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Optimal Hub-Solution for Remote Field Development in Arctic

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For

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Optimal Hub-Solution for Remote Field Development in the Arctic

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Background

There are great challenges regarding oil and gas production in remote areas. To develop an effective logistics chain for commodities to and from remote fields, a hub solution is suggested as an option in earlier studies. This solution can potentially result in great costs savings, increased safety of crew and ease the transport of people. The solution does also introduce great challenges regarding marine operation, planning and technical solutions.

Objective

In fall 2014, Knut Støwer and I studied the usage of a hub in the supply chain to remote field developments. We concluded that the usage of hub becomes more cost effective compared to a conventional solution a certain distance from shore, depending on number of installations.

The objective in this master thesis is to investigate technical solutions of a hub in the supply chain to offshore installations, and use an optimization model to analyze and compare the different solutions.

Scope of Work

The candidate is recommended to cover the points mentioned under:

1. Do a literature study of usage of hub vessels/solutions in maritime logistics chains.
2. Use relevant standards and regulations to develop technical solutions for a hub that is to be used in the arctic area.
3. Develop further the optimization model used in the project thesis to make it realistic for relevant technical solutions of hub.
4. Use optimization as a tool to compare different solutions. How the size and cargo handling systems onboard affect the solutions will be important to measure.
5. Implement the mathematical model into Xpress IVE.

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Preface

This Master Thesis finalize my studies at the Department of Marine Technology, Norwegian University of Science and Technology (NTNU). My specialization within Marine Technology is Marine Design and Logistics, with emphasis on optimization. The work has been carried out during the spring 2015.

The overall objective of this Master Thesis is to investigate technical solutions of a hub in the supply chain to offshore installations, and use an optimization model to analyze and compare the different solutions. The optimization model is a great tool to find the best overall design and solution of the logistics chain, and to analyze when a hub solution might be favorable compared to a conventional solution. The mathematical model is however not a very good decision tool for deciding detail designs in the chain, and suggestions to solutions presented are based on known technology and regulations rather than results from the model, while how parameters affects the logistics chains are analyzed with the model. The problem is inspired by the work Knut Støwer and I carried out in our Project Thesis, fall 2014. The objective of the Master Thesis is defined by me in cooperation with my supervisor Professor Stein Ove Erikstad.

Working on the Master Thesis has been an inspiring challenge where knowledge from my previous years of study has been necessary for a good result. I find marine optimization problems particularly rewarding because it combines several fields of study and require knowledge from both programming, mathematics and marine technology. (Nordbø, 2013) and (Akselsen, 2014) did two case studies where usage of hub-vessels in upstream logistics were analyzed and discussed. These papers has been important for my work, and by using the knowledge they provide I have tried to take it further and to give more general answers to how the hub solution should be designed, and when it might be a good solution compared to the conventional solution. I hope that the results and discussion in this thesis will be valuable for later research in the field.

During my work, I have learned how challenging it is to find errors in a programming code when you are working alone. I have experienced the challenges related to making an efficient solution method and usage of a mathematical model to analyze real life problems. Small errors in the model may result in wrong conclusions and solutions.

I will like to thank my supervisor Professor Stein Ove Erikstad for valued guidance through the work. I would also like to thank Knut Støwer for great contribution in programming the Matlab script and for great teamwork during the Project Thesis in fall 2014, which inspired me to write the Master Thesis in this subject.

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Abstract

This report present a new solution method to analyze usage of hub-vessels in upstream logistics for remote fields.

The objective in this thesis is to analyze which parameters that affect the logistics chain for remote fields in the Barents Sea. Usage of hub-vessels to centralize the flow, and hence take advantage of economies of scale are analyzed and compared to a conventional supply chain.

An initial supply problem in the Barents Sea is designed to be able to examine the logistical chain. Parameters in the problem, such as demand, capacity, speed of vessels and supply frequency at the installations are based on supply problems described in the literature. In conventional offshore supply problems, are commodities and special equipment transported directly from base to installations by usage of PSVs. In the hub-solution are two bigger vessels (hub-vessels) used to transport the supplies to a given location in the Barents Sea, where they connect to a buoy and function as a forward placed base. The two hub-vessels switch between functioning as a forward placed base and transporting supplies between base and hub-position.

The report presents a solution method where optimal solutions for numerous different test cases are obtained and compared. An optimization model finds optimal fleet composition for problems with and without hub-vessels, by minimizing the total cost. The planning period for all problems are two weeks, and it is assumed that the optimal schedules are repeated every two weeks. The mathematical model used in the analysis is inspired by the model presented in (Fagerholt, 2000). First, three to six installations are generated with random location inside an *installation matrix*. The initial *installation matrix* span from 15°E to 37°E and 71°N to 74°N. The installation matrix is moved 2°N (four times) after optimal solution for 50 problems are obtained and saved. The installations are generated with a given random seed in Matlab, to make it possible to compare and reproduce the results. Finally, the results are analyzed by plotting optimal solution for all cases against distance from shore.

Based on guidelines and results from the model will optimal position for hub-vessels approximately be 75% of the distance between base and installation-centroid. This will increase the range for helicopters transporting people to the offshore installations by approximately 50%, without violating current guidelines. It is recommended that the hub-vessels connect to an anchored buoy when serving as a forward placed base in the Barents Sea. This ensures quick and easy abandonment of position if needed due to drifting icebergs or bad weather.

For the initial cases with three to six installations, the hub-solution will represent a higher cost than the conventional solution, regardless of distance from shore. To supply a field with six installations located approximately 500 nautical miles from shore, a fleet with two hub-vessels and two PSVs is needed, or a fleet with four PSVs for direct shuttle between base and installations. Increased distance, demand, number of installations and frequency of visits decreases the cost difference between the two solutions. The cost of the two solutions are comparable for a hypothetical problem where the installations are visited seven times a week.

Analysis of the hub-solution shows that two-vessels are needed for all problems in addition to one, two or three PSVs, depending on the spread of the field and the number of installations.

The results show that the hub-solution is only cost efficient in a few special cases. Further analysis of all advantages and drawbacks including hub-vessels should be done. Detailed design considerations of the hub-vessels is needed to lower the uncertainty represented in the charter costs. This would be applicable for a case study, where demand and requirements are known.

Sammendrag

Målet for denne oppgaven er å analysere hvilke parametere som påvirker logistikkjeden til felt lokalisert langt fra land i Barentshavet. Bruk av store hub-fartøy for å sentralisere transport av varer mellom base og installasjoner, og dermed dra nytte av stordriftsfordeler er analysert og sammenlignet med en konvensjonell forsyningskjede hvor PSVer brukes hele veien fra base til installasjoner.

Et teoretisk forsyningsproblem i Barentshavet er definert som et utgangspunkt for videre analyser av problemet. Parameterne, som etterspørsel og antall besøk ved installasjonene, hastighet til fartøyene, kostnader og kapasitet er basert på tidligere forsyningsproblemer diskutert i relevant litteratur. I en konvensjonell løsning transporterer PSVer varer og utstyr direkte fra base til installasjonene, og returnerer overskuddsvarer og søppel tilbake til basen. For en løsning som tar i bruk hub-fartøy; vil disse skipene transportere varer mellom basen og en fast posisjon i Barentshavet, hvor de vil fungere som en base for PSVene. Minst to hub-fartøy er nødvendig, hvor de veksler på å fungerer som base og å seile tilbake til land for å levere søppel/overskuddsvarer og for å hente nye forsyninger.

Bruk av hub-fartøy i logistikkjeden er analysert systematisk, hvor optimal flåtesammensetning for en mengde teoretiske forsyningsproblemer er funnet og analysert. Optimeringsmodellen som beskriver problemet finner optimal flåtesammensetning for både hub-løsningen og konvensjonell løsning ved å minimere kostnad. Planleggingstiden for modellen er to uker. Denne relativt lange planleggingsperioden er valgt for å sikre økt fleksibilitet i rutene PSVene kan seile. Det er antatt at rutene blir gjentatt hver andre uke. Den matematiske modellen er inspirert av modellen presentert i (Fagerholt & Lindstad, 2000). Tre til seks installasjoner har blitt generert med tilfeldig lokasjon innenfor en *installasjonsmatrise* med koordinater 15°E til 37°E og 71°N til 74°N. *Installasjonsmatrisen* er flyttet 2°N (fire ganger) etter at optimal løsning for 50 problemer er funnet og lagret i en datamatrise. Gjentatte tilfeldige nummer som angir lokasjon av installasjoner er generert for å gjøre det mulig å sammenligne og gjenta resultatene. Resultatene er sammenlignet og analysert ved å plotte optimale kostnader (flåte sammensetning) for felt lokalisert fra 0 til 500 nautiske mil fra land.

Optimal plassering av hub-fartøyet når det fungerer som base i Barentshavet vil være ca. 75% av distansen *Base – installasjons-sentroiden.* Denne posisjonen vil øke rekkevidden til helikopter som frakter arbeidere til installasjonene med ca. 50% i forhold til hva som er mulig i dag, uten å bryte dagens retningslinjer. For å holde posisjonen når fartøyene fungerer som base, er anbefalt løsning å fortøye til en bøye som er fast forankret på denne posisjonen. Dette vil sikre rask frakopling i tilfelle flytende isfjell på kollisjonskurs eller dårlige værforhold skulle gjøre det nødvendig.

For et forsyningsproblem med tre til seks installasjoner vil hub-løsningen være en dyrere løsning enn en konvensjonell løsning hvor bare PSVer er brukt. For et felt med seks installasjoner lokalisert i gjennomsnitt 500 nautiske mil fra land vil to hub-fartøy og to PSVer eller fire PSVer og ingen hub-fartøy være nødvendig. Økt etterspørsel, økt distanse, hyppigere

besøk ved installasjoner og felt med mange installasjoner favorierer hub-løsningen i forhold til den konvensjonelle. For et problem hvor installasjonene krever besøk hver dag, vil kostnadene for de to løsningene være sammenlignbare for felt lengre enn 400 nautiske mil fra land. For alle problem analysert er to hub-fartøy nødvendig i tillegg til en, to eller tre PSVer avhengig av distanse fra land og antall installasjoner.

Resultatene viser at en hub-løsning bare vil være lønnsom i veldig spesielle tilfeller. Løsningen introduserer flere fordeler og avhenger av flere kostnader enn de som er inkludert i modellen presentert her, så videre analyser er nødvendig for å konkludere hvilke løsning som er best for felt lengst til havs. En høy grad av usikkerhet er tilknyttet til kostnadene brukt i modellen, så variasjon i relativ kostnad mellom hub-fartøy og PSV vil påvirke resultatene.

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Abbreviations

CALM	Catenary Anchor Leg Mooring
CAPEX	Capital Expenditures
FLP	Facility Location Problem
FSMVRP	Fleet Size and Mixed Vehicle Routing Problem
DP	Dynamic Positioning
H&S	Hub & Spoke
IP	Integer programming
MDO	Marine Diesel Oil
MILP	Mixed Integer Linear Programming
MIP	Mixed Integer Programming
nm	Nautical Miles
OPEX	Operating Expenditures
OR	Operation Research
PSV	Platform Supply Vessel
SAR	Search and Rescue
SWOT	Strength, Weaknesses, Opportunities, Threats
TSP	Traveler Salesman Problem
UTM	Universal Transverse Mercator
VRP	Vehicle Routing Problem

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1 Introduction

This chapter is an introduction of the following work and gives the reader a basic understanding of the problem. Some background knowledge about Arctic, optimization and the methods used in this master thesis are introduced here.

1.1 Oil and Gas production in the Barents Sea

The Arctic region is expected to become an important oil and gas province with its huge undiscovered oil and gas reserves. According to (Earnst&Young, 2013) and (Ørbech-Nilssen, 2012) the arctic region might account for as much as 20% of the world's undiscovered recoverable oil and gas resources. The likelihood for oil and gas reserves in the Arctic has been known for decades, and in the Barents Sea alone; 100 exploration wells are drilled since 1980 (Norwegian Petroleum Directorate, 2013). Even with promising discoveries early in the 1980s, many years passed without any field developments. Snøhvit, as the first gas field developed in the Barents Sea, started production in 2007, 24 years after discovery (Statoil, 2007). The Goliat Field Development, new promising oil and gas discoveries such as Gohta (Lundin) and Johan Castberg (Statoil) and new exploration areas has increased the interest of the Barents Sea in the resent years (Qvale & Andersen, 2014).

There are many reasons for the delay between discoveries and field developments in the Barents Sea. One of the reasons was the disagreement between Norway and Russia of how to divide the Barents Sea east region. First in 2010, after many years of negotiations, they agreed to a boundary in the middle of earlier claims from Russia and Norway (Bakken, 2010). This agreement was important for both the fisheries[1], shipping and the oil and gas companies. Another important reason for the late development has been the lack of knowledge and technology related to offshore Arctic Oil and Gas development. As areas further north in the Barents Sea are opened for exploration, challenges regarding the harsh environment and remote locations becomes important to solve. This thesis discusses the usage of hub-vessels in the upstream logistics chain for remote fields in the Barents Sea.

1.2 Usage of Hub-vessels in Upstream Logistics for Remote Fields

(Alumur & Kara, 2008) describes hubs as special facilities, used in a distribution system to concentrate flow between origin and hub. Instead of serving each destinations directly from the origin, the destinations are served from a hub located closer to the destinations than the origin. To concentrate the flow, bigger hub-vessels are used between origin and hub in order to take advantage of economies of scale (Alumur & Kara, 2008). A hub-vessel in this thesis refers to a bigger vessel than a conventional PSV, capable of transporting the same type of commodities. The hub-vessels sail to and from an onshore base and an optimal position in the Barents Sea,

[1] The cod stock in Barents Sea is the biggest in the world, and has been important for both Norway and Russia

where they connect to a buoy and function as a forward placed base for the PSVs. When a hub-vessel is out of required commodities, it returns from its position in the Barents Sea and ideally a fully loaded hub-vessel arrives at the same position ready to serve the PSVs. Parameters affecting the hub location include location of the installations, cost, safety aspects and issues related to helicopter transport to and from the installations. To ensure a steady flow of commodities to the installations, at least two hub-vessels are needed in the logistics chain. If total demand exceed the capacity of these vessels, bigger or more vessels are needed. PSVs transport the supplies from the hub-vessels to the installations and return backload. Figure 1 illustrates the important differences between a hub-solution and a conventional platform supply chain.

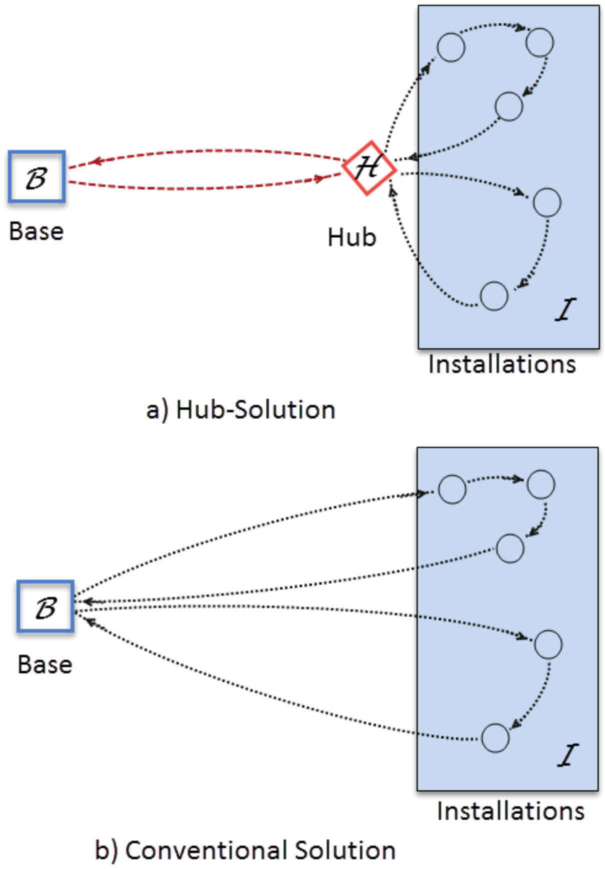

Figure 1 - Illustration of the setup with base, hub position and installations. The top figure shows the scenario with a hub as an intermediary. The bottom figure shows a conventional scenario, where there is no hub in place. Arcs between base, hub and nodes are there to show possible routes and do not show a complete set of routes.

In fall 2014, Knut Støwer and I wrote our Project Thesis about usage of hub in upstream logistics[2] for oil and gas installations. The focus in the project thesis was to analyze when a hub

[2] The logistics of commodities to and from installations is called upstream logistics, while oil and gas flow from installations is called downstream logistics in the literature.

solution becomes economically favorable compared to a conventional solution. The results showed that a hub could be cost effective when the installations are located far from shore. The distance from shore, where the hub-solution became economical favorable depended on the field's distance from shore. The work in this thesis mentions several mistakes done in the project thesis, and it aims to present a more precise and correct analysis of the hub-solution.

(INTSOK Norwegian Oil & Gas Partners, 2014) suggest forward placed supply hub facilities close to field operations as a solution to support offshore oil and gas operations in the Barents Sea. The report describes the solution as promising, but state that little research of the concept exists. For remote fields without close infrastructure, a hub vessel might give basic medical services, serve as a first line support facility in case of oil recovery and/or refill station for helicopters transporting people to and from the installations. These functions are examples of additional possibilities usage of hub-vessels represent. To analyze the feasibility of a hub-solution in the upstream chain for remote field developments; Operational Research is used as a decision tool to develop the best design of the upstream logistics chain. Known technology and regulations are used to discuss different aspects of the problem that the mathematical model fail to measure.

1.3 Optimization as a Decision Support Tool

The amount of research related to optimization of maritime logistics chains about doubles every decade (Christiansen, Fagerholt, Nygreen, & Ronen, 2013). A driving force for the research in the recent years has been high charter costs and/or high bunker price, which tighten the margins for the companies. Optimization of the companies' available resources are therefore crucial to survival in a competitive market. The cost of chartering and operating a PSV is one of the largest costs in the logistics chain for supply of offshore installations. Maximizing the utilization of the vessels is therefore an important objective for the oil companies (Aas, Halskau Sr, & Wallace, 2009). (Fagerholt & Lindstad, 2000) and (Halvorsen-Weare, Fagerholt, Nonås, & Asbjørnslett, 2012) present two mathematical models for optimization of two real maritime transportation problems faced by Statoil. Both studies resulted in great cost savings, and are good examples of how OR can be utilized to reduce costs in an upstream chain.

The mathematical model presented in chapter 6 is a modification of the model first presented in (Fagerholt & Lindstad, 2000) and later reused by (Nordbø, 2013) and (Akselsen, 2014). The model has earlier been used to analyze several well-defined problems with location of installations predefined. In this thesis, the model is used to analyze numerous cases, with installations randomly generated inside a predefined area. Cases with different parameters, such as number of installations, demand, service frequency, spread and distances are analyzed to obtain the best design of the hub solution, and to give an answer to when a hub solution might be cost effective compared to the conventional solution. The same random seed is used when parameters are changed to be able to compare the results and to see how different parameters affect the results. This way, the optimization model is used as a decision- and design-tool to analyze when and how a hub solution should be used, rather than to find the optimal solution for a well-defined problem. To be able to analyze enough cases, the solution time must be kept low, and a simple and precise model is necessary.

Optimization Studies of the hub location problem often assume three things: that there is a link between all hub pairs, economies of scale is incorporated with a factor α in the model, and that no direct shuttle between two non-hub nodes are allowed (Alumur & Kara, 2008). In the model discussed in this thesis, service between two non-hub nodes (installations) are allowed, but not between installations and land base. The α-factor is not incorporated directly in the mathematical model, but the cost per ton cargo is lower for the hub-vessel than for a PSV. How this affect the total cost is analyzed in chapter 8.

1.4 Objective and Scope of Work

The main focus in this Master Thesis is to use optimization as a decision tool to analyze the best design of an upstream logistics chain with hub. A goal is to investigate whether a hub solution is a possible and cost efficient solution for remote offshore fields. The mathematical model is not used as foreseen in the start of semester, because the model does not measure small changes in design. Instead of measuring details in the logistics chain, is an effective solution method developed and implemented into Matlab/Xpress IVE for structured and valuable analysis of the overall design of the chain. The scope of work includes the following:

1. Do a literature study of usage of hub vessels/solutions in maritime logistics chains.
2. Use relevant standards and regulations to develop technical solutions for a hub that is to be used in the arctic area.
3. Develop further the optimization model used in the project thesis to make it realistic for relevant technical solutions of hub.
4. Use optimization as a tool to compare different solutions. How the size and cargo handling systems onboard affect the solutions will be important to measure.
5. Implement the mathematical model into Xpress IVE.

Optimization is used to compare the conventional solution and the hub solution. It is however not feasible to use the model to analyze how the size and cargo handling systems onboard affect the solutions. Different solutions for cargo handling will require different amount of time, which is possible to add or subtract from the routes generated. These differences are however small, compared to route durations and the uncertainty represented in the different aspects of the problem, and hence not measurable in the model. Measuring detail design will be more interesting for a case study, where certain parameters are known.

