, a new column must be added to the route pool
        end

        FullRoute = [1 Trial 1]; %The trial route is temporarily accepted as a full route

        CurrTime = CommonStartTime;
        ArrTime = [];
        DeckCargo = 0;
        BulkCargo = 0;
        TW_sat = []; %Time window satisfied array
        TW_LegSlack = [];
        for leg = 1:length(FullRoute)-1
            startLeg = FullRoute(leg);
            endLeg = FullRoute(leg+1);

            startIdx = find(InstNos==startLeg);
            endIdx = find(InstNos==endLeg);

```

```

Lat1 = Lats(startIdx);
Lon1 = Lons(startIdx);
Lat2 = Lats(endIdx);
Lon2 = Lons(endIdx);

Dist = LegDistCalculator(Lat1,Lon1,Lat2,Lon2);

LegDur = round((Dist/CommonSailingSpeed)/5,1)*5;

if LegDur == 0
LegDur = 0.5;    %I.e. to sail between JOS-installations
end

LegDists(leg) = Dist;

CurrTime = CurrTime + LegDur;
ArrTime(leg) = mod(CurrTime,24);

if InstNos(endIdx) == 1
ServTime = 0;
else

NextDeckDemand = ceil(DeckDemand(endIdx)/ReqFreq(endIdx));
NextBulkDemand = ceil(BulkDemand(endIdx)/ReqFreq(endIdx));

DeckCargo = DeckCargo + NextDeckDemand;
BulkCargo = BulkCargo + NextBulkDemand;

ServTimeDeck =
round((NextDeckDemand/(CommonDeckUnitSize*CommonHeaveRateDeck))/5,1)*5;
ServTimeBulk = round((NextBulkDemand/CommonBulkRate)/5,1)*5;

ServTime = max(ServTimeDeck,ServTimeBulk);

end

if ArrTime(leg) <= 24 && ArrTime(leg) > CIHrs(endIdx) - ServTime || ArrTime(leg) <
OpHrs(endIdx) - AcceptableIdle
TW_sat(leg) = 0;
else
TW_sat(leg) = 1;

if ArrTime(leg) < OpHrs(endIdx)
ActualIdle = OpHrs(endIdx) - ArrTime(leg);
else
ActualIdle = 0;
end

if CIHrs(endIdx) == 24
TW_LegSlack(leg) = 24;
else
TW_LegSlack(leg) = CIHrs(endIdx) - ServTime - ArrTime(leg);

if TW_LegSlack(leg) > 12
TW_LegSlack(leg) = 12 - ServTime;
end

end

end

CurrTime = CurrTime + ServTime + ActualIdle;

end

CapUtilDeck = DeckCargo/CommonDeckCapacity;

```

```

CapUtilBulk = BulkCargo/CommonBulkCapacity;

%Check if ALL feasible requirements are satisfied

if CapUtilDeck < 1 && CapUtilBulk < 1 && mean(TW_sat) == 1

%--- Procedure for removing dominated (longer)
%routes to the same subset of installations---
VisitExists = 0;

ChkMat = RoutePool(:,1:end);

n2sort = size(ChkMat,2)-1;
sortArray = 2:n2sort;

SortCheck = sortrows(ChkMat,sortArray);

while length(Trial) ~= size(SortCheck,2)-1
Trial(end+1) = 0;
end

SimilarRow = find(sum(ismember(SortCheck(:,2:end),Trial),2)>=length(Trial));

if isempty(SimilarRow) == 1

VisitExists = 0;
else
VisitExists = 1;
RowIdx = SimilarRow;

SimRoute = SortCheck(RowIdx,1);
%
end

%--- End of domination procedure part 1

rCount = rCount + 1;
RoutePool(rCount,1) = rCount;
RoutePool(rCount,2:1+length(Trial)) = Trial;

TW_LegSlack(end) = []; %Does not need to know slack at the depot
TW_SlackMat(rCount,1) = rCount;
TW_SlackMat(rCount,2:1+length(TW_LegSlack)) = TW_LegSlack;
TW_LegSlack = [];

DeckSlack = CommonDeckCapacity-DeckCargo;
BulkSlack = CommonBulkCapacity-BulkCargo;

CargoSlack(rCount,1) = rCount;
CargoSlack(rCount,2:3) = [DeckSlack BulkSlack];

TotDur = CurrTime - CommonStartTime;
TotDist = sum(LegDists);

DurDistMat(rCount,1) = rCount;
DurDistMat(rCount,2:3) = [TotDur TotDist];

if mod(rCount,500) == 0
fprintf('%d\n', rCount);
end

if TotDur > 72 || min(TW_SlackMat(rCount,:)) <= 3.5 || CargoSlack(rCount,2) >
0.6*CommonDeckCapacity || CargoSlack(rCount,3) > 0.75*CommonBulkCapacity

RoutePool(rCount,:) = [];
TW_SlackMat(rCount,:) = [];
CargoSlack(rCount,:) = [];

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DurDistMat(rCount,:) = [];
rCount = rCount - 1;
end

if VisitExists == 1

for chk = 1:length(SimRoute)
if DurDistMat(SimRoute(chk),3) < DurDistMat(rCount,3)
%Dominated (existing) routes are removed!
RoutePool(rCount,:) = [];
TW_SlackMat(rCount,:) = [];
CargoSlack(rCount,:) = [];
DurDistMat(rCount,:) = [];
rCount = rCount - 1;

else
%Non-dominated routes are added to the
%route pool
RoutePool(SimRoute(chk),2:end) = RoutePool(rCount,2:end);
TW_SlackMat(SimRoute(chk),2:end) = TW_SlackMat(rCount,2:end);
CargoSlack(SimRoute(chk),2:end) = CargoSlack(rCount,2:end);
DurDistMat(SimRoute(chk),2:end) = DurDistMat(rCount,2:end);
RoutePool(rCount,:) = [];
TW_SlackMat(rCount,:) = [];
CargoSlack(rCount,:) = [];
DurDistMat(rCount,:) = [];
rCount = rCount - 1;
end
end

end %if VisitExists == 1 - check whether sequence exists

end %Feasibility check for capacity and time slack

end %Feasibility check for transit between zones

end %For-loop for all possible permutations of routes

end %End of IF-statement on whether nInt > s when adding 3 and onwards

end %End of inner selection loop for available installations (more than one)
end %End of outer IF-statement for nInt > s after adding the FIRST stop
nInt = 0;
RouteInProgress = [];
AvInsts = InstNos(2:end); %Reset the list of available installations
end %End of outer selection loop for available installations (picks the FIRST stop)
end %End of for-loop for number of stops

end %End function

```