1.5 Maneuvering through the Report

The rest of the report is organized as follows: In chapter 2 important literature is summarized and discussed. Chapter 3 describes the supply problem, and introduce modeling assumptions. Chapter 4 gives the reader a better understanding of the actuality of the problem and the technological challenges related to operation in the Barents Sea. In chapter 5 the solution method is described. Chapter 6 presents and describes the mathematical model. In chapter 7, suggestions to design and important considerations are discussed. Analysis and results are presented in chapter 8. A discussion of the results are given in chapter 9. Chapter 10 concludes the thesis, while suggestions of further work are given in chapter 0.

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2 Literature Review – State of the Art

This chapter describes and discusses the most relevant and important literature for the research in this thesis. The articles and research are found through search in the library, books, search on the internet and from earlier courses at NTNU.

The optimization model used to analyze the hub solution has similarities to two well-studied optimization problems; the Vehicle Routing Problem (VRP) and the Facility Location Problem (FLP). A supply vessel problem is in many ways more complex than a traditional VRP. The planning horizon is typical over several days, installations may be visited more than one time during the planning horizon and a vessel can sail different routes as long as it is within the time limits. An extension of the VRP is the fleet size and mix vehicle routing problem (FSMVRP). In a FSMVRP; the optimization model simultaneously finds best composition of a heterogeneous fleet and the most cost efficient schedules for the fleet. In an offshore supply problem, PSVs with different size and cost are available, and the problem is therefore often described as a FSMVRP.

Usage of hub vessels in upstream logistics for remote oil and gas fields has been described in the literature as a promising solution, but to the author's knowledge never been used as a commercial solution. Two case studies where usage of hub-vessels in the upstream logistics chain has been analyzed, have concluded that the solution is not cost efficient for those cases. To understand the usage of hub facilities and how they are implemented in mathematical models, a literature review of hub and spoke problems is discussed in this chapter. Hub and Spoke networks (H&S-networks) are used in both shipping, telecommunication and in the airline industry. The main benefit of the usage of hub facilities is to take advantage of economies of scale.

The rest of this chapter is organized as follows; In subchapter 2.1 vehicle routing problem and maritime fleet size and mix vehicle routing problem is discussed. 2.2 present the Location-Routing problem. 2.3 review papers where hub is discussed and used in logistics chains. 2.4 mentions important research related to the High North, and petroleum development in Norway.

2.1 VRP and The Maritime Fleet Size and Mix Vehicle Routing Problem

In the classical VRP is the objective to determine a set of routes for a set of vehicles. Demand from customers must be fulfilled without violating the cargo capacity of the vehicles (Lundgren, Rönnqvist, & Värbrand, 2010). To understand the mathematical model presented in this thesis, is it of great help to study the classical VRP. The basic theory is the same for the VRP as for the extended Maritime FSMVRP. It is therefore helpful to examine the VRP first. Figure 2 shows an illustration of a traditional VRP where three routes (vehicles) serve eleven customers from the same depot.

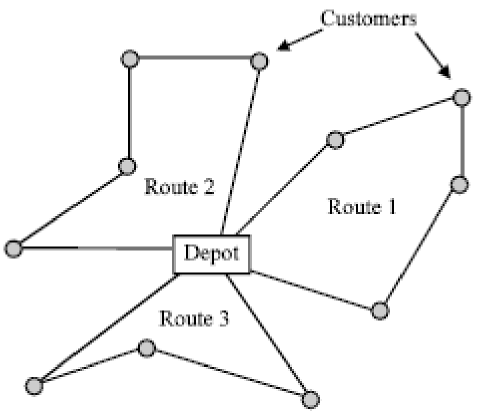

Figure 2 - Illustration of a VRP (Ghoseiri & Ghannadpour, 2009)

(Lundgren et al., 2010) suggest equation 2.1 as an objective function for a VRP, where K is the set of vehicles and N is the set of nodes in the problem.

$$\min z = \sum_{k \in K} \sum_{i \in N} \sum_{j \in N, j \neq i} c_{ij} x_{ijk} \tag{2.1}$$

Where c_{ij} is the cost of traveling from node i to node j. x_{ijk} is one if vehicle k travels between node i and node j, and zero elsewise.

This formulation includes demand - and vehicle allocation constraints in addition to sub-tour eliminations. This model creates the routes in the process to find the optimal solution. A problem including many customers has a large number of constraints because of the sub-tour elimination, which must be formulated for a very large subset S.

An alternative formulation, which is used in most maritime problems, is the set partitioning model. This model is a two-step approach of the optimization problem. First, all possible routes are generated, and the optimal solution is found by choosing the cheapest route-combination that does not invalidate the constraints. (Lundgren et al., 2010) suggest equation 2.2 as an objective function for a VRP formulated as a set-partitioning problem. J is the set of all feasible routes, and N is the set of customers. In this model, the sub-tour elimination happens in phase one (route generation).

$$\min z = \sum_{j \in N} c_j x_j \tag{2.2}$$

Where c_j is the cost of route j. x_j is one if route j is used and zero elsewise.

The FSMVRP is an extended VRP often solved as a set-partitioning problem. An early reference to the FSMVRP is (Golden, Assad, Levy, & Gheysens, 1984). The focus in their paper is the mathematical model and heuristics to solve it. A FSMVRP has often many restrictions regarding opening hours, vessel-capacity and more. Routes that invalidate a constraint will in some set-partitioning models not be created in the route-generation phase. This will reduce the number of variables in the problem solved in phase two, and it becomes easier to solve for an optimization software.

(Fagerholt & Lindstad, 2000) present a mathematical problem for a supply vessel problem faced by Statoil. The problem is a FSMVRP, where feasible routes are generated and used as an input to an integer-programming (IP) model. The supply vessel problem discussed in the paper include a land-base outside the North West coast of Norway, and seven offshore installations located in the Norwegian Sea. (Fagerholt & Lindstad, 2000) categorizes the cargo into six categories, and argues that deck capacity is the binding constraints. In the problem discussed; a vessel in the available pool[3] can sail more than one route in the planning period. (Fagerholt & Lindstad, 2000) present the following objective function for the supply vessel problem:

$$\min M \sum_{k \in K} C^k \delta^k + m \sum_{k \in K} \sum_{r \in R_k} D_r^k x_r^k \tag{2.3}$$

Where C^k is the cost of chartering the vessel k, δ^k is one if vessel k is used and zero otherwise. D_r^k is the duration of schedule r for ship k, and x_r^k is one if vessel k sails schedule r. M and m is a big and a small number.

This model “prioritize” to find the optimal fleet because charter costs represent the biggest cost in the problem. When optimal fleet is found, the model finds the schedules that is most efficient. Restrictions regarding demand, number of visits etc. is included in the model. Part two of the mathematical model presented in chapter 6 in this thesis is based on the model presented by (Fagerholt & Lindstad, 2000).

The authors in (Halvorsen-Weare et al., 2012) also solve a supply problem faces by Statoil. The authors suggest a solution that also include capacity constraints for the onshore supply depot, maximum and minimum duration of voyages and spread of departures. Constraints like this are important in real-life problems, but knowledge of depot and installations are necessary, and therefore not applicable in the problem studied in this thesis.

[3] A pool of vessels defines the vessel which is available at a given cost

2.2 The Location-Routing Problem

A location-routing problem (LRP) is a VRP where optimal routes and depot position must be found simultaneously (Laporte, Nobert, & Taillefer, 1988). The location of hub and base are defined as variables in the mathematical model presented in this thesis, and the model has therefore similarities to a LRP.

In a case study, the exact position for a hub and base will be highly interesting, and important to find, but for the research in this thesis, the most optimal hub location is assumed to be 75% of the distance between land base and installations centroid. This distance is based on results from the project thesis and guidelines for helicopter transport. Keeping the solution time for the model low has been highly important for the solution method presented in this thesis, and it is therefore beneficial to define only one hub (and base) location.

2.3 Usage of Hub in Logistics Chains

(Nordbø, 2013) and (Akselsen, 2014) are studying the usage of hub in upstream logistics for oil&gas – fields in their Master theses. They are using a modified version of the mathematical model presented in (Fagerholt & Lindstad, 2000). (Nordbø, 2013) aims to optimize the upstream chain for a potential field development outside Jan Mayen. The installations are served from the land base in Kristiansund, located in the western part of Norway (577 nm away from Jan Mayen). (Nordbø, 2013) concludes that usage of hub in upstream logistics is an interesting concept that might reduce the total cost, but further research is necessary. (Akselsen, 2014) studied the usage of hub in a logistics chain with three installations located in the Barents Sea. Her main objective was to find an optimal location of Statoil's supply base serving the three installations. Usage of hub in the supply chain was not found profitable in her case study.

To optimize the liner shipping between Asia and Europe, models for hub and spoke networks[4] in shipping has been developed and discussed in numerous of studies. (O'Kelly, 1987) proposed the first recognized mathematical formulation of the H&S - network. He presented a quadratic integer-programming problem. The objective in (O'Kelly, 1987) is to site 2,3 and 4 hubs to serve interactions between sets of 10, 15, 20 and 25 U.S cities at lowest cost. The objective to most H&S-problems is to find the best hub location(s) in a logistics chain or in telecommunication. The problems have therefore similarities to the well-studied Facility Location Problem (FLP), which is explained in chapter 2.2. Optimization Studies of the hub location problem often assume three things: that there is a link between all hub pairs, economies of scale is incorporated with an factor α in the model, and that no direct shuttle between two non-hub nodes are allowed (Alumur & Kara, 2008).

(Zheng, Meng, & Sun, 2014) present a mathematical model for the trade between Asia and Europe. The paper's focus is sabotage legislation, but it presents important aspects with a hub and spoke network. The mathematical models for H&S-networks in the papers reviewed, is

[4] In the literature hub and spoke networks refer to networks with several smaller vehicles(spokes) operating individually and pool their assets together to contribute to one bigger vehicle (hub).

significantly more detailed than the model presented in this thesis, but they provide helpful understanding of the benefits related to hubs. All papers emphasis the importance of the economies of scale effect related to hub facilities. The transportation cost between hub facilities is multiplied with a discount factor $\alpha, 0 \leq \alpha \leq 1$, representing the effect of economies of scale in the mathematical models. (Gelareh & Nickel, 2011) uses an α-factor between 0.6 and 0.9 to represent the cost savings in a hub location problem tailored for urban transport and liner shipping. According to (Alumur & Kara, 2008) is the discount factor α heavily affected by number and location of the hub(s). Most hub location problems assumes that this discount factor is not dependent on the amount of flow, which according to (O'Kelly, 1998) may result in miscalculated flows, and may erroneously result in selection of wrong hub location and allocations. They suggest a non-linear cost function, which decrease as flows increase. (Kimms, 2006) argue that economies of scale can occur on all kinds of connections, and that bigger flow always give cheaper transportation cost per unit. The α – factor is not incorporated directly in the mathematical model used in this thesis, but transportation cost per unit is lower for the hub-vessels than for the PSVs.

For more studies of H&S-networks, please refer to the review paper by (Alumur & Kara, 2008) and to (Campbell & O'Kelly, 2012) which reflect on the origins of the hub location research, and commentates on the present status in the field.

2.4 Arctic Oil and Gas

To get a better understanding of the Arctic challenges and the problems faced in the High North, research related to oil and gas development in the Arctic region has been reviewed and discussed. The literature reviewed in this chapter focus on the importance of development of new safe technology and/or the importance of cooperation between the countries with jurisdictional claims in the Arctic Ocean – namely Norway, Russia, Canada, Denmark/Greenland, Iceland and the United States (Earnst&Young, 2013).

The harsh environment in the Barents Sea is a huge challenge for both marine operations and design of vessels and equipment that needs to function regardless weather and conditions. To ensure safe marine operations; petroleum - and natural gas - structures operating in arctic has to be designed according to EN ISO 19906:2010. The standard is established by The European Committee for Standardization.

INTSOK Norwegian Oil and Gas Partners has established a project "The Russian – Norwegian oil and gas industry cooperation in the High North" (RU-NO Barents Project), which focus on the importance of a good cooperation between Norway and Russia to be able to develop the Barents Sea in a safe and efficient way. The project promote stronger industrial links between the two countries. It also analyze existing technologies, methods and best practice Russian - and Norwegian industry can offer the High North. The RU-NO Project mentions five major areas that are crucial for offshore oil and gas development in the High North. The five areas mentioned are *logistics and transport*, *drilling*, *well operations and equipment*, *environmental protection*, *pipelines and subsea* and *floating and fixed installations*. The most important publication for the problem discussed in this thesis has been the Logistics and Transport report by INTSOK (INTSOK Norwegian Oil & Gas Partners, 2014). The report suggest hub solution as a potential and promising solution in upstream logistics, but emphasizes the need of more research. (INTSOK Norwegian Oil & Gas Partners, 2014) suggestion regarding to hub location is:

"It is recommended that forward supply bases, for instance multipurpose floaters functioning as storage facilities and helicopter landing sites, are established close to field operations in order to secure operational efficiency and security."

(INTSOK Norwegian Oil & Gas Partners, 2014) emphasizes especially the issue of the associated high costs of offshore development as important when solutions are discussed and developed. High costs represent a significant barrier for development. The conditions in the High North are extreme, and challenges regarding icing on vessels, remoteness, darkness, Sea ice, polar lows and fog are important to consider for safe operations. The report points out lack of long term met ocean - and ice data as a concern for development in arctic, and it should therefore be a prioritized task to collide such data.

(Earnst&Young, 2013) emphasizes the importance of developing large oil and gas fields to make the remote fields economical sustainable. A field development in the High North will be expensive, and the companies depend on high incomes from the fields. Another challenge for the Arctic Area is that the region is largely composed of natural gas, which is significantly more expensive to transport over long distances than oil (Budzik, 2009). The estimation to U.S Geological Survey of the undiscovered Oil and Gas north of the Arctic Circle is shown in Appendix H. The estimation of total resources of Barents Platform and Norwegian Margin are reprinted in Table 1.

Table 1 - Estimated Undiscovered Technically Recoverable Oil and Gas Resources in some Arctic areas (Budzik, 2009)

USGS Petroleum Province Name	Crude Oil (billion barrels)	Natural Gas (trillion cubic feet)	Natural Gas Liquids 1/ (billion barrels)	Total Resources, Oil Equivalent 2/ (billion barrels)
Barents Platform	2.06	26.22	0.28	**6.70**
East Barents Basin	7.41	317.56	1.42	**61.76**
Sverdrup Basin	0.85	8.6	0.19	**2.48**
Norwegian Margin	1.44	32.28	0.50	**7.32**
Norwegian Margin	1.44	32.28	0.50	**7.32**

3 Problem Description and Modeling Assumptions

There are great challenges regarding oil and gas production in remote areas. To develop an effective logistics chain for commodities to and from remote fields, usage of hub is discussed and analyzed. This solution can potentially result in great costs savings, increased safety of crew and ease the transport of people. The solution does also introduce great challenges regarding technical solutions, and operational/planning problems. Operational Research (OR) is used to analyze the hub solution, and to compare it with a conventional solution. The objective of the optimization model presented in chapter 6 is to minimize cost, which is one of many important aspects to consider in a supply problem. Important considerations, such as best hub position and positioning system, is discussed in Chapter 7. Additional benefits and disadvantages related to usage of hub is given in a SWOT-analysis in appendix A.

Figure 3 illustrates the hub and installations in the Barents Sea. (INTSOK Norwegian Oil & Gas Partners, 2014) concludes that a hub is an interesting and possible solution for remote fields in the High North, but further research is necessary to evaluate the solution. In the following subchapters, the different parts in the upstream logistics chain is explained, together with assumptions in the mathematical model.

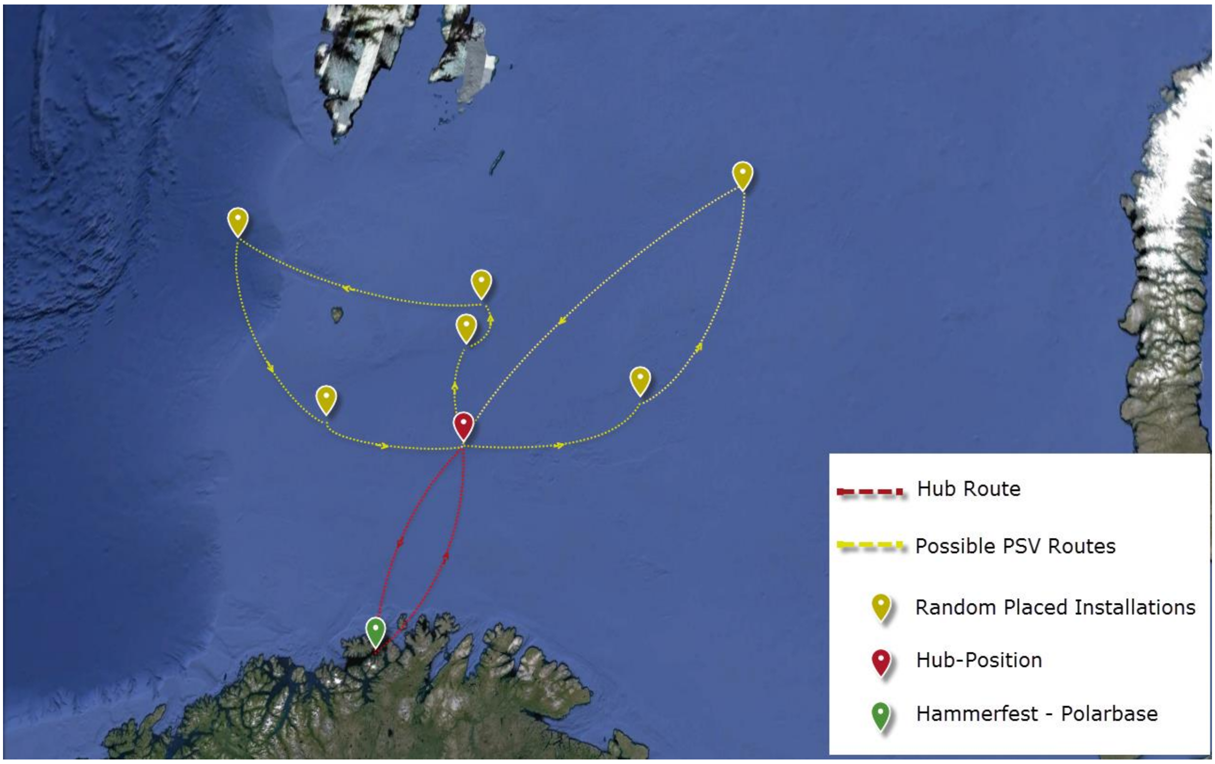

Figure 3 - Illustration of how a hub-solution in the Barents Sea might look like. (Source: Google earth)

3.1 Supply Base

Commodities needed offshore are transported to a supply base and loaded onboard supply-vessels at the base's quay. An onshore supply base typically supplies several fields located nearby. Supply bases are usually designed to handle normal sized PSVs, and it might therefore be an extra cost related to expand the quay for hub-vessels. This extra cost is not accounted for in the optimization model. The possibilities and cost of expanding the base will however be interesting to examine for a case study where usage of hub-vessels are analyzed.

Hammerfest is chosen as the base location in the problem discussed in this thesis. Position and coordinates are given in Figure 3 and Table 2 (travelmath, 2015).

Table 2 - Latitude and longitude of Hammerfest, Norway

	UTM	Geographic Coordinates
Latitude	70°39'42' N	70.7
Longitude	23°41'17' E	23.7

Hammerfest include both the supply base Polarbase and the LNG plant on Melkøya, and is hence the most important port for petroleum activities in Northern Norway (INTSOK Norwegian Oil & Gas Partners, 2014). Polarbase and the port in Kirkenes has plans to expand their ports, which makes both ports future candidates for a land-base serving the fields in the Barents Sea. Sarnes Fjord in Honningsvåg is an important port for rescue operations, and a port used by vessel waiting on weather window. Sarnes Fjord is also selected by Statoil as the most likely location for a shore based oil terminal for Johan Castberg field (INTSOK Norwegian Oil & Gas Partners, 2014). The location of base is important to determine for generation of routes in the model. It is however, the distance *base-hub* and *base-installations* that is important in the analysis.

Cost for cargo handling and loading in base is included in the model. This cost does not influence the choice of optimal fleet composition, but is included since it is an important cost to consider in an upstream logistics chain. Relevant data and assumptions for the base in the model is given in Table 3.

Table 3 - Data for base in the problem

Cost for handling cargo in base [NOK/ton]	1000
Opening hours	24/7

3.2 Hub-Vessel

The hub vessel is a bigger vessel than a normal PSV, which transport the commodities from an onshore base towards the installations offshore. In an optimal distance from shore, the hub-vessel will hold its position by connecting to an anchored buoy. From here, it will work as an offshore storage unit, supplying the PSVs with commodities for the offshore installations. When the hub-vessel is empty, it return to shore for delivery of waste, and another hub-vessel arrives to serve as an offshore storage unit. To make sure that one hub vessel always is stationed on the given offshore position; at least two hub-vessels are needed. If the total demand from the installations exceed the capacity of two hub-vessels, extra vessel(s) is/are added to the model. A hub vessel can sail more than one trip per period as long as it does not violate the feasible sailing durations. The mathematical model does only allow complete roundtrips in the time-period.

The vessels must be able to carry the same type of supplies as a traditional PSV, but needs to be significantly bigger to take advantage of economies of scale. The vessel must also be equipped with suitable cranes and systems to load and offload supplies to and from a PSV offshore. The opening hours for the hub-vessels are assumed to be 24/7.

The α-factor (ref. ch.2.3) in this problem is 0.56. This is a relatively small value compared to hub-problems discussed in the literature. A PSV is a specialized cargo vessel, with expensive systems onboard. A hub-vessel might be a simpler vessel, which means a low α-factor may be correct.

Historical data shows that the deck capacity is the binding capacity resource for supply vessels (Halvorsen-Weare et al., 2012). The capacity used in this problem is inspired by real numbers provided by Statoil in (Akselsen, 2014). (Akselsen, 2014)does not comment further the data used, and the focus in this thesis is therefore the relative data rather than the actual numbers. These numbers will also be important when comparing other logistics chains with the one analyzed in this thesis. The Hub-capacity, the capacity-hub/capacity-PSV ratio and Capacity-hub/Installation-demand per week ratio are given in Table 4.

Table 4 - Capacity data for the hub-vessels

Charter cost per year [NOK]	120 000 000
Speed [knot]	10
Capacity [ton]	1200
Capacity-Hub/Capacity-PSV Ratio	$\frac{1200}{450} = 2.67$
Capacity-hub/Installation-demand per week ratio	$\frac{1200}{230} = 5.22$

The position of the hub is chosen to be 75% of the distance between land-base and the centroid to the installations. The coordinates ($\overline{lat}, \overline{lon}$) to the centroid is given by weighting the values of the latitude and longitude to each installation i equally over the installations N, and finding the mean with equation 3.1.

$$\overline{lat} = \frac{a}{|N|} \sum_{i \in N} lat_i \tag{3.1a}$$

$$\overline{lon} = \frac{1}{|N|} \sum_{i \in N} lon_i \tag{3.1b}$$

The results from Knut Støwer's and my Project Thesis showed that a hub location 75% or 100% of the distance out to the installation-centroid are more cost efficient than a location 50% of the distance. As discussed in chapter 8, there are significant uncertainties regarding these results, but locating the hub 75% of the distance to the centroid introduce other benefits that is worth considering when using a hub. This position of the hub-vessel is illustrated in Figure 4. This position makes it possible for the hub to function as a refilling station for transport helicopters. A different hub-location or no hub at all will reduce the helicopter-capacity over long distances (ref ch. 7.1).

The usage of a hub-vessel in the logistics chain will first be of interest from an economical perspective when the cost of operating the hub vessels are lower than using a bigger number of PSVs on the same distance. When decide whether to use a hub in the upstream logistics or use the PSVs the whole way from base to installations, other benefits and concerns related to the two solution should be considered together with the cost. Possible savings for helicopter transport and safety advantages related to usage of hub are interesting to investigate further. For the problem in this thesis, the mathematical model only consider the charter costs for hub-vessels and PSVs, and will therefore not alone give an answer to whether a hub solution is the best choice or not. The SWOT-analysis in Appendix A focuses on different aspects of the hub solution.

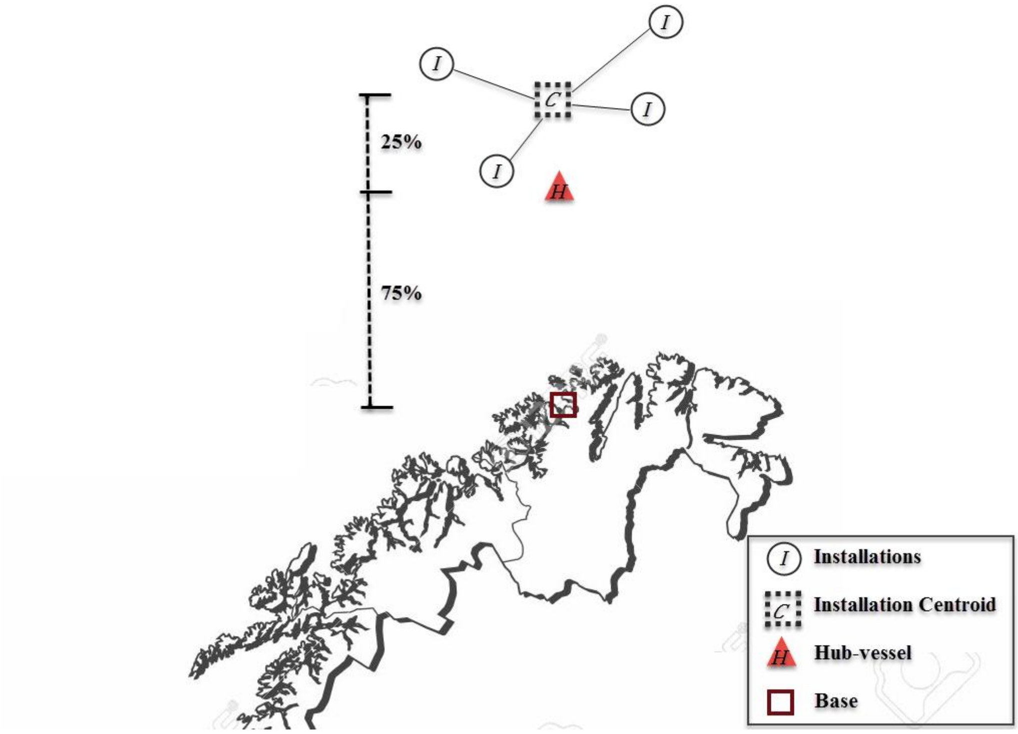

Figure 4 - Position of hub in the Barents Sea. Background map from (Hammer, 2015)

3.3 Platform Supply Vessel

A PSV is a special purpose vessel that is used to transport commodities to offshore installations and return waste back to shore. The PSVs are designed to bring all goods that is required for daily operation of the platforms. Figure 5 shows a general arrangement of a PSV, to illustrate the shape and cargo capabilities for a typical PSV. As seen from the figure, the PSV has a large stern deck area, where general cargo paced in containers or similar are placed. Under main deck, the vessel has multiple tanks to carry different types of bulk and liquefied cargo.

PSVs are usually chartered from offshore ship-owners, rather than owned by the oil companies. The charter cost depends upon many factors, such as length of charter contract, vessel capacity, availability of PSVs on the market etc. In addition to charter costs, the oil companies pay for fuel costs and harbor dues (Aas et al., 2009). As seen in Figure 6 the day rates can be as much as $40 000 for long charter contracted PSVs, and optimization of the routes to keep the number of PSVs to a minimum can result in great cost savings.

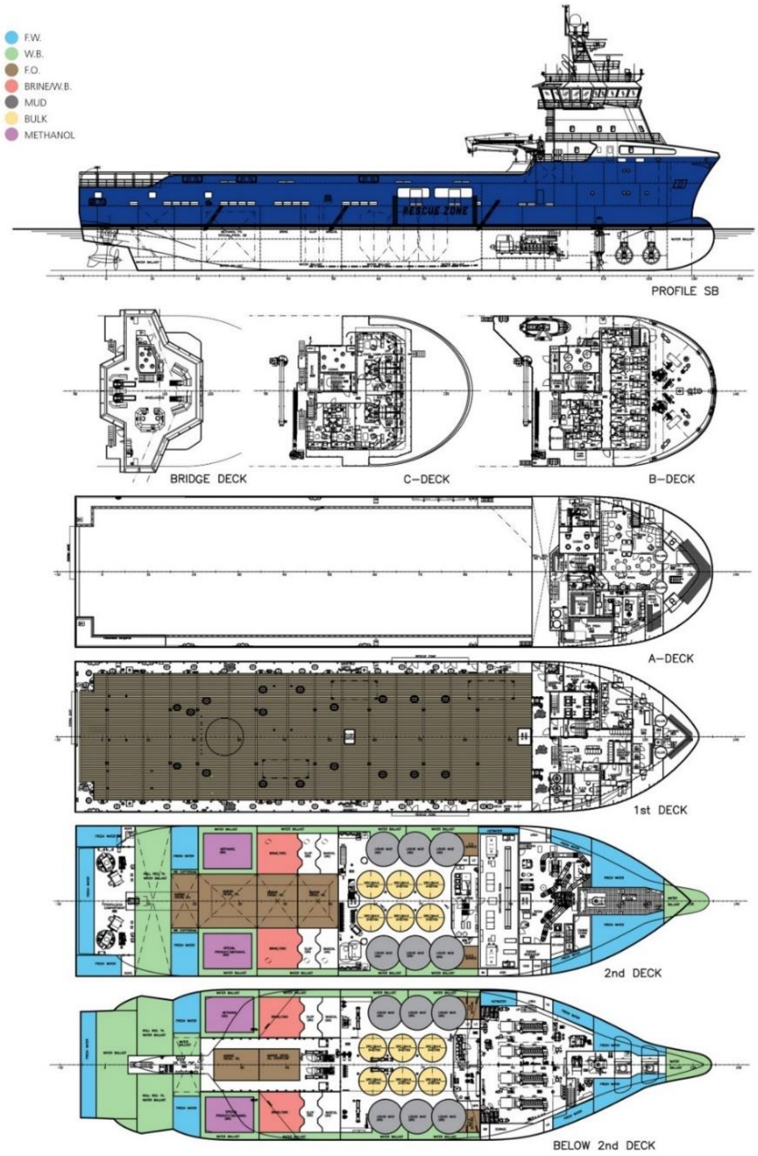

Figure 5 - Rem Fortress - An example of general arrangement to a PSV (Mercator Media 2015, 2012)

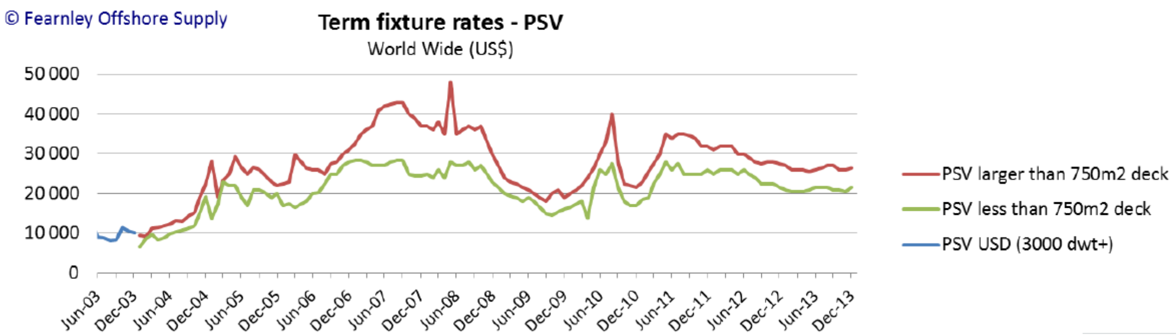

Figure 6 - Term fixture rates for PSV World Wide. Cost in US Dollars. (Fearnley Offshore Supply, 2014)

The charter costs are the dominant costs in the logistics chain, and it is therefore this cost that is used in the basic optimization model. The fuel cost might however be significantly for remote fields where the vessels sails long distances to the platforms. Figure 6 shows the long-term costs for PSVs worldwide (Fearnley Offshore Supply, 2014). The figure shows that the rates has been far from stable from 2003 to 2013, and it is therefore not possible to use exact charter costs in the model. It is logical to assume that charter cost for a hub-vessel will partly follow the charter cost for a PSV. Due to a high level of uncertainty in parameters are the fleet composition and relative cost calculated in the model interesting to analyze rather than the actual cost in itself. The optimal fleet composition will stay the same with different charter costs.

The modeling assumptions and data for the PSVs in the problem discussed are given in Table 5. The capacity is based on real data from Statoil (Akselsen, 2014). It does not represent the total deck capacity, which typical can be 1500 tons (Ship-technology, 2015)

Table 5 - Data and modeling assumptions for the PSVs

Charter cost per year [NOK]	80 000 000
Speed [knot]	12
Capacity [ton]	450

3.4 Offshore installations

Offshore installations need regularly delivery of commodities and special equipment to operate. The amount of goods and number of services each period depend on the size and activity of the platforms. The required demand and number of visits each week is given in Table 6. These are real numbers from Statoil given in (Akselsen, 2014), and used here as a basis for first results. Changes in demand and number of installations are done in further analysis of the problem, to see how this affect the result. The location of the installations are randomly generated inside an *installation matrix*.

Table 6 - Demand and service interval for platform

Number of visits a week	3
Demand [ton cargo per week]	230
Opening hours	24/7

3.5 Assumptions and limitations in the mathematical model

In the mathematical model the hub-vessels function as a forward placed base, and PSVs are sailing between hub and installations. A PSV can visit only one, some or all installations per route. The total delivery on a route can however not exceed the cargo capacity of the PSV.

The fleet of PSVs is homogenous which means all vessels have the same cargo capacity, speed and cost. The cargo capacity is given by ton cargo transported, and limitation of type of cargo is not specified. It is assumed that the PSVs are hired on long-term contracts and repeat optimal schedule every period (two weeks). The time and cost for maintenance and classing of the vessels are not included in the model.

According to (Statoil, 2015) 75% of the volume that is sent to the platforms return as backload. It is therefore assumed in the mathematical model that PSVs always have space for return load, and no restrictions regarding backload are implemented in the model.

The mathematical model includes important aspects from a real supply vessel problem, but it only describes the real problem to a certain extent. There are for instance no restrictions ensuring an even distribution of the routes throughout the period. For a real life problem is it however easy to switch the order of the optimal schedules to make a more even distribution of the visits to each platform. Both hub vessels and the base are assumed to operate 24/7. In a real life problem, the cost of service at a base outside normal working hours would be more costly due to overtime for the workers. Production installations usually have a more predictable demand than exploration installations, but it will always be a certain level of uncertainty, which is not accounted for in the mathematical model.

4 Barents Sea – Exploration in a Harsh Environment

It is believed that around 20-25% of the world's undiscovered petroleum resources are located in the Arctic area, and field developments might therefore be important to cover the world's need for energy (Ørbech-Nilssen, 2012). The risks associated with the conditions and the environment in the High North are not fully known, and an oil spill in the region might result in an environmental disaster. Research about conditions and consequences of production together with new technology must be established before a development in the Northern Parts of the Barents Sea can be realized. This chapter briefly explains some of the weather and climate aspects that must be considered for safe and efficient operation in the High North.

4.1 The Ice-Edge in the Barents Sea

The ice conditions in the Arctic has changed rapidly the last years. The ice edge defines the transition between open clean water and water with floating ice, and has recently been moved further north, due to climate changes (Regjeringen, 2015). All exploration areas (2015) are now south of the ice edge. Figure 7 shows the old and the newly updated ice edge in the Barents Sea. If the climate prognosis are correct will the Barents Sea be ice-free in the summer within 30-40 years (Norvegian polar institute, 2011).

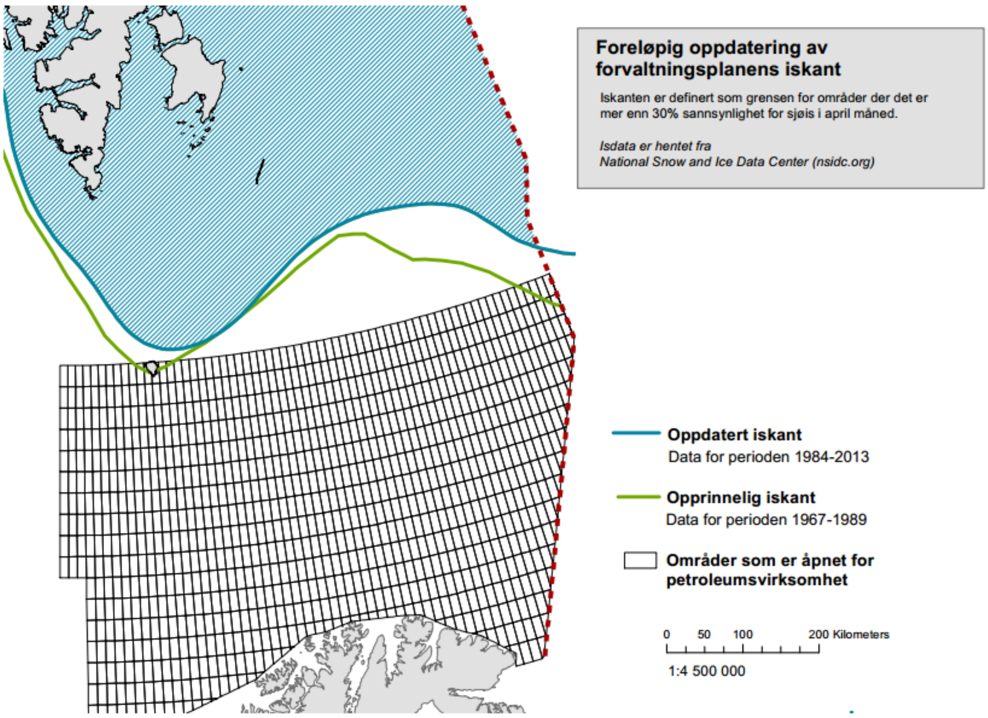

Figure 7 - Ice edge in the Barents Sea. The ice edge is moving further north. The blue line is the updated ice-edge, while the green is the ice edge based on data from 1967 – 1989. (Regjeringen, 2014)

4.2 Weather Conditions in the Barents Sea

There are little empirical data of the conditions experienced in the Barents Sea, and reliable weather data is therefore hard to come across. Most of the reliable data are from the weather station at Bear Island, the coast of Finnmark or from three met ocean data collecting buoys located in the Barents Sea (INTSOK Norwegian Oil & Gas Partners, 2014). There are several special weather phenomenon in the Barents Sea that contribute to a high operating. The most important ones are discussed in the following.

Extreme Temperatures and Icing

Sea spray freezing to ice (icing) on installations and vessels provide significant challenges for marine operations. According to (Paik & Thayamballi, 2007), icing take place when the water temperature is below six degrees, and the air temperature is below zero degrees. Capsizing due to the weight of the ice represent the greatest risk. Icing may also cause reduced operability, freezing mechanisms, slippery deck and shutdown of communication and evacuation systems. The extreme temperatures during winter and big temperature differences between summer and winter makes the design of vessels and equipment challenging. Low temperature together with wind chill causing challenges regarding the environment for humans working outside.

Sea Ice

According to (INTSOK Norwegian Oil & Gas Partners, 2014) design-relevant knowledge of the ice is strictly limited and unreliable. The maximum sea ice extent seen in the Barents Sea has decreased in the past decade. According to (Meteorologisk institutt, 2015) has the sea ice extent since 1980 decreased by 42 000 km^2/year in March and 91 000 km^2/year in September. The decline has resulted in little or no sea ice in the Barents Sea south, where the blocks for licensing round 23 are located. Ice class is however recommended for vessels operating in the area.

Polar Lows

Polar lows are a weather phenomenon that occurs in the Arctic area, caused by cold winds from ice-covered areas blowing over warmer sea. The polar lows can endure for a couple of hours to a couple of weeks, and are hard to forecast because off its sudden occurrence, and small size (diameters of tens or hundreds of kilometres) (Davenport, 2009).

Fog, snow and Darkness

Fog occurs frequently and representing an increased risk due to low visibility of drifting icebergs or vessels. Fog is also a challenge in terms of helicopter operations. During winter, the sun will not rise above the horizon. The complete darkness during winter represent an increased risk related to marine operations and SAR operations (INTSOK Norwegian Oil & Gas Partners, 2014).

4.3 Exploration Areas

The Norwegian government announced in January 2015 exploration licenses for 57 blocks in Barents Sea south. The new blocks are shown as pink in Figure 8. The most remote block is 243 nautical miles from shore. Today, it is possible for helicopters to transport people to fields located maximum 200 nautical miles offshore (Dalløkken & Andersen, 2015). By reducing the weight and capacity of the helicopters, it is possible to fly 243 nm with the technology and helicopters available today. In Canada, Statoil is already flying 273 nautical miles with a Sikorsky S-92 helicopter equipped with extra fuel tanks, and reduced capacity from 19 to 9 persons (Dalløkken & Andersen, 2015). This reduction in capacity represent a great cost for the operator. Statoil and Rosneft are exploring Perseevsky, a field located 330 nautical miles from Longyearbyen and 425 nautical miles from the coast of Finnmark (Dalløkken & Andersen, 2015). If Perseevsky is to be supplied from the coast of Norway, new solutions must be developed for both the helicopter transport and other aspects of the upstream logistics. Usage of hub-vessels as a refill station for helicopters might be a solution to increase the capacity of the helicopters (ref.ch. 7.1).

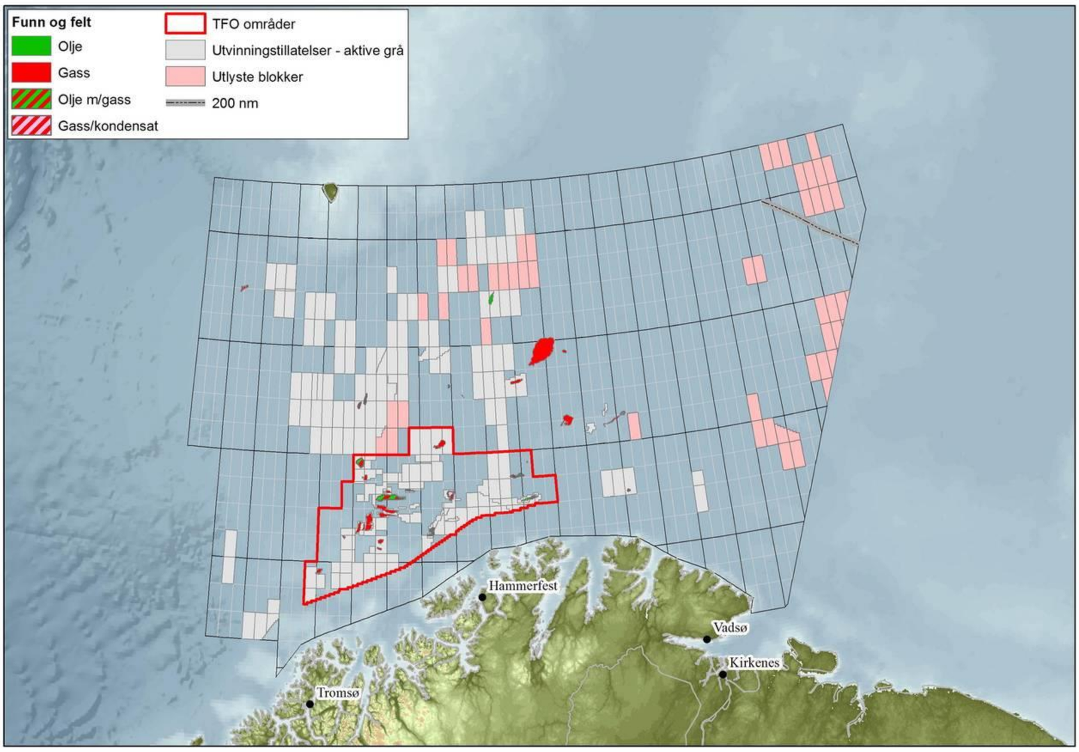

Figure 8 - Map of oil&gas acttivity in the Barents Sea South. The map shows only blocks controlled by norway. (regjerningen, 2014)

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5 Solution Method

This chapter describes the solution method developed to examine the logistics chains with and without usage of hub-vessels. To find optimal design and analyze which parameters that affect the upstream chains, a voyage-based optimization model is solved numerous of times with randomly placed installations inside an *installation matrix*. The solution method is approximately the same for the logistics chains with and without hub-vessels. The differences are explained in detail further on in this chapter. Figure 9 provides a simplified illustration of the solution method. How the Matlab script and Xpress Solver works are explained in detail further on.

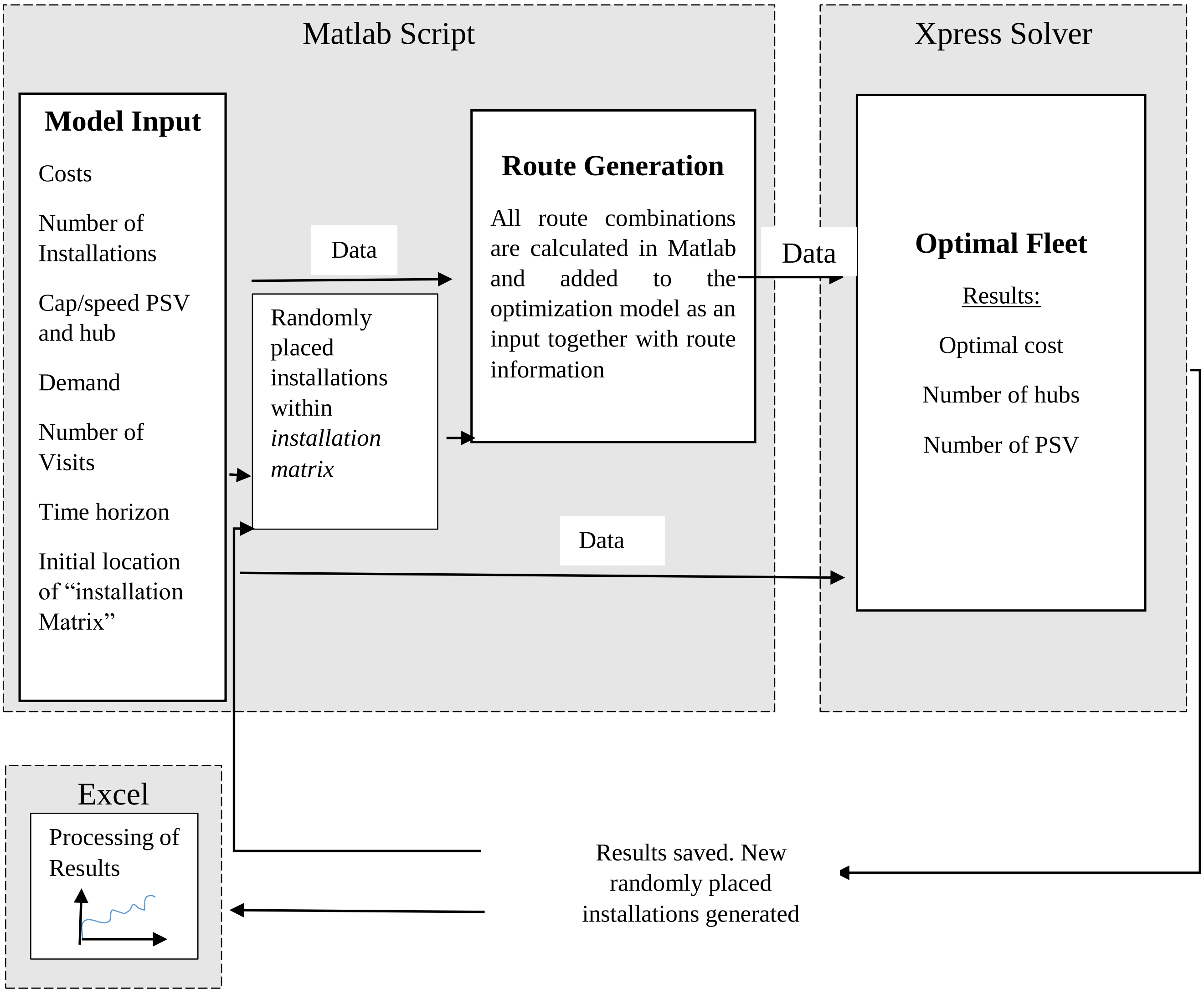

Figure 9 - Illustration of solution method

5.1 Installation Matrix

For each run, randomly located installations (3-6 typically) are generated inside an *installation matrix* (ref Figure 9), which is an outer bond for possible locations for the installations. The size of the *installation matrix* is almost the same as the exploration area described in 4.3. The *installation matrix* is moved two degrees north after a certain random cases (typical 50) are analyzed. The location is moved north to examine how the distance from shore affect the logistics chains.

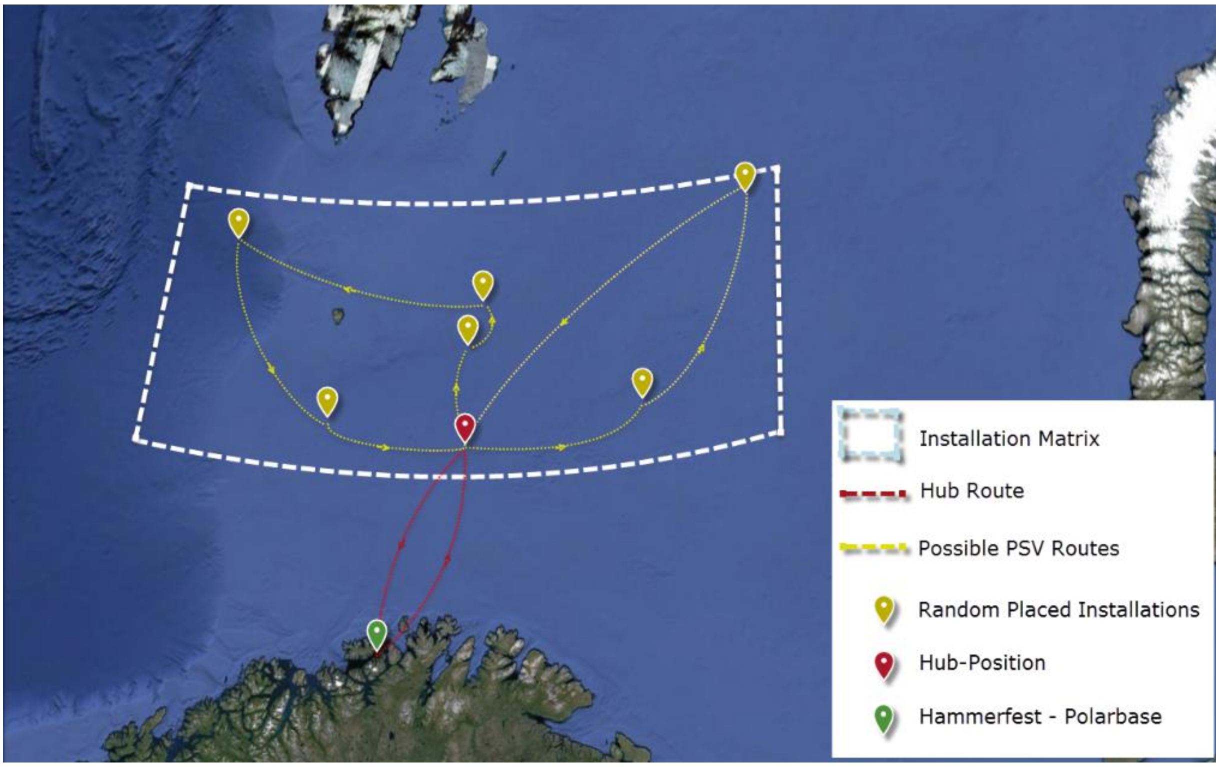

Figure 10 - Illustration of "installation matrix"

The four positions of the *installation matrix* that are analyzed, together with max and min distance from shore are given in Table 7. Note that the shortest distance will be a location with heading 0°N from Hammerfest (base), and the longest distance will be from Hammerfest to North-East Corner of the *installation matrix*. The distance from base and *installation matrix* are important for the analysis, and not the actual position of the installation matrix. Position 3 and 4 of the installation matrix cover parts of Svalbard, which is obviously not a realistic position of an offshore installation. The size of the installation matrix decrease when moved north, due to the distance between longitude lines degreases towards the poles.

Table 7 - Location of installation matrix and maximum and minimum distances from Base

Installation Matrix	South-west corner	North-west Corner	North-East Corner	South-east Corner	Min Distance from Base [nm]	Max Distance from Base [nm]
Position 1	71°N, 15°E	75°N, 15°E	75°N, 37°E	71°N, 37°E	25	320
Position 2	73°N, 15°E	77°N, 15°E	77°N, 37°E	73°N, 37°E	150	400
Position 3	75°N, 15°E	79°N, 15°E	79°N, 37°E	75°N, 37°E	270	500
Position 4	77°N, 15°E	81°N, 15°E	81°N, 37°E	77°N, 37°E	390	600

5.2 Multiple Run Script

A Matlab script is developed to do the analysis in an efficient and systematic way. This Matlab-script is inspired by the script presented in (Akselsen, 2014), but it is fundamentally different from hers. The Matlab script runs Xpress IVE, which returns the objective value. The objective values are saved in a data file for Matlab together with relevant measurements for later analysis of the problems. The total amount of problems solved to optimality in one run of the script is 800 for each solution.

The solution method of one run can be divided into three phases:

Phase one: Generate a number of random placed installations inside the installation-matrix

Phase two: Generate all possible routes the vessels can sail

Phase three: Solve the model by choosing the best combination of routes from phase two

These tree steps are repeated 50 times for a given number of installations (3-6), before the *installation-matrix* is moved two degrees north, and 50 new randomly generated cases are solved. A pseudo code for easy understanding of the different steps in the script is given in Figure 11, while the complete script (for a given set of parameters) is given in Appendix A. A random seed is used when generating the locations for the installations, which means that the same random numbers are reproduced for two sets of equal size. The random seed makes it easy to compare and reproduce the results.

```
Data: Input (coordinates for initial installation matrix,initial number of installations,
demand, service intervall, period, cost, hub- and PSV capacity etc)
Initialization;
For nInst = 3 through 6 do
    For coordinates = [«installations matrix» + 2°N for every run do
        Seed random generator;
        For numRun 1 through 50 do
            Generate nInst installation coordinates;
            Define all routes;
            Calculate distance and duration of all routes;
            Set hub location;
            Calculate number of hub vessels needed;
            Write data to input file for Xpress IVE model;
            Run the Xpress IVE model, which return optimal value;
            Save optimal value together with all measures (see Appendix E for
            MEASURES)
        End
        Save results vector for this scenario to file;
    End
End
```

Figure 11 - Pseudo code for multiple run script in Matlab

The most important parts in the multiple-run scripts are explained in the following sections:

Input – Parameters from the real problem

All inputs are defined in the Matlab script. Input data include problem period, charter cost, size and speed of hub-vessels and PSVs, number of vessels in the pool, demand and required visits per period by installations. The coordinates to the initial *installation matrix* is defined together with the distance it is moved further north after a given number of runs. When the model runs several times with the same parameters, the location of the installations will change inside the *installation matrix* with a random seed.

Route Generation

All possible routes between hub/base and installations are calculated in Matlab. To calculate the routes; all installations are denoted as the set I, and a subset of I as r_i. By finding all subsets $r_i \in I$, all possible combinations of installations a vessel can visit on a route is found. If the number of installations is n, the number of subset is $2^n - 1$. 3 installations gives 7 routes, 4 installations gives 15 routes and so on.

For a given example of three installations, all possible subsets of installations visited on a route is given in Table 8. A route is presented as a binary vector where “1” means that the installation is visited and “0” means it is not. A vector [1 0 1] means installations 1 and 3 is visited but not installation 2.

Table 8 - All possible routes for a problem with 3 installations

Installation	**1**	**2**	**3**
Route 1	1	1	1
Route 2	1	1	0
Route 3	1	0	0
Route 4	1	0	1
Route 5	0	0	1
Route 6	0	1	1
Route 7	0	1	0

The binary vector does not account for which order the installations are visited. The duration of each route is simply the duration of the most efficient route, which include the given installations. To find the most efficient route, a Traveler Salesman Problem (TSP) is solved for the given set of installations visited on each route. The TSP is solved by using full enumeration, which is an acceptable solution strategy, given that the number of installations are relatively small. The duration of each route is saved together with information of the installations the route includes. The duration consists of sailing time, service time at the installation(s) and harbor-time before departure. The model used in this thesis does not include constraints to divide the visits equally through the period, and the order and time the installations are visited is therefore not important.

5.3 Optimization

The mathematical model used in the optimization model is described in chapter 6. The optimization model is a set-partitioning problem with candidate routes as variables. The routes that require the smallest fleet and fulfill all constraints are an optimal solution. The optimization problem is formulated with the Mosel programming language, and solved in Xpress IVE 7.5. The complete Mosel code is given in appendix C.

5.4 Processing of Data and Presentation of the Results

The results from Xpress IVE is saved together with the measures listed in appendix E. All 50 runs with the same parameters are saved as a matrix in a Matlab data file. The results from all runs are then implemented into Microsoft Excel for processing and presentation.

5.5 Solution-Time

The mean solution time for solving one problem with given number of installations are shown in Figure 12. By multiplying the numbers by 400, and adding the answers together; the solution-time for running the entire multiple-run-script is provided. The total time for all 1600 runs are approximately 14 hours. The computer used for the analysis are a Dell XPS with an Intel Core i5-2410M CPU @ 2.30GHz, 6.0 GB RAM. As shown in Figure 12 increases the solution time exponentially with number of installations. Duration of the shortest route limits the number a route can be sailed within the planning period, end hence the number of constraints. The shortest route for a hub-solution is shorter than the shortest route for the conventional solution, and hence is the solution time longer.

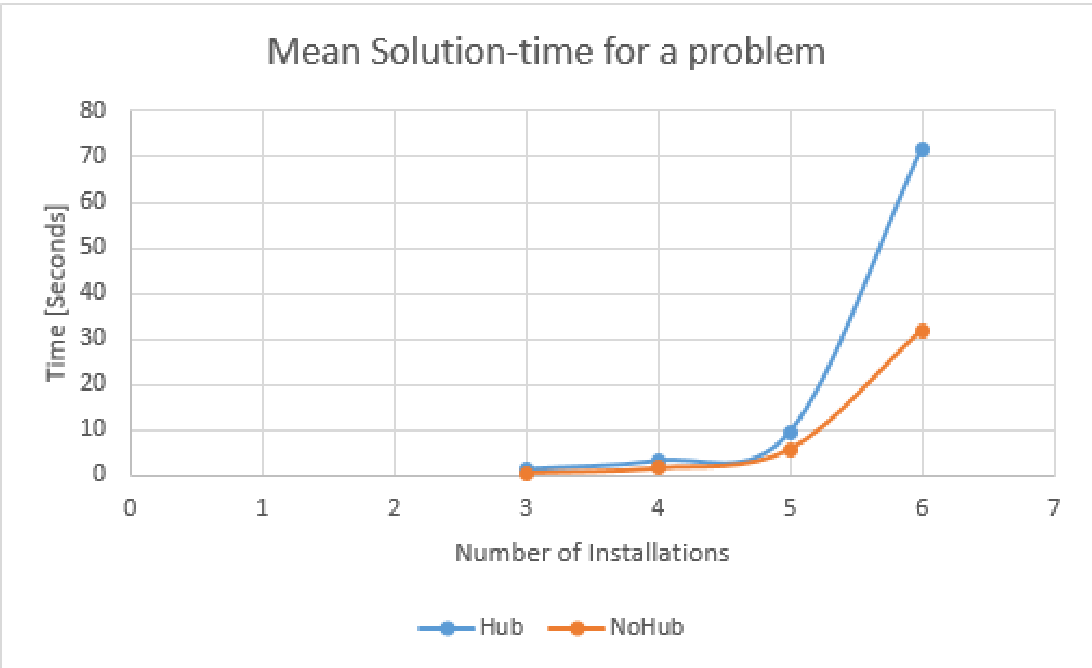

Figure 12 - Solution time for problems with different number of installations

6 Mathematical model

In this chapter, the mathematical model used for the analysis is described short and to the point. The mathematical model is based on the (Fagerholt & Lindstad, 2000) mathematical formulation of a supply vessel problem faced by Statoil and later modified and re-used by (Akselsen, 2014) in her master thesis. In some analysis in this thesis, small changes in the mathematical model presented in this chapter is made to obtain certain results or examine different aspects of the problem. Where changes are made, they are explained together with relevant results in chapter 8. The fundamental parts will however be as explained in this chapter.

To understand the mathematical model it is important to keep in mind the supply vessel problem described in chapter 3. The mathematical model for the problem using hub-vessels and the conventional supply vessel problem are identical. To analyze the conventional solution, the cost of using a hub is set to zero, and distance between base and hub is set to zero. These adjustments gives the same location for hub and base, and no hub costs when the conventional solution is analyzed.

6.1 Integer programming model

The integer-programming model is given as follows:

Sets

H	Set of hub locations, indexed by h
B	Set of base locations, indexed b
R	Set of routes from hub to installations, indexed by r
P	Set of PSVs, indexed by p
I	Set of installations, indexed by i
K	Set of times a route r can be sailed per period, indexed by k

Parameters

T_{hr}	Duration of route r, from and to hub h
C^{ET}	Cost for chartering a PSV p for one period
C^{EO}_{bh}	Cost for chartering a hub-vessel h per period
C_b	Cost for using base b one period
W	Maximum limit of sailing hours per period
S_i	Required number of weekly visits for installation i

A_{ir}	Gives which installation i visited on route r
Q_p	Deck-load capacity for PSV p
D_i	Demand for installation i per period
M^P	Small number, dependent on max demand
M^R	Big number, dependent on min route duration

Variables

$$\delta_h = \begin{cases} 1, & if\ hub\ location\ h\ is\ used \\ 0, & otherwise \end{cases}$$

$$\gamma_b = \begin{cases} 1, & if\ base\ location\ b\ is\ used \\ 0, & otherwise \end{cases}$$

$$\alpha_p = \begin{cases} 1, & if\ PSV\ p\ is\ used \\ 0, & otherwise \end{cases}$$

$$\rho_{bh} = \begin{cases} 1, & if\ a\ vessel\ shuttle\ between\ base\ b\ and\ hub\ h \\ 0, & otherwise \end{cases}$$

$x_{prh} =$ Integer variable. Number of times PSV p sails on route r starting and ending in hub h each period

$q_{iprk} =$ Integer variable. Volume of cargo delivered to installation i on route r by PSV p time number k the route is sailed

$$\beta_{prk} = \begin{cases} 1, & if\ PSV\ p\ is\ used\ on\ route\ r, time\ number\ k \\ 0, & otherwise \end{cases}$$

The objective function then becomes:

$$\min Z = \sum_{p \in E} C^{ET} \alpha_p + \sum_{b \in B} \sum_{h \in H} C^{EO}_{bh} \rho_{bh} + \sum_{b \in B} \sum_{i \in I} C_b D_i \gamma_b \tag{6.1}$$

With constraints as follows:

$$\sum_{h \in H} \sum_{p \in P} \sum_{r \in R} A_{ir} x_{orh} \geq S_i \qquad i \in I \tag{6.2}$$

$$\sum_{h \in H} \delta_h = 1 \tag{6.3}$$

$$\sum_{b \in B} \gamma_b = 1 \tag{6.4}$$

$$\sum_{h \in H} x_{prh} - M^P \alpha_p \leq 0 \qquad p \in P, r \in R \qquad (6.5)$$

$$\sum_{r \in R} x_{prh} - M^P \delta_h \leq 0 \qquad p \in P, h \in H \qquad (6.6)$$

$$\sum_{h \in H} \rho_{bh} = \gamma_b \qquad b \in B \qquad (6.7)$$

$$\sum_{b \in B} \rho_{bh} = \delta_h \qquad h \in H \qquad (6.8)$$

$$\sum_{r \in R} T_{hr} x_{prh} \leq W \qquad p \in P, h \in H \qquad (6.9)$$

$$\sum_{p \in P} \sum_{r \in R} \sum_{k \in K} q_{iprk} \geq D_i \qquad i \in I \qquad (6.10)$$

$$q_{iprk} - M^r \beta_{prk} \leq 0 \qquad i \in I, p \in P, r \in R, k \in K \qquad (6.11)$$

$$\sum_{k \in K} \beta_{prk} = \sum_{h \in H} x_{prh} \qquad r \in R, p \in P \qquad (6.12)$$

$$\sum_{k \in K} \sum_{i \in I} q_{iprk} \leq Q_p \qquad r \in R, p \in P \qquad (6.13)$$

$$q_{ipr,k+1} \leq q_{iprk} \qquad i \in I, p \in P, r \in R, k \in (K-1) \qquad (6.14)$$

$$\beta_{ipr,k+1} \leq \beta_{prk} \qquad p \in P, r \in R, k \in (K-1) \qquad (6.15)$$

$$\delta_h \in [0,1] \qquad h \in H \qquad (6.16)$$

$$\gamma_b \in [0,1] \qquad b \in B \qquad (6.17)$$

$$\alpha_p \in [0,1] \qquad p \in P \qquad (6.18)$$

$$\rho_{bh} \in [0,1] \qquad h \in H, b \in B \qquad (6.19)$$

$$x_{prh} \geq 0, integer \qquad p \in P, r \in R, h \in H \qquad (6.20)$$

$$q_{iprk} \geq 0, integer \qquad i \in I, r \in R, p \in P, k \in K \qquad (6.21)$$

$$\beta_{prk} \in [0,1] \qquad p \in P, r \in R, k \in K \qquad (6.22)$$

The objective function (6.1) minimize the cost of chartering and operating PSVs, hub-vessels and base. Constraint (6.2) ensure that each installation is visited at least as many times as required. Constraints (6.3) and (6.4) ensure that only one hub and one base is used in the model. The coupling constraint (6.5) ensure that if PSV p is used on a route r, the charter cost for this PSV is added to the objective function. Coupling constraint (6.6) ensure that the hub location is the same in the whole model. Constraints (6.7) and (6.8) ensure that no vessels are to sail from unused hubs and bases. The maximum time limit for each vessel is handled in constraint (6.9). Constraint (6.10) ensure that total supply to each installation per period has to be equal or bigger than the demand for installation i. (6.11) and (6.12) are coupling together the variables β, q and x. Constraint (6.13) ensure that capacity on a PSV is not exceeded on a tour. (6.14) and (6.15) is anti-symmetry constraints for variables indexed k, for easier solving of the problem. (6.16)-(6.22) ensure non-negativity, binary and integer restriction for variables.

7 Location and Positioning of hub-vessels

In this chapter, recommendation to hub position and different solutions for position-keeping is discussed. The solution method presented in chapter 5, is used to analyze how different parameters affect the chain and choice of supply solution. The results of these analyses are presented in chapter 8. How small changes in design affect the whole chain is hard to measure with the optimization model. The best solution for station keeping of hub-vessels for example, is not easily measured with an optimization model minimizing cost. To decide hub location; results from the mathematical model together with rules and guidelines regarding helicopter transport has been the deciding factors. Based on the weather conditions in the Barents Sea and known technology; a suggestion to how hub-vessels can hold their position is presented. Therefore, the focus in this thesis is to use the optimization model to understand when a hub solution might be a favorable solution, and use regulations and known technology to suggest how technical challenges might be solved.

7.1 Location of stand by position for hub vessels

The potentially remote locations in the High North is a major challenge for helicopter transport (Dalløkken & Andersen, 2015). The amount of fuel a helicopter can carry is the limiting factor for the maximum distance a helicopter can fly. For offshore helicopters in Norway is it required that a helicopter is able to fly to its destination, perform an approach and be able to return to an onshore airport and still have sufficient fuel for 30 minutes flying time (Norsk Olje&gass, 2011). The *066 – Norwegian oil and gas recommended guidelines for flights to offshore installations* are established to ensure safe flights to and from offshore installations on the continental shelf in Norway (Norsk Olje&gass, 2011). Today, helicopters can reach all installations located outside of Norway without violating the guidelines. Great distances in the Barents Sea will however be a problem with today's guidelines. According to the guidelines; a helicopter is not allowed to land on a vessel with mono hull and helicopter deck in front (type A) during nighttime. A landing is only allowed in "special cases". This restriction will be a problem for marine operations in the Barents Sea during winter. In the future, new versions of these guidelines will probably be developed, where long distances and conditions in the High North are considered.

An important restriction in (Norsk Olje&gass, 2011) for helicopter transport is: "*The helicopters must always carry enough fuel to reach land with the required reserves. The use of an "offshore alternate" is not permitted"*. This restriction limits the possible transport range for a helicopter. This means that a helicopter must have enough fuel to reach the hub, and fly back to shore if landing is not possible. If it is possible to land on the hub-vessel; the distance *hub-installation-shore* must not be longer than maximum flying distance for the helicopter. The hub-position that maximize the distance possible to reach with current guidelines are therefore 67% of the distance: *base – installations*. This location of the hub, with helicopter patterns is shown in the Figure 13. If something prevent the helicopter from landing on the hub, it has to return to shore. If it is possible to land on the hub-vessel, the helicopter refuel, and continues towards the installations. This will increase the maximum range of the helicopter by about 50%. The distance chosen in the Matlab script is 75% of the distance *Base – Installation Centroid*. In practice, the installations will be located around the installation-centroid, and hence experience different distances from hub-vessel. This location of the hub will most likely ensure that the helicopters can reach all installations and have sufficient fuel to return to shore if landing is not allowed.

A base on Svalbard or Yuzhny Island (island east of the Barents Sea) could potentially serve installations located north in the Barents Sea. This solution require expensive infrastructure to be built. A base on one of these islands could also potentially work as an emergency base for helicopters flying from the coast of Norway. This solution would probably require a much simpler helicopter base. Using an AW609, an airplane/helicopter hybrid is also discussed as a potential solution for transporting people longer than 300 nautical miles offshore, without refilling (Dalløkken, 2014). A drawback with AW609 is its maximum capacity of 9 people.

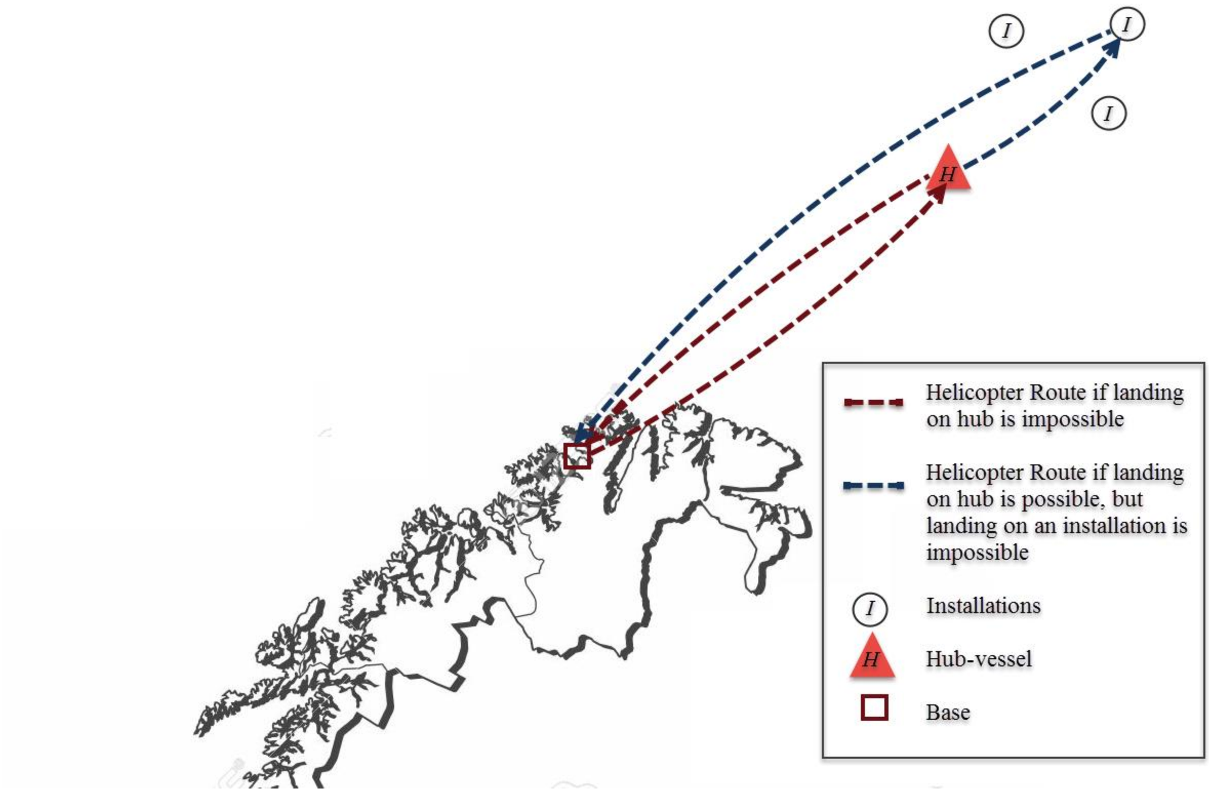

Figure 13 - Illustration of usage of hub as a refilling station for helicopters. If the helicopter is not able to land on hub, it return to base. If it lands, the helicopter refill and can continue towards the installations, with possibility of returning to shore if landing is not allowed.Background map from (Hammer, 2015)

7.2 Positioning Solution for the Hub

The hub-vessel might hold its position by using either Dynamic Positioning (DP) or an anchor arrangement. (Nordbø, 2013) argues that a DP-system is necessary to avoid collisions during loading and unloading offshore. A DP-system on a big hub-vessel will require powerful thrusters and expensive equipment. In addition to the CAPEX related to a DP-system, the fuel consumption during DP-operations will have a negative impact on the cost and environment. (INTSOK Norwegian Oil & Gas Partners, 2014) addresses high costs as a major barrier for petroleum development in the High North, and other solutions should therefore be considered.

An alternative to use DP, is to hold position by using anchors. To achieve an efficient upstream chain, a requirement for an anchor solution will be easy connection and disconnection. An iceberg on collision course represent a high risk for the anchored hub-vessel, and quick disconnection of anchors will be important to achieve satisfactory safety. Another reason for a need to abandoning the position fast could be polar lows, which are hard to forecast. The usage of the hub-vessels' own anchors will probably be too slow and inefficient in these cases. A permanent anchored buoy that is easily connected and disconnected might be a cost efficient and promising solution. Both CAPEX and OPEX will probably be acceptable for an anchored buoy; installation of the buoy will be a relatively easy operation for an anchor handler, and the hub-vessels fuel consumption when anchored will be minimal (compared to standby on DP). Connection to the buoy might happen the same way as FPSOs or tankers connect to a buoy. Typical mooring systems for an FPSO are spread mooring, external mooring, internal mooring and disconnectable turret mooring (Paik & Thayamballi, 2007). All these alternatives require quite extensive constructions in the bow of the hub-vessel. A construction in the bow would also increase resistance in transit, and hence the fuelconsumption. A better alternative might be a catenary anchor leg mooring (CALM) system, which is proven to be an efficient single point mooring technique for loading/off-loading terminals (Sagrilo et al., 2002). Figure 14 shows an illustration of the CALM system with a tanker connected.

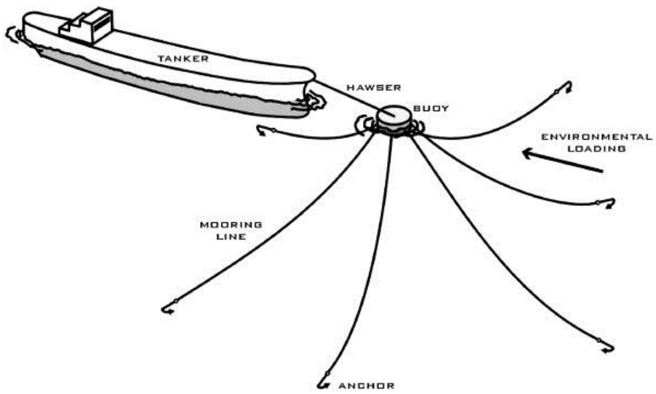

Figure 14 - Illustration of the CALM-system (Sagrilo et al., 2002)

This solution will require a longer safety distance than the DP-solution due to less capability to prevent movement sideways. Bulk and liquefied cargo are pumped through hoses from the hub-vessels to the PSV, and an increased distance will not be a major problem for loading/offloading of these goods. Loading/off-loading containers offshore require a crane, which adds momentum to the vessel. An increased distance requires a bigger crane, which might limit the weight of the containers due to the increased momentum.

The hub-vessel will always have the bow against the weather, and big movements sideways will not happen in wave heights lower than 4.5 meters, which is the wave-limit for offshore loading/unloading (The Norwegian Oil Industry Association, 2008). The consequences of an impact between a PSV and the hub-vessel are not as extreme as for an impact with a production facility. This fact might allow a shorter safety distance between a PSV and a hub-vessel, than the required safety distance between a production unit and a PSV.

(The Norwegian Oil Industry Association, 2008) present regulations and weather limitations for marine operations on the Norwegian shelf. These regulations are important to bear in mind when designing a hub-vessel for the Barents Sea.

8 Analysis of the Logistics-Chain

The objective in this thesis is to analyze the design of the upstream logistics chain for supply of offshore installations in the Barents Sea, and examine how different parameters affect the upstream chain. To be able to understand and interpret the results; analysis of both the hub solution and the conventional solution is done simultaneously. By doing this, it is possible to compare how the hub solution and the conventional solution is affected by the same changes, and thereby conclude which parameters that favor the hub solution compared to the conventional solution. The mathematical model is used in the analysis as a decision tool. The mathematical model makes it possible to analyze how different parameters affect the logistics chain in an efficient and systematic way. To achieve reliable and valuable results is it important to determine which parameters that needs to be included in the analysis, and understand how they affect the model.

The mathematical model is originally made for a well-defined problem, with assumptions related to that case study. Assumptions that where reasonable in earlier analysis, might not be reasonable for the problem analyzed here. As an example; the model in (Akselsen, 2014) does not include fuel costs, which is a reasonable assumption for the problem discussed in her thesis due to relatively short distances from shore. In the problem discussed in this thesis, the distance between an installation and shore might be over 500 nautical miles, and the assumption is therefore not that good anymore.

The actual costs calculated in the model is not important results, because of the uncertainty presented in all cost elements in the model. The important results are however the relatively cost between hub-solution and conventional solution, and the fleet composition for both solutions. Since the PSVs in the model are homogenous, will a change in charter cost for the PSVs not affect the optimal fleet composition.

8.1 The effect of period-time in the model

The work presented in the project thesis showed that usage of hub-vessels was considered cost efficient compared to a conventional solution at certain distances from shore. The distance decreased with an increased number of installations. The code used for the analysis contained several errors, which resulted in a wrong conclusion. One of the problems was that Xpress IVE in most of the simulations only estimated an optimal solution, because no integer solution was found. This estimated value found by Xpress IVE gives the optimal solution within uncertainty. When distance from shore increase; the route durations increase. This limits the number of times a PSV can sail a route within a certain period. To increase the flexibility in the model, the period is increased to two weeks in the following analysis.

By expanding the planning period from one week to two weeks; Xpress IVE finds integer optimal solutions for all problems. This means that Xpress IVE finds optimal fleet size for all cases analyzed. Another error fixed is the cost calculations for hub-vessels. To see how this affect the result; optimal solution for 800 different cases are plotted in Figure 16. Fifty cases with randomly generated installations are analyzed for each position of the *installation matrix*, for 3-6 installations. The distances between base and installation-centroid are plotted against the cost. Since all installations has the same demand, changes in cost indicates a change in number of vessels needed to meet the required demand and service interval. These results are therefore interesting for analysis of how many vessels that are needed to supply fields located different distances from shore.

By comparing the results from the project thesis shown in Figure 15 with the results in Figure 16 where errors are corrected; you see for instance that the hub vessel never becomes cost efficient with parameters as given in chapter 3. The results from the project thesis shows the mean values for 1000 runs for each position of the *installation matrix*, while the new results shows the actual results with the actual distances. The different presentation of the results in addition to different random number seed makes it hard to compare the results. The reason to present the results from the project is to show how the planning period affect the trend in the results, and how the conclusion becomes very different with increased flexibility in the model.

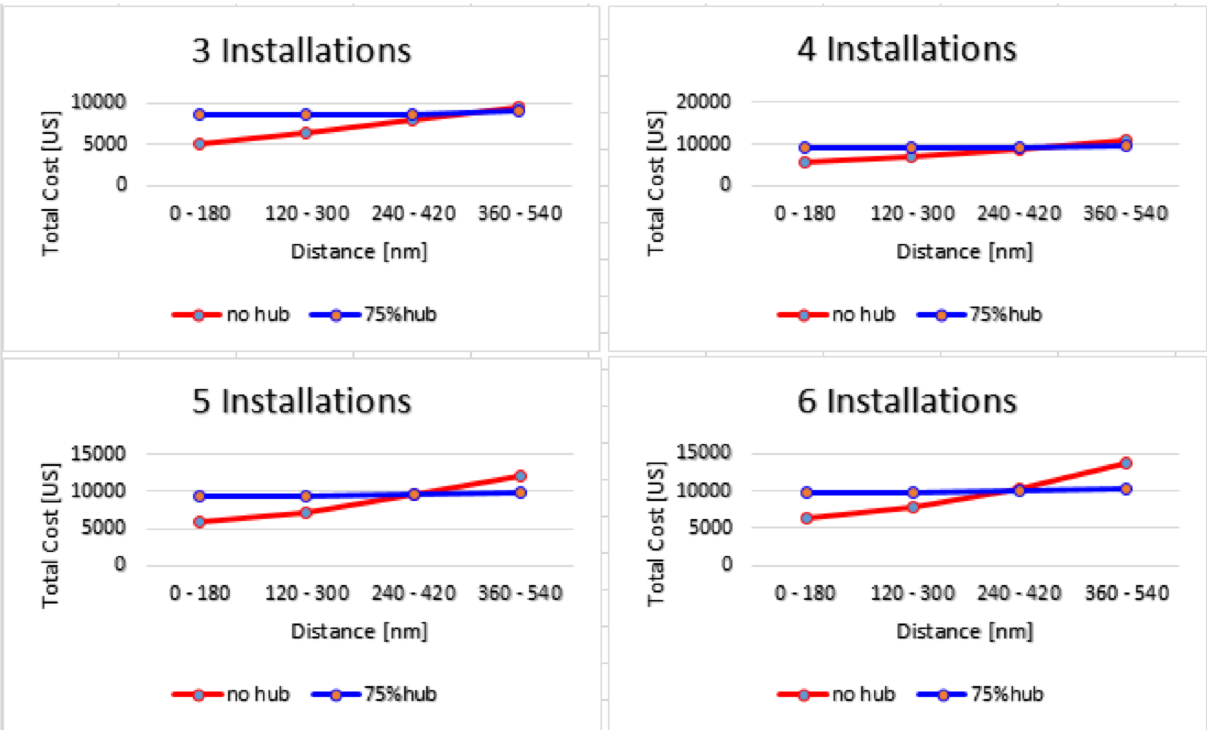

Figure 15 - Results from Project Thesis. The data shows the mean value (cost) of 1000 runs for each location. The runs where done for 3 – 6 installations. The period for these results are one week.

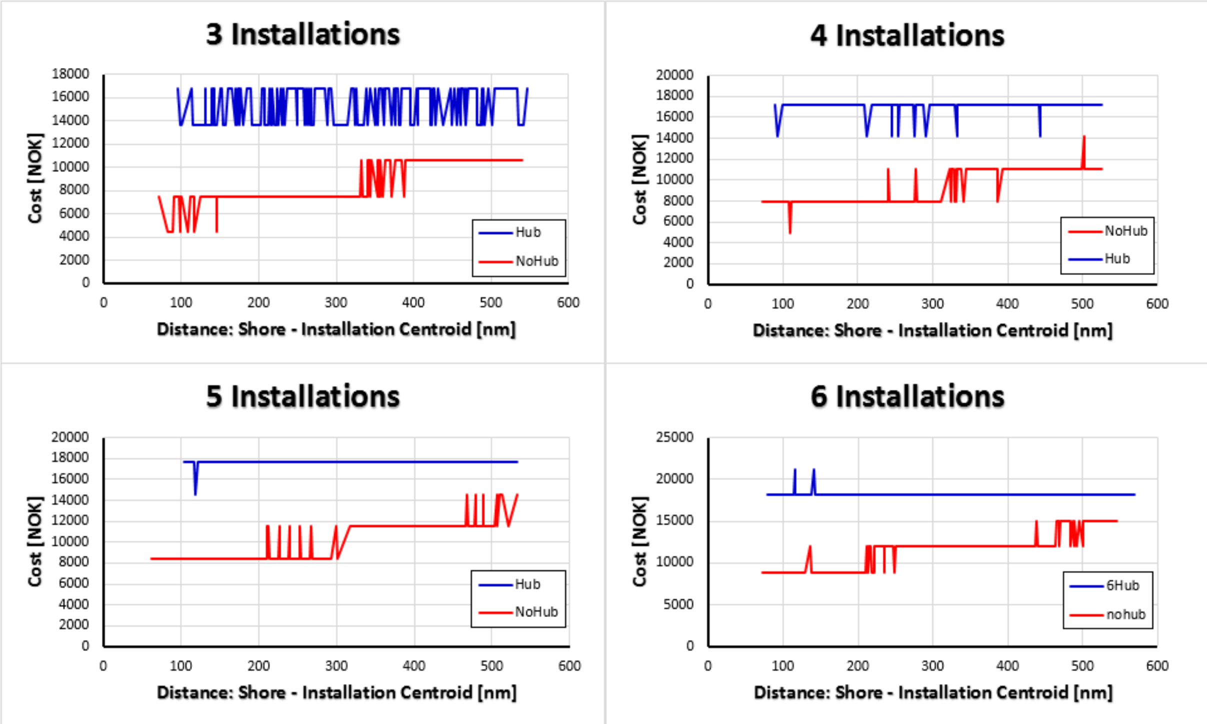

Figure 16 - Results from several runs with two weeks period. Changes in the cost indicate that a PSV is added or removed from the fleet.

As expected is the fleet composition for the conventional solution clearly dependent on distance from shore. Extra PSVs are added when distance from shore increases due to longer routes, which decreases the number of roundtrips a PSV can sail. The overlapping is due to different spread of the installations in the different runs, which affects the length of the routes. A field with great distances between installations may require more PSVs than a more remote field with installations closer together. For three installations; one to three PSVs are sufficient to cover the demand. For six installations; three to five PSVs are needed to not violate the restrictions.

Number of PSVs needed increases with number of installations, for both the conventional- and hub-solution.

No dependency is however seen between distance and fleet-composition for the hub-solution. No hub-vessels are added to the fleet when the distance from shore or number of installations are increased. This means that two hub-vessels are enough to meet the required demand in all cases. In Figure 17 the *sum of all distances* in the problem with three installations are plotted against the cost. This plot shows that the cost of a hub solution has some dependency on spread of the installations, while no dependency is seen between spread and cost for the conventional solution.

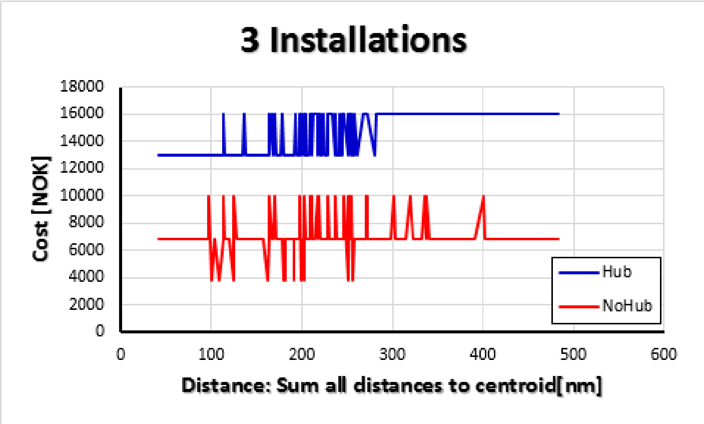

Figure 17 - Plot of cost against the sum of all distances to centroid [nm] for three installations

It is interesting to notice how the size of the fleet change with distance from shore for the hub-solution. For six installations, it does not change at all (except for two cases). The fleet composition for the conventional solution increase at the same time, which indicates that the hub-solution might become cost efficient for remote fields with higher demand and/or more installations than analyzed here. The capacity of the hub-vessels are not utilized for most of the runs, due to the fact that the same number of hub-vessels are needed for all problems with three to six installations.

Increased solution time is the reason why only cases with maximum six installations are analyzed.

8.2 Include fuel Costs

The results given in Figure 16 is very helpful to estimate the number of PSVs needed for a field. To examine how fuel consumption affect the total cost for remote fields, an alternative objective function is presented in the following.

To calculate the fuel consumption for a ship, hull details, speed and machinery are needed (Amdahl et al., 2011). The price for MDO changes with time, and to get a correct total fuel cost for the fleet, both fuel consumption and the price for MDO must be correct. Because no design effort is defined in this thesis, the fuel consumption will be estimated based on existing vessel(s). The bunker price used in the model is $560 per Metric Ton, which is the price for MDO in Gothenburg 22.04.2015 (Ship&Bunker, 2015). Fuel consumption is implemented in the model based on data given in (Emblemsvåg & Bras, 1997) for Far Scandia which is a 85 m long PSV. Important data for the vessel is presented in Table 9.

Table 9 - Relevant Data for Far Scandia

Mode of Usage	Speed [nm/h]	Fuel Consumption [1000 kg/day]
In Port	0	1.0
Stand By (DP)	0	4.0
Economic Speed	10	14.3
Full Speed	14.0	21.4
Service Platform	0	4.8

When loading from hub-vessel to PSV, it is assumed that the fuel consumption for the PSV is the same as when serving the installations. The objective function for the mathematical model will be as follows:

$$\min Z = \sum_{p\in E} C^{ET}\alpha_p + \sum_{b\in B}\sum_{h\in H} C^{EO}_{bh}\rho_{bh} + \sum_{b\in B}\sum_{i\in I} C_b D_i \gamma_b + \sum_{p\in P}\sum_{r\in R}\sum_{h\in H} C^{f}_{rp} x_{prh} \qquad 8.1$$

With C^{f}_{rp} as fuel cost for psv p, sailing route r. $x_{prh}$is the same as before; it is an integer variable giving how many times a PSV p sails a route r from hub or base position.

The coefficient C^{f}_{rp} is calculated by using equation 9.2. a) if a hub is used, and 9.2 b) for a conventional solution.

$$C^{f}_{rp} = \left(C^{Transit} \cdot T^{transit} + C^{service} \cdot (T^{hub} + T^{\hat{i}nstallations})\right)P^{MDO} \qquad 8.2(a)$$

$$C^{f}_{rp} = \left(C^{Transit} \cdot T^{transit} + C^{service} \cdot T^{\hat{i}nstallations} + C^{harbor} \cdot T^{Harbor}\right)P^{MDO} \qquad 8.2(b)$$

Where $C^{f}_{rp}$is the total fuel cost for a PSV p sailing route r. $C^{tranist}, C^{service} and\ C^{harbor}$ is fuel consumption in the three different main phases the PSV is operating. $T^{transit}, T^{service}, T^{harbor} and\ T^{hub}$ is the time each vessel uses in the different phases on each route. $P^{MDO}$is the MDO price.

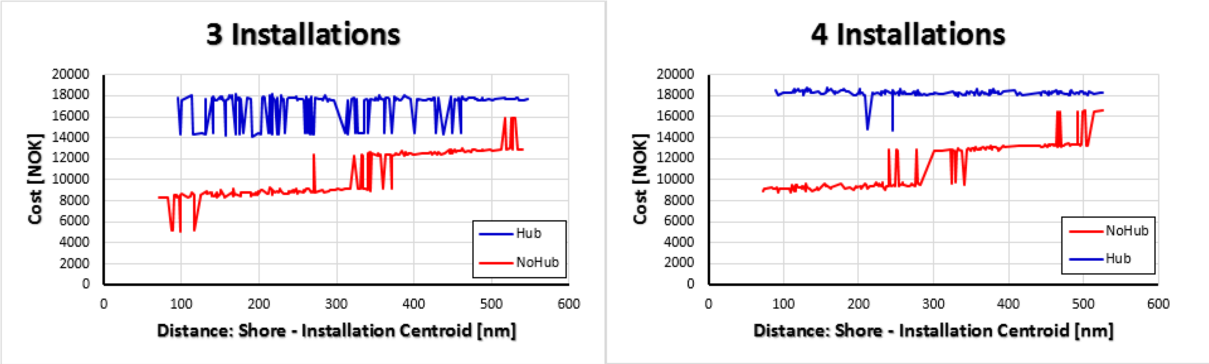

Figure 18 - Analysis including fuel cost for PSVs

The solution-time for the optimization model increased significantly compared to the earlier model. To be able to analyze sufficient number of problems; maximum solution time for one run was limited to 600 seconds. Only results for problems with 3 and 4 installations was possible to achieve within the solution time. The results does not include fuel cost for hub-vessels, and the difference should therefore be bigger than shown in Figure 18. The fuel cost would however be lower for the hub-solution than for the conventional solution due to lower speed and fewer schedules. These results show that fuel costs in a supply problem for remote fields are significant. This implementation of the fuel cost in the mathematical model makes the model unsuitable for the solution method used, due to the increased solution-time for problems with more than four installations. For a case study will it be valuable to include the fuel cost and hence allow a long solution time. For the analysis in this thesis however, the large number of cases to solve makes it necessary to keep the solution-time low.

8.3 How Demand affects the results

Figure 19 shows the results for cases with half demand, while Figure 20 shows the results for double demand compared to the initial problem (ref ch. 3). Results for problems with six installations and double demand are missing because of maximum solution-time was exceeded. Figure 21 compares result for problems with five installation, but different demand. The difference in cost for the tree hub solutions are loading and offloading cost at base, which is dependent on the amount of cargo. The results shows that extra PSVs are needed earlier when demand increase.

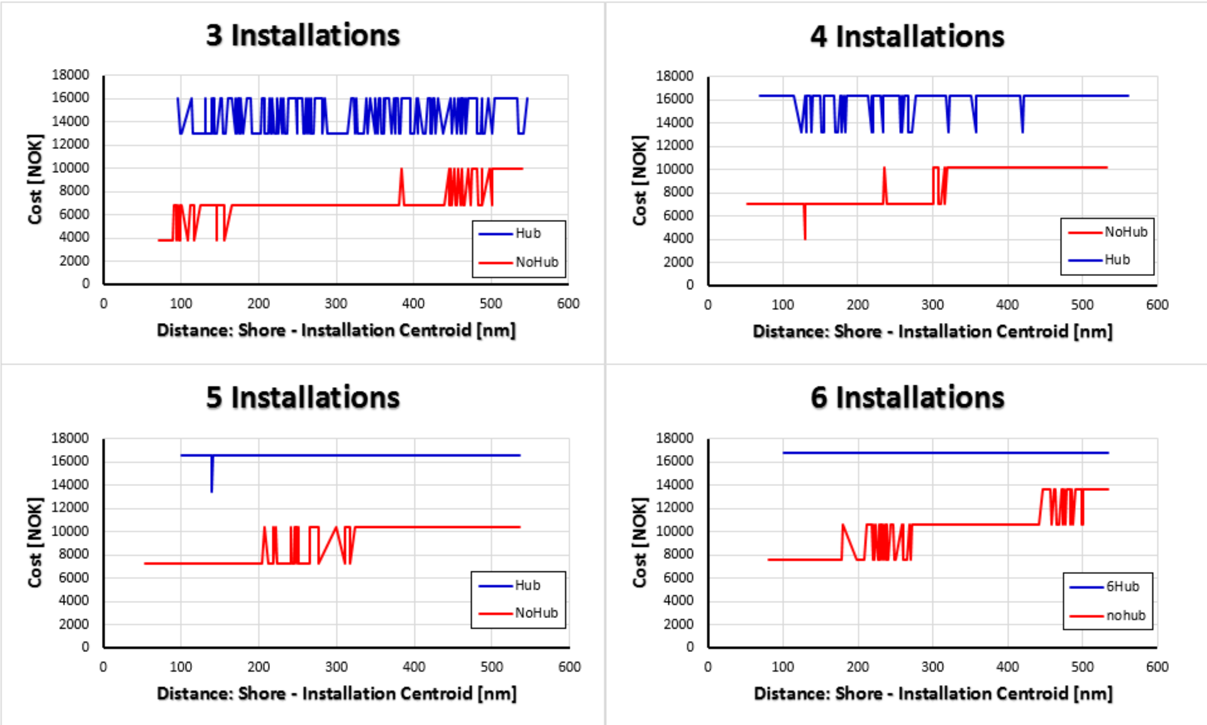

Figure 19 - Half Demand

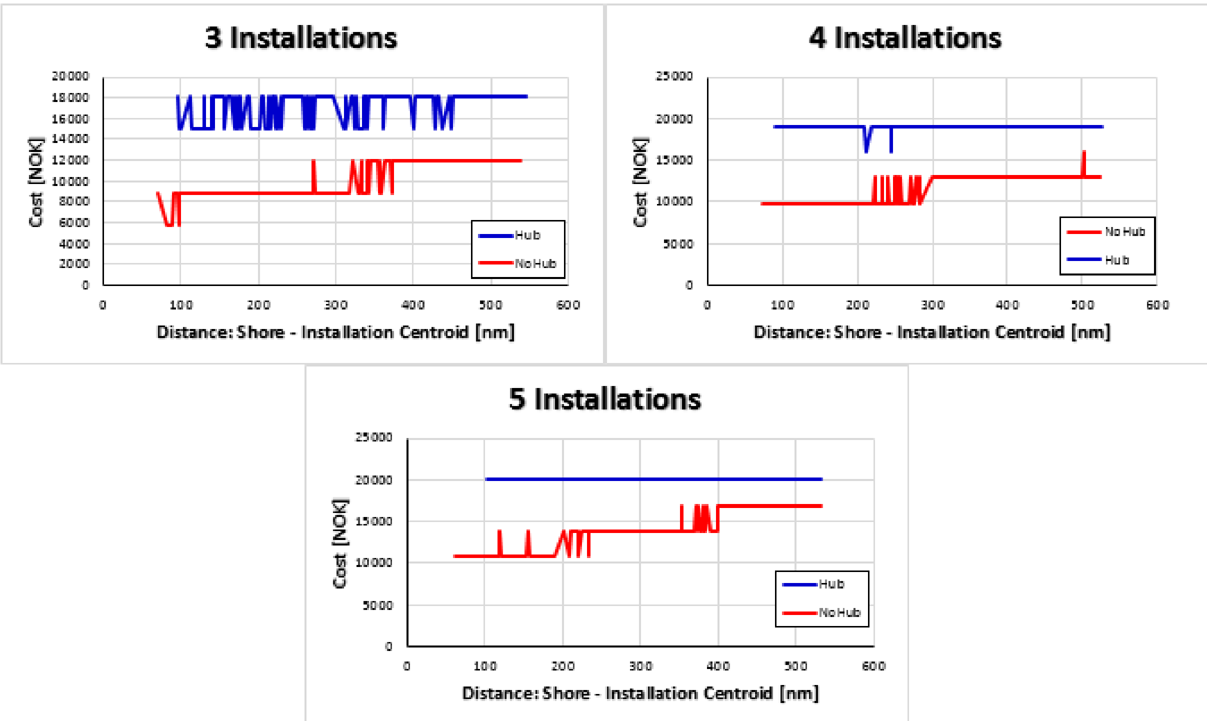

Figure 20 - Double Demand

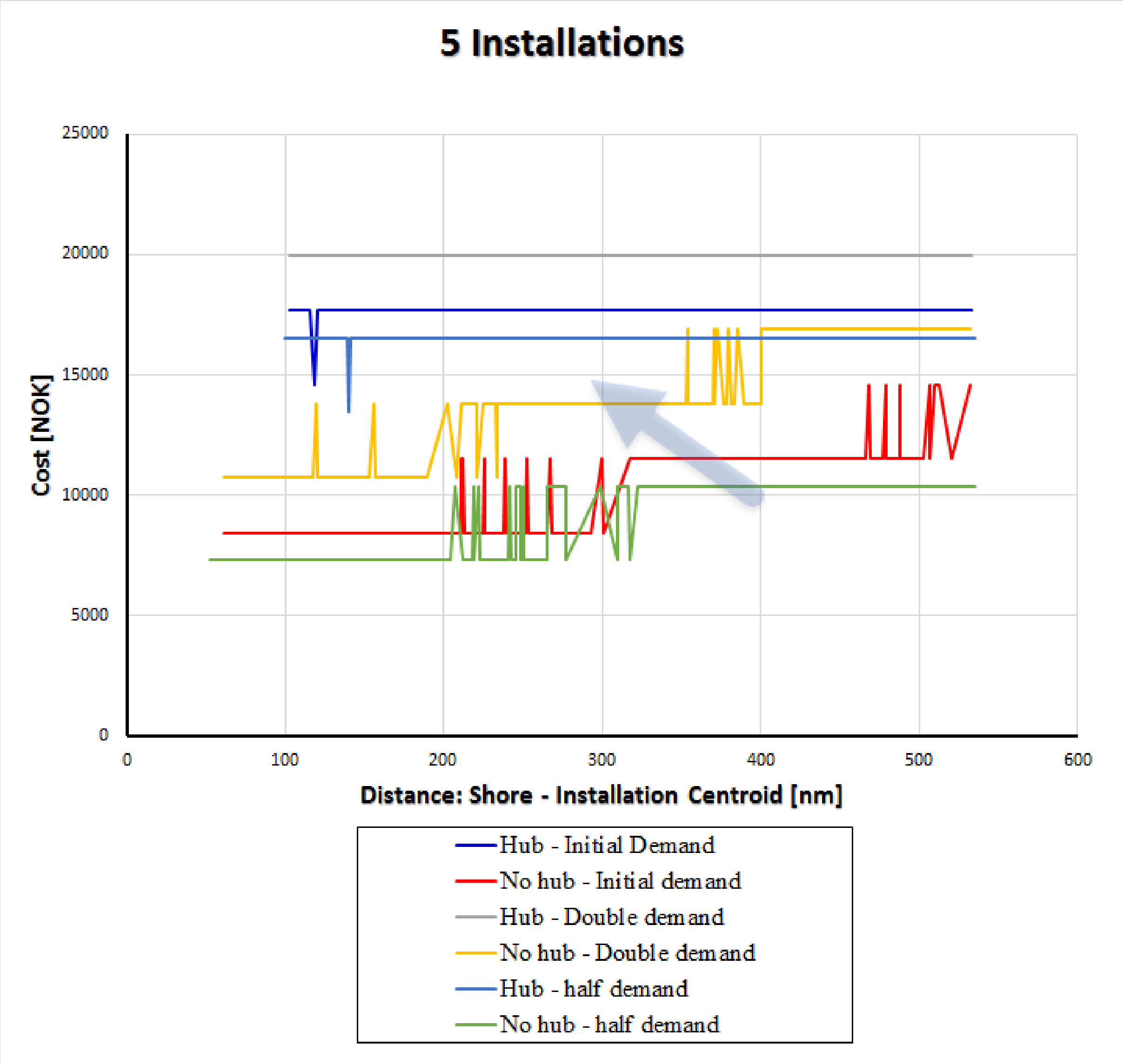

Figure 21 - Five Installations - different demand. The arrow shows the trend in fleet composition for the conventional solution.

8.4 The Effect of Increasing the Service Frequency at the Installations

The service interval for the problem described in chapter 3 is three times per week, for all installations. The service frequency depends on activity and cargo capacity on the installation. An installation with high activity and low cargo capacity needs more frequent visits than a bigger installation with the same or lower activity. To analyze how this affect the hub- and conventional-solution; problems where all installations require seven visits a week are analyzed. How this affects the fleet composition for each solution is shown in Figure 22. A higher service frequency favor the hub-solution, because the duration of the routes the PSVs sail between hub-vessel and installations are significantly lower than corresponding routes from base to installations. Figure 22 shows that the cost of both solutions are approximately the same when the distance between shore and installation centroid is 400 nautical miles.

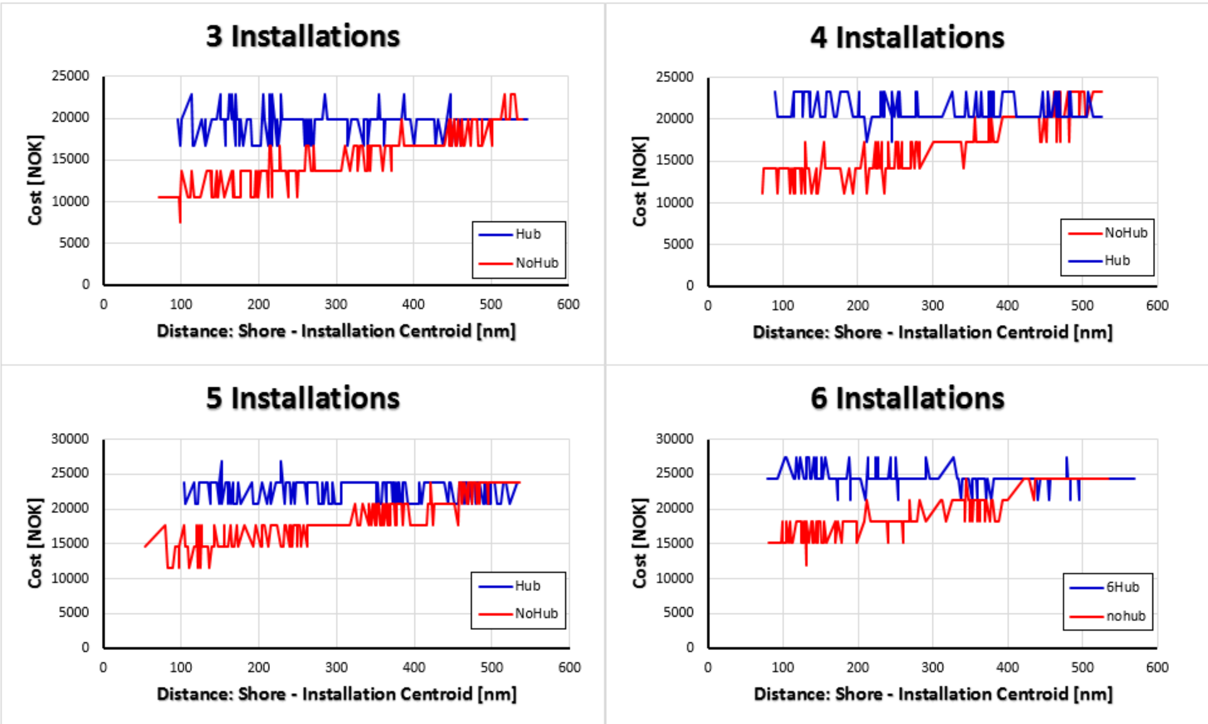

Figure 22 - Results when all installations require seven visits a week.

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9 Discussion

A discussion of the hub-solution and interpretation of the results is given in this chapter. How the results from the mathematical model reflect a real supply problem is considered. Furthermore, challenges and advantages related to the hub-solution are discussed.

The optimal objective values from Xpress IVE, presented in Figure 16, indicate that a conventional solution always have lower cost than a hub-solution (given assumptions and parameters as explained in chapter 3). The cost of chartering a hub-vessel is assumed to be 1,5 times the cost of chartering a PSV. According to the results the smallest fleet possible for a hub-solution includes two hub-vessels and one PSV. This represent the same cost as four PSVs, without fuel cost considered. The fuel cost is probably lower for a hub-solution than for a conventional solution, due to lower speed and lower total distance sailed by the fleet. To service six installations located approximately 500 nautical miles from shore; two hub-vessels and two PSVs or four PSVs without usage of hub-vessels are needed. The cost difference is equal to the charter cost of one extra PSV. The fuel cost savings for the hub-solution will (most likely) be less than the cost of chartering one extra PSV, which makes the conventional solution cost efficient also for problems where fuel cost is included. However, the charter costs assumed may not be accurate, and the cost difference will change with different relative charter costs. It is likely that the cost of chartering a hub-vessel will be higher than chartering a PSV, and the conclusion will probably be the same with a little different relatively costs for hub-vessels and PSVs.

The objective values from Xpress IVE are not interesting by themselves. How the objective values change by changing different parameters, and relative values of different solutions are however very interesting to analyze. The trend in the results for the conventional solution is as expected; fields with a higher number of installations and longer distance from shore require a bigger fleet of PSVs than smaller fields closer to shore. The results in Figure 16 indicates that one extra PSV is added to the fleet every 200 nautical miles a field is moved further from shore. This distance decreases with increasing demand and/or increasing number of visits. The fleet-composition for the hub-solution change little or nothing when distance from shore is changed. Depending on the number of installations, one, two or three PSVs are needed, in addition to two hub-vessels. This result indicates that the capacity of the hub-vessels are not utilized for most of the cases, and not a suitable solution for fields close to shore.

The only costs included in the initial problem are charter costs for vessels and service costs at the base. This is a simplification, and further analysis of all costs related to the supply problem must be examined to conclude whether the hub-solution represent higher costs than a conventional solution. In addition to the fleets fuel cost, cost related to helicopter transport is interesting to examine. Maximum distance a helicopter in Norway flies are today 200 nautical miles offshore. To increase this distance, capacity must be reduced and extra fuel tanks be installed. A hub-vessel located 75% of the distance *Base – Installations* might work as a refill station for the helicopters without violating the *066 Guidelines*. The maximum distance could increase to 300 nautical miles, with the same helicopters and capacity as today. A helicopter is according to the guidelines required to always be able to return to an onshore base, and have enough fuel for 30 minutes of flying after arrival. If a helicopter is not able to land on a hub-vessel located 200 nautical miles from shore, it return to shore as it does today. If it lands, it can refill and proceed to the installations located 300 nautical miles from shore. If the helicopter is not allowed to land, it has sufficient fuel for the trip back to shore. The total distance *hub-installation-base* will be equal to the distance *base-hub-base*.

The best solution for position keeping in the Barents Sea will most likely be connection to an anchored buoy. High costs are a major barrier for field development offshore, and usage of anchors will represent a relatively low CAPEX and especially OPEX, due to easy installations of buoy and low fuel consumption when connected. Easy and fast disconnection of the buoy is important to achieve, due to avoid impact with drifting icebergs. Polar lows may suddenly appear and fast disconnection is necessary to increase safety. An alternative solution for position keeping, which is discussed in chapter 7.2, is usage of DP. A DP-solution is more likely to be more expensive, but would make loading/offloading offshore easier and safer than the buoy solution. Further analysis of the weather conditions in the Barents Sea and analysis of consequences of an impact between hub-vessel and PSV need to be analyzed, before conclude which solution is the best choice. High safety and low costs will be important factors to consider.

The usage of hub-vessels introduce great challenges and possibilities in upstream logistics. In addition to function as a refill station for helicopters, could a hub-vessel function as an oil recovery base. SAR operations in the Barents Sea are challenging, and most of the area are not sufficiently covered by SAR helicopters. A hub-vessel with a central position related to activity in the Barents Sea will increase the SAR helicopter range, and increase the safety in the area.

The lead-time on cargo is an important factor to consider, due to high cost on rented equipment and consequences of stop in production. The lead-time on commodities will be lower for the hub-solution compared to the conventional solution, due to shorter distance between hub and installations than between base and installations. The lead-time on special equipment that is not normally onboard the hub-vessel will increase. If a special ordered equipment/tool arrives at base just after a hub-vessel leave the harbor, the item must be shipped with the next hub-vessel. The hub-vessels arrives at the harbor less frequent than the PSVs, and hence the longer lead-time. Cargo needs to be ordered earlier than for a conventional solution, and the consequence of not placing the order in time is greater. A table that shows the sailing duration as a function of distance and speed is given in Appendix G. The fastest roundtrip a hub-vessel may manage from a position 300 nautical miles from shore is approximately three days. The longest lead-time for a special item (ordered right after a hub-vessels leave harbor) is then approximately five days with transit time for hub-vessels, harbor-time, loading offshore and PSV sailing time included. For a conventional solution is it likely that one PSV is on its way back to harbor when the order is placed, and maximum lead-time will approximately be three days (depending on the time before first available PSV arrives at the base). This lead-time will vary with distance and speed of the vessels. The potential longer lead-time on rented equipment represent a cost, which is not included in the model. If the logistics are well planned, lead-time on special equipment will differ little between the two solutions, and hence the extra cost related to this will be minimal compared to other costs in the logistics chain.

Usage of hub-vessels are technological feasible and introduce some advantages, which is interesting for field developments in the Barents Sea. The design of the hub-solution will be dependent of future regulations, future technology and conditions, and may not be as described in this thesis. An alternative hub-solution is usage of Bjørnøya as a forward placed base. Bjørnøya has a central location in the Barents Sea, between the cost of Norway and Svalbard. Bjørnøya is however a nature reserve and it is unlikely that an offshore base will be allowed on the island (LOVDATA, 2002).

The mathematical model used in the analysis is originally developed to analyze a well-defined problem faced by Statoil. Assumptions regarding for instance demand, visits, capacity are inspired by earlier literature of offshore supply problems. These parameters varies with type of activity, type of platforms and field characteristics. The analysis are kept very general by analyzing several cases with different values for the parameters. The mathematical model describes the important parts of a supply problem, and hence gives valuable and realistic results. It is however important to remember that the model only describes the real problem to a certain extent, and that the whole picture is not captured by the model. The model does not include opening hours for base/vessels or maintenance of vessels for instance. Opening hours are not included because it was important to generate equal conditions for all cases. Including opening hours would make it harder to analyze which parameters that affect the results. By including openings hours is it likely that an extra PSV would be added to the fleet earlier – because of longer duration of routes due to increased waiting time in harbor. The hub-vessels' schedules include some slack for all problems, and would probably not be affected by a longer harbor time. The slack in the solutions are not considered directly, but from the results are the hub-solution very robust, due to no change in fleet composition when parameters are changed dramatically. The slack in the schedules for the conventional solution is lowest at distances right before an extra PSV is added to the fleet, and biggest right afterwards. The reason for the areas shown in the results (ref Figure 15) where more remote fields may require a smaller fleet than closer ones is that other parameters, such as spread affect the size of the fleet in addition to the distance *Base- installation centroid*. At these distances where the fleet size is irregular regards to distance from shore, small changes in speed could result in great cost savings due to the possibility of reducing the fleet by one PSV. If a vessel were added to avoid violating a capacity demand, a bigger PSV would be cheaper to charter instead of an extra one. These considerations would be important for case studies for fields located at these distances from shore.

The solution methodology in chapter 5 is developed for general analysis of the hub-solution. Earlier studies of the hub-solutions only consider a hub for well-defined problems, and does not present a conclusion of when a hub-solution may be favorable in regards to distance. (Nordbø, 2013) does additional analysis with increased number of installations in his case study, and conclude that an increased number of installations favor the hub-solution. This conclusion match the results in this thesis.

The objective in this thesis was to use the mathematical model to analyze the design of different solutions/technologies related to the hub-vessels and the design of the whole logistics chain. Small changes in design were hard to measure with the model, and design considerations are therefore done partly with the model and partly based on known technology and regulations. The position of the hub solution is based on results from our project thesis together with guidelines for helicopter transport. The solution methodology work well do analyze how different parameters affect the solutions, and to understand when a hub-solution becomes interesting. By generating randomly located installations, most of the realistically field layouts are covered, and the effect of spread of the installations can be analyzed.

The main reason for analyzing the conventional solution was to relate the results for the hub-solution with something well known, and hence make it easier to analyze the results. A side effect of these results is that the fleet composition for a supply problem can be predicted early in a planning period based on these results. These results could be of help to understand how different parameters affect the conventional solution, and hence a better understanding of the conventional supply vessel problem.

Further analysis of the hub-solution, which include for instance fuel-cost, helicopter advantages, increased safety, may conclude that the hub-solution represents a lower cost or a more equal cost compared to a conventional solution. The results from this thesis could be valuable for further research because it gives the fleet composition for the two solutions, and adjustment of charter costs and additional costs are easily included to the already existing results.

10 Conclusion

The results and discussion indicates that usage of hub-vessels in the upstream logistics chain represent a higher cost than a conventional solution. The cost difference decreases with increasing distance from shore, increasing service frequency and/or increasing number of installations. With charter costs as given in the supply problems in this thesis, a forward placed base is likely to become cost efficient for fields located more than 500 nautical miles from shore. Increased number of visits at the installations favor the hub-solution.

The optimal location for hub-vessels is according to discussion and results from the model approximately 75% of the distance *base – installation-centroid*. This location is cost efficient and allow helicopters transporting people to increase their range by about 50%.

When functioning as a forward place base in the Barents Sea is a recommendation that the hub vessels connect to an anchored buoy. This will be a less costly solution compared to a DP-system.

For remote fields, the planning period must be longer than for fields close to shore, to increase flexibility in the model.

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11 Further Work

The work done in this thesis is based on many assumptions and simplifications for a offshore supply problem in the Barents Sea. A design study of the hub-vessel should be carried out to achieve reliable data and cost for the problem. This would give valuable inputs of the vessel and a better mathematical model describing the problem could be achieved.

Detailed cost calculations for all aspects in the logistics chains should be carried out for both the hub-solution and the conventional solution. By addressing all costs related to the upstream chain will it be possible to conclude how the total cost of a hub-solution will be compared to a conventional solution.

Further research of Arctic conditions and requirements must be establish to check the availability a hub-vessel functioning as a forward placed base will experience in the Barents Sea. This will be important for checking the feasibility of the solution.

In this thesis is it assumed that the hub-vessels will operate in the Barents Sea due to the remote locations and the likelihood for recoverable petroleum resources in the area. Usage of hub-vessels is not limited to this area, and research of where it is applicable could be carried out to check the global potential of the solution.

From an operational research point of view can the model be extended with opening hours for the base and the installations. The model does not include constraints that spread the departures through the period. A way of doing this is given in the mathematical model presented in (Halvorsen-Weare et al., 2012), where spread of the departures are included.

An extension of the model could be developed; where PSVs are allowed to shuttle between base and installations to decrease lead-time on special equipment.

A model where the hub-vessel has a dynamic position would be very interesting to analyze. Optimal location of the hub-vessel might change during the period, and could potentially reduce the fleet of PSVs. Another aspect worth investigating, could be a problem with reduced availability of the hub. If only one hub-vessel is used, it will be unavailable for the PSVs the time when it sails back to base for refill of commodities.

To investigate the dynamics in the logistics chain, a simulation model including stochastic data for demand and weather could be developed. The unavailability of the hub, due to wave heights over the limit for cargo handling offshore could be investigated in an efficient and reliable manner with a simulation model like this.

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Appendix A Matlab script

```
clear all
tStart = tic;

rng(12345);

%% Input variable manipulation variables

% Number of runs (will generate random installations within the same param-
%eters this many times:)
numRun = 50;

% Number of installations in each scenario
numInstallations = 6;

% Number of offset locations - (how many times the installation matrix is
% moved "instLatOffset" degrees north
numInstOffset = 4;

% Offset of installations for each simulation
instLatOffset = 2;
instLonOffset = 0;

% numHubLoc = 2, means 75% of distance: centroid - Base. =1, 50%,=3 100%
numHubLoc = 2;

% Set equal to 1 if you want to simulate without hub
noHub = 1;

% Initialize results matrix
results = zeros( numRun, 19 );

% Run simulation for 3 to "numInstallations" installations
for instNum = 3:numInstallations
    tNumInstallations = tic;

    fprintf('\n\n============\n\nInstallations: %d \n', instNum);
```

```
    % For each installation set size, increasy the lowerLat limit
    for instOffset = 1:numInstOffset
        tNumInstOffset = tic;

        fprintf('Offset: %d \n', (instOffset-1)*instLatOffset);

        % For each set of installation and position, increase the relative
        % distance from base
        for hubLoc = 2:2 % 2:2 because 75% distance is used
            tNumHubLoc = tic;

            fprintf('\nHUB SW LAT:  %d\n\n', hubLoc);

            % Running the actual simulation "numRun" times
            for run = 1:numRun
                tGenFiles = tic;


                %% Input variables
                % Coordinates for land supply bases
                    %Hammerfest: 70.661667 23.40
                baseCoordinates = [
                    70.661667, 23.40;
                    ];
                nBases = size(baseCoordinates,1);

                %Cost for making use of supply base per ton cargo transported from base [10^3 NOK / ton]
                Cb = [1.0];     % vector if more than one base

                % Setting lower and upper limits for longitude and latitude
                lowerLat = 71 + ((instOffset - 1) * instLatOffset);
                upperLat = lowerLat + 3;

                lowerLon = 15;
                upperLon = 37;

                randomLat = lowerLat + (upperLat-lowerLat) .* rand(instNum,1);
```

```
randomLon = lowerLon + (upperLon-lowerLon) .* rand(instNum,1);
instCoordinates = [randomLat(:), randomLon(:)];

nInst = size(instCoordinates,1);

% Weekly demand per installation [ton]
instDemand = [
    230, 230, 230, 230, 230, 230, 230;
    ].*4;

sumDemand = sum( instDemand );
% Weekly required number of services per installation [#]
instService = [
    3, 3, 3, 3, 3, 3, 3;
    ].*2; %multiplied by two to get 3 a week

% South west corner for hub positions
a = Measure.centroidCoords( instCoordinates );
b = Measure.centroidCoords( baseCoordinates );

% approx distance between base and installation centroid
bal = a(1) - b(1);

if noHub == 0
    if hubLoc == 1 % 50% of the way
        hubLat = b(1) + (bal * 0.5);
    elseif hubLoc == 2 % 75%
        hubLat = b(1) + (bal * 0.75);
    elseif hubLoc == 3 % 100% - set it equal to instCentroid
        hubLat = a(1);
    end

    hubSW = [ hubLat, 26; ];
else % noHub is in effect
    hubSW = baseCoordinates(1,:);
end


% Number of hub locations in longitudinal direction
```

```
            hubNLon = 1;
            hubStepLon = 4;
            % Number of hub locations in latitudinal direction
            hubNLat = 1;
            hubStepLat = 0.5;

            % Period [weeks]
            periodWeeks = 2;

            % Capacity per vessel [ton] changed for different runs
            qHUB = 1200;
            qPSV = [450 450 450 450 450 450 450 450 450 450] ;

            % Service speed per vessel [knot]
            vShuttle = 10;
            vPSV = 12;

            % Number of PSV available - affects the solution time
            nPSV = 8;

            %Yearly cost for chartering one vessel [10^3 NOK]
            CYearEO = 120000;
            CYearET = [80000 80000 80000 80000 80000 80000 80000 80000] ;

            % CET is cost per unit chartered and used PSV per planning period
            CET = CYearET.*(periodWeeks/52);

            %% Create hub locations as a grid
            hubGrid = zeros(hubNLon, hubNLat,2);   %Keep the grid points in a 3-dim matrix (hg=hubGrid)

            for i = 1:hubNLon
                for j = 1:hubNLat
                    hubGrid(i,j,1) = hubSW(1) + hubStepLat * (i-1);
                    hubGrid(i,j,2) = hubSW(2) + hubStepLon * (j-1);
                end
            end

            % Reshape matrix so it becomes a list of coordinates [lat,lon]
```

```matlab
hubCoordinates = reshape(hubGrid, hubNLon*hubNLat, 2);
nHubs = size(hubCoordinates,1);

%% Find distances between all installations and hubs

% Distances from all hub positions to all installations
distHubInst = zeros( nHubs, nInst);
for i = 1:nHubs
    for k = 1:nInst
        distHubInst(i,k) = Measure.distTwoPoints( hubCoordinates(i,:), instCoordinates(k,:) );
    end
end
durationHubInst = distHubInst ./ vPSV;

% Distances between all installations
distInst = zeros( nInst );
for i = 1:nInst
    for k = 1:nInst
        distInst(i,k) = Measure.distTwoPoints( instCoordinates(i,:), instCoordinates(k,:) );
    end
end
durationInst = distInst ./ vPSV;

% Distances between all supply bases and hub locations
distBaseHub = zeros( nBases, nHubs );
for i = 1:nBases
    for k = 1:nHubs
        distBaseHub(i,k) = Measure.distTwoPoints( baseCoordinates(i,:), hubCoordinates(k,:) );
    end
end
durationBaseHub = distBaseHub ./ vShuttle;

% Distances between all supply bases and installations
distBaseInst = zeros( nBases, nInst );
for i = 1:nBases
    for k = 1:nInst
        distBaseInst(i,k) = Measure.distTwoPoints( baseCoordinates(i,:), instCoordinates(k,:) );
    end
end
```

```
durationBaseInst = distBaseInst ./ vPSV;

%% Route generation

% Generate all set partitions. i.e. all possible combinations
% This gives us routes on the form [ 1 1 0 ] <- inst 1 and 2 are included
% in this route

% Create a vector of platforms using numbers
installations = 1:nInst;

% Initialize N, holding number of possible routes
N = 0;
for i = 1:nInst
    N = N + nchoosek(nInst,i);
end
% Initialize route matrix with N rows and nInstallations col
routeMatrix = zeros(N, nInst);

route = 0;
for i = 1:nInst
    c = nchoosek(installations,i);
    for j = 1:size(c,1)
        route = route + 1;
        for k = 1:i
            routeMatrix(route, c(j,k) ) = 1;
        end
    end
end
Air = routeMatrix';
nRoutes = size(routeMatrix,1);

% Find the shortest/cheapest/fastest route possible that contains the given
% installations

% durationHubRotue (Thr in input file) contains the duration of each
% route starting and ending in the same hub. So each row contains the
```

```
                % durations for each routes (column) giving us D_hr - distance for each
                % hub, per route

                durationHubRoute = zeros(nHubs, nRoutes);
                for h = 1:nHubs
                    for r = 1:nRoutes
                        % Initialize matrix
                        nodes = zeros(nInst,1);

                        % Finds the node number included in this tour
                        % [ 1 1 0 ] gives [ 1 2 ]
                        k = 1;
                        for i = 1:nInst
                            if routeMatrix(r,i) == 1
                                % Store the node number that is included in this tour
                                nodes(k) = i;
                                k = k + 1;
                            end
                        end
                        % Removes all the zero elements from the vector
                        nodes = nodes(nodes~=0);

                        % Find all possible permutations containing the nodes found
                        % Number of rows in P is equal to (number of rows)! (read as factorial)
                        % [ 1 2 ] gives [ 1 2 ] and [ 2 1 ]
                        permutations = perms(nodes);

                        % Set the best length found so far to Inf. If no better length
                        % is found, the function halts the execution as something is
                        % clearly wrong
                        bestLength = Inf;

                        % Loop over all rows of P
                        for i = 1:length(permutations)
                            thisLength = 0;

                            % Sum the length of the route(current permutation of perm)
```

```
                            % Starting with row 1, element 1 -> 2
                            % 4 is the amount of time expected at each installation
                            for k = 2:length(nodes)
                                thisLength = thisLength + 4 + distInst( permutations(i,k-1), permutations(i,k) ) / vPSV;
                            end

                            % Adding the distance from the hub to the first installation
                            thisLength = 4 + thisLength + distHubInst( h, permutations(i,1) ) / vPSV;

                            % Adding the distance from the last installation to the hub
                            thisLength = 4 + thisLength + distHubInst( h, permutations(i,size(permutations,2))) / vPSV;

                            % Checks to see if the current routes length is shorter
                            % than the best one so far and sets it as the best length
                            % if that is the case.
                            if thisLength < bestLength
                                bestLength = thisLength;
                            end
                        end

                        % Checking to see if the code above has found any solutions at
                        % all.
                        if bestLength == Inf
                            error('Best length for route is Inf! The xpress model won''t handle that, so the script halts.');
                        end
                        durationHubRoute(h,r) = bestLength;
                    end
                end

                %% Calculates nTimes which is set so that the shortest route
                periodHours = periodWeeks * 24 * 7;

                %nTimes = 19;
                nTimes = floor(periodHours / min(min( durationHubRoute )));

```

```
            %% Calculate nVessel

            % Initialize and set values to 2
            nVessel = zeros(nBases, nHubs) + 2;

            nTrips = ones( nBases, nHubs );

            % This block is copied from Akselsens script
            % Adds extra hub vessel if it is needed
            for i = 1:nBases
                for j = 1:nHubs
                    if ( (2*durationBaseHub(i,j) > (periodHours/(2*nTrips(i,j)))) && ...
                            (nVessel(i,j)* qHUB < sumDemand) ) %Logic constraint saying duration and demand is wrong
                        nVessel(i,j) = nVessel(i,j) + 1; %(2*bhDuration) fordi NoTrips representerer antall rundturer hub-base-hub
                    elseif ( ...
                            (nVessel(i,j)* qHUB >= sumDemand) && ... % number of vessels * hub vessel capacity must exceed demand
                            (2 * durationBaseHub(i,j) > (periodHours/(2*(nTrips(i,j)+1)))))
                        %Capasity is right, but can't sail the trips, so need another vessel


                        nVessel(i,j) = nVessel(i,j) + 1;
                        nTrips(i,j) = nTrips(i,j)+1;
                    end
                end
            end

            %% Calculate C_bh^E0 - Cost for serving hub-vessels in echelon 14
            CbhEO = zeros( nBases, nHubs );
            for i = 1:nBases
                for j = 1:nHubs
                    if noHub ==0
                    CbhEO(i,j) = nVessel(i,j) * CYearEO/52 * periodWeeks;
                    else
                        CbhEO(i,j) = 0;
                    end
                end
```

```
end

%% Calculate big M values
Mr = max(instDemand);
Mp = ceil(periodHours / min(min(durationHubRoute)));

%% Write to file!
fileNameStart = 'InputHub';
fileEnding = '.dat';
fileName = strcat(fileNameStart, num2str(run), fileEnding);

fID = fopen(fileName, 'w+');

fprintf(fID, '! Something about this being an input file\n');
fprintf(fID, '\n');
fprintf(fID, 'nHubs : %d\n', nHubs);
fprintf(fID, 'nBases : %d\n', nBases);
fprintf(fID, 'nRoutes : %d\n', nRoutes);
fprintf(fID, 'nPsv : %d\n', nPSV);
fprintf(fID, 'nInstallations : %d\n', nInst);
fprintf(fID, 'nTimes : %d\n\n', nTimes);

fprintf(fID, 'Thr : [\n');
for i = 1:nHubs
    for j = 1:nRoutes
        fprintf(fID, '%.0f\t', durationHubRoute(i,j));
    end
    fprintf(fID, '\n');
end
fprintf(fID, ']\n\n');
fprintf(fID, 'CET : [\n');
for i = 1: nPSV
    fprintf(fID, '%.0f\t', CET(i));
end
fprintf(fID, '\n]\n');

fprintf(fID, 'CbhEO : [\n');
for i = 1:nBases
    for j = 1:nHubs
```

```
                fprintf(fID, '%.0f\t', CbhEO(i,j));
            end
            fprintf(fID, '\n');
        end
        fprintf(fID, ']\n\n');

        fprintf(fID, 'Cb : [\n');
        for i = 1:nBases
            fprintf(fID, '%.0f\t', Cb(i));
        end
        fprintf(fID, '\n]\n');

        fprintf(fID, 'W : %.0f\n\n', periodHours);

        fprintf(fID, 'Si : [\n');
        for i = 1:nInst
            fprintf(fID, '%.0f\t', instService(i));
        end
        fprintf(fID, '\n]\n\n');

        fprintf(fID, 'Di : [\n');
        for i = 1:nInst
            fprintf(fID, '%.0f\t', instDemand(i));
        end
        fprintf(fID, '\n]\n\n');

        fprintf(fID, 'Air : [ \n');
        for i = 1:nInst
            for j = 1:nRoutes
                fprintf(fID, '%.0f\t', Air(i,j));
            end
            fprintf(fID, '\n');
        end
        fprintf(fID, ']\n\n');


        fprintf(fID, 'Qp : [ \n');
        for i = 1:nPSV
            fprintf(fID, '%.0f\t', qPSV(i));
        end
        fprintf(fID, '\n]\n\n');
```

```
            fprintf(fID, 'M_p : %0.f\n', Mp);
            fprintf(fID, 'M_r : %0.f\n', Mr);

            fclose(fID);

            disp(sprintf('Generating file for simulation %d took %.2f seconds', run, toc(tGenFiles)));

            %% Running mosel for each of the input files generated above

            moselPath = 'C:\xpressmp75\bin\mosel.exe -c "exec ';
            execString = 'C:\Users\torestan\Documents\01_Studies\01_Masteroppgave\Optimering\SimuleringMedDobbelDemand\noHub\updated01.mos ''DataFile="';
            fileName = strcat('InputHUB', num2str(run),'.dat');
            syntaxFix = '"''"';
            moselRun = tic;
            [a,b] = system(strcat(moselPath,execString,fileName,syntaxFix));
            disp(sprintf('Running mosel on file for simulation %d of %d took %.2f seconds. Installations: %d, lowerLat: %d', run, numRun, toc(moselRun), instNum, lowerLat));
            % Convert b to cell array split by lines
            result = strsplit(b,'\n');

            objectiveValue = str2num(cell2mat(result(3)));

            results(run, 1) = objectiveValue; % Objective value from xpress
            results(run, 2) = nInst; % Number of installations
            results(run, 3) = Measure.sumAllDist( distInst ); % Sum of all distances
            results(run, 4) = Measure.sumDistCentroid( instCoordinates, Measure.centroidCoords(instCoordinates)); % sum from all distances to centroid
            results(run, 5) = Measure.distBaseHubInstCentroid(instCoordinates, hubCoordinates, baseCoordinates); % Distance base-hub-installation-centroids
            results(run, 6) = Measure.sumAllRoutes(durationHubRoute); % Sum of all route durations
            results(run, 7) = Measure.meanAllRoutes(durationHubRoute); % Mean of all routes
            results(run, 8) = Measure.shortestTSP(durationHubRoute, routeMatrix); %
            results(run, 9) = Measure.distTwoPoints( Measure.centroidCoords(baseCoordinates), hubSW ); % Distance
```

```
                results(run, 10) = sum( instDemand(1:instNum) ); % Sum of installation demand
                results(run, 11) = mean( instDemand(1:instNum) ); % Mean of installation demand
                results(run, 12) = CYearEO; % Cost of chartering shuttle
                results(run, 13) = qHUB; % HUB Capacity
                results(run, 14) = qPSV(1); % PSV capacity
                results(run, 15) = sum( instService(1:instNum) ); % Sum of installation service need
                results(run, 16) = mean( instService(1:instNum) ); % Mean of installation service need
                results(run, 17) = toc(moselRun); % Time it takes for mosel to find the optimal solution
                results(run, 18) = Measure.distTwoPoints( Measure.centroidCoords( baseCoordinates ), Measure.centroidCoords( instCoordinates ) ); % Distance base-inst
                results(run, 19) = CYearET(1);      %PSV cost
                %Legges noe til, så må linje 30 oppdateres

              delete('InputHUB*.dat');


            end % End each run

            % Simulation for numRun scenarios run. Save the result and move
            % on

            % Legge til i filnavn
            % HUBSW-plassering
            % Installasjons-koordinat-grensen
            % Antall installasjoner

            hubSWLoc = strcat(num2str(hubSW(1)));
            instLimit = strcat(num2str(lowerLat));


            fileName = strcat( 'lat', instLimit, 'hubLat', floor(hubSWLoc(1)), num2str(numRun),'runs', num2str(instNum), 'inst.mat');

            save(fileName, 'results');

        end % Hubloc
    end % Instoffset
```

```
end % Numinst


fprintf('Running the entire script took %.2f seconds.\n', toc(tStart));
```

Appendix B Matlab script – measures

```
classdef Measure
    %MEASURE Functions measuring different aspects
    %   Detailed explanation goes here

    % Define constants that are common for all functions
    properties (Constant)
        % A place to put constants like earth radius
    end

    % Static so that I can use the functions without having an instance of
    % the class
    methods (Static)

        %DISTTWOPOINTS Returns distance (great circle) between two
        %coordinates
        % coord1 = [lat, lon]
        % coord2 = [lat, lon]

        function dist = distTwoPoints(coord1, coord2)
            earthRadiusInMeters = 6371000;
            dist = round((rad2nm(distance( ...
                coord1(1), coord1(2), ...
                coord2(1), coord2(2), ...
                earthRadiusInMeters)/earthRadiusInMeters)));
        end


        %%
        % Calculates distMatrix, giving the respective distances
        % between all the nodes

        function dist = distMatrix(coordMatrix)
            % Initialize distMatrix
            dist = zeros( size(coordMatrix,1), size(coordMatrix,1) );

            for i = 1:size(dist,1)
                for j = 1:size(dist,1)
                    dist(i,j) = Measure.distTwoPoints( ...
```

```
                        [coordMatrix(i,1), coordMatrix(i,2)], ...
                        [coordMatrix(j,1), coordMatrix(j,2)]);
                end
            end
        end

        %%
        % Returns the sum of the distances between all the nodes.
        % Input is a matrix with distances between all nodes. For example
        % one calculated by Measure.distMatrix()
        function Dtot = sumAllDist(distMatrix)
            % Initialize Dtot
            Dtot = 0;

            % Sum all the distances
            for i = 1:size(distMatrix)
                for j = i:size(distMatrix)
                    Dtot = Dtot + distMatrix(i,j);
                end
            end
        end

        %%
        % Return matrix of hub coordinates based on southwest corner
        % coordinate, distance between hubs and how many hubs are wanted
        function hubCoords = createHubMatrix(swCoord, latStep, latNum, lonStep, lonNum)
            % Initilialize hubCoordinate matrix
            hubCoords = zeros(latNum,lonNum,2);
            % Finds the coordinates for all the possible hub locations
            for i = 1:latNum
                for j = 1:lonNum
                    hubCoords(i,j,1) = swCoord(1) + i*latStep;
                    hubCoords(i,j,2) = swCoord(2) + j*lonStep;
                end
            end
            % Reshape the 3 dimensional matrix to a list of two-dimensional
            % list of coordinates
            hubCoords = reshape(hubCoords, latNum*lonNum, 2);
            return;
```

```
        end

        %%
        % Returns the length of a minimum spanning tree using some simple
        % algorithm (Prim or Kruskals method)
        function mst = primMST()
            % Just needs some work ...
        end

        %%
        % Finds all installation visits matrix
        % 1 route per row, 1 installation per column
        % value is 1 if route visits installation, 0 else
        %
        % For nInstallations = 3 the following is returned
        % ans =
        %       1     0     0
        %       0     1     0
        %       0     0     1
        %       1     1     0
        %       1     0     1
        %       0     1     1
        %       1     1     1
        function routeMatrix = createRouteMatrix(nInstallations)
            % Create a vector of platforms using numbers
            installations = 1:nInstallations;

            % Initialize N, holding number of possible routes
            N = 0;
            for i = 1:nInstallations
                N = N + nchoosek(nInstallations,i);
            end
            % Initialize route matrix with N rows and nInstallations col
            routeMatrix = zeros(N, nInstallations);

            route = 0;
            for i = 1:nInstallations
                c = nchoosek(installations,i);
                for j = 1:size(c,1)
                    route = route + 1;
```

```
                for k = 1:i
                    routeMatrix(route, c(j,k) ) = 1;
                end
            end
        end
    end

    %%
    % Returns the centroid of a set of nodes given as coordinates
    % Just calculates the mean of the latitudes and longitudes
    function centroid = centroidCoords(nodeCoords)
        centroid = zeros(2,1);
        centroid(1) = mean( nodeCoords(:,1) );
        centroid(2) = mean( nodeCoords(:,2) );
    end

    %%
    % Calculates distance from
    function sumDist = sumDistCentroid(nodeCoords, centroid)
        centroidDistance = zeros( size(nodeCoords, 1) );

        % Calculate distance between centroid and nodes
        for i = 1:size(centroidDistance,1)
            % rad2nm returns distance based on the arc on the
            % surface of a sphere with radius equal to
            % earthRadiusInMeters
            centroidDistance(i) = Measure.distTwoPoints( ...
                [nodeCoords(i,:)], ...
                [centroid]);
        end
        sumDist = sum(sum(centroidDistance));
    end

    %%
    % Returns the value of the shortest tour possible that includes the
    % nodes given by perm
    % e.g. perm = [ 1 0 1 ] means that the route includes node 1 and 3
    % and this function returns the value of the cheapest/shortest option
    % This is done by brute force, so it checks n! solutions. So if
```

```
        % there are many nodes, this may take a long time and use a lot of
        % memory
        %%
        %
        function bestLength = shortestTour(perm, instCoords, hubLat, hubLon, vPSV)
            % Initialize matrix
            nodes = zeros(length(perm));

            dist = Measure.distMatrix(instCoords);

            j = 1;
            for i = 1:length(perm)
                if perm(i) == 1
                    % Store the node number that is included in this tour
                    nodes(j) = i;
                    j = j + 1;
                end
            end


            % Remove all the zero elements from the vector
            nodes = nodes(nodes~=0);

            % Find all possible permutations containing the nodes found
            % Number of rows in P is equal to (number of rows)! (read as factorial)
            permutations = perms(nodes);

            % Set the best length found so far to Inf. If no better length
            % is found, the function halts the execution as something is
            % clearly wrong
            bestLength = Inf;

            % Loop over all rows of P
            for i = 1:length(permutations)
                thisLength = 0;

                % Sum the length of the route(current permutation of perm)
```

```
                % Starting with row 1, element 1 -> 2
                for j = 2:length(nodes)
                    thisLength = thisLength + dist( permutations(i,j-1), permutations(i,j) ) / vPSV;
                end

                % Adding the distance from the hub to the first installation
                thisLength = thisLength + ...
                    (Measure.distTwoPoints( [hubLat, hubLon], ...
                    [instCoords(permutations(i,1),1), instCoords(permutations(i,1),2)] ) )/ vPSV;

                % Adding the distance from the last installation to the hub
                thisLength = thisLength + ...
                    (Measure.distTwoPoints( [hubLat, hubLon], ...
                    [instCoords(permutations(i, size(permutations(i),1)),1), instCoords(permutations(i,size(permutations(i),1)),2)] ) )/ vPSV;

                % Checks to see if the current routes length is shorter
                % than the best one so far and sets it as the best length
                % if that is the case.
                if thisLength < bestLength
                    bestLength = thisLength;
                end
            end

            % Checking to see if the code above has found any solutions at
            % all.
            if bestLength == Inf
                error('Best length for route is Inf! The xpress model won''t handle that, so the script halts.');
            end
        end

        % Returns the distance from base centroid to hub centroid to
        % installation centroid
        function totalLength = distBaseHubInstCentroid(instCoordinates, hubCoordinates, baseCoordinates)
            instC = Measure.centroidCoords( instCoordinates );
            hubC = Measure.centroidCoords( hubCoordinates );
```

```
            baseC = Measure.centroidCoords( baseCoordinates );
            totalLength = Measure.distTwoPoints( baseC, hubC ) + Measure.distTwoPoints( hubC, instC );
        end

        % Returns the duration of all the routes
        function sumAll = sumAllRoutes(routes)
            sumAll = sum(sum(routes));
        end

        % Returns the mean of all the routes
        function meanAll = meanAllRoutes(routes)
            meanAll = mean(mean(routes));
        end

        % Returns the duration of the route that contains all the
        % installations
        % Disregarding that there are multiple hub positions, so it returns
        % one value, not one for every hub position
        function shortestTSP = shortestTSP(durationHubRoute, routeMatrix)
            for i = 1:size(routeMatrix,1)
                if sum(routeMatrix(i,:)) == size(routeMatrix, 2)
                    % All installations are part of this route, so its
                    % value is the shortest TSP value as long as the routes
                    % in durationHubRoute contain the optimal TSP
                    shortestTSP = max(durationHubRoute(:,i));
                end
            end
        end

    end % End methods
end % end classdef
```

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Appendix C Xpress IVE script

```
! Tore Stang's Master Thesis Spring 2015
!

model hublogistics
!gain access to the Xpress-Optimizer solver
uses "mmxprs";

! Line break is not an expressio separator. All commands must end with a ;
options explterm
! Everything except indices must be declared before it is used
options noimplicit

!Import parameters from input file
parameters
    DataFile = 'InputHub1.dat';
    !Maximum time to run the model
    LIMIT = -600;
end-parameters

!Declare sizes that is to be imported
declarations
    nHubs        :   integer;
    nBases       :   integer;
    nRoutes      :   integer;
    nPsv         :   integer;
    nInstallations: integer;
    nTimes       :   integer;
end-declarations

!Import values from Datafile
initializations from DataFile
    nHubs;
    nBases;
    nRoutes;
    nPsv;
    nInstallations;
    nTimes;
end-initializations
```

```

!Declare the sets:
declarations
    Hubs         :   set of integer;
    Bases        :   set of integer;
    Routes       :   set of integer;
    Psv          :   set of integer;
    Installations:   set of integer;
    Times        :   set of integer;
end-declarations

!Defines the size of the sets
Hubs := 1 .. nHubs;
Bases :=1 .. nBases;
Routes :=1 .. nRoutes;
Psv :=1 .. nPsv;
Installations := 1 .. nInstallations;
Times := 1 .. nTimes;

!finalize the sets
finalize(Hubs);
finalize(Bases);
finalize(Routes);
finalize(Psv);
finalize(Installations);
finalize(Times);

!Declare parameters
declarations
    Thr     :   array(Hubs,Routes)             of integer; ! Duration of route r originating and ending at hub h
    CET     :   array(Psv)                     of integer; ! Cost for a PSV Should be an array!
    CbhEO   :   array(Bases, Hubs)             of integer; ! Cost of a hub vessel
    Cb      :   array(Bases)                   of integer; ! Cost of base - Will not be important in these analysis
    W       :                                     integer;    ! limit of sailing hours per period
    Si      :   array(Installations)           of integer; ! required number of services per period
    Air     :   array(Installations, Routes)of integer; ! equal one if installations i is visited on route r
    Qp      :   array(Psv)                     of integer; ! Capacity on psv - 4.2 in report                            IS THIS ACTIVE?
    Di      :   array(Installations)           of integer; ! Demand installation i
```

```
    M_p     :                              integer;     ! Big number
    M_r     :                              integer;     ! Big number
end-declarations

!initializations of declared parameters
initializations from DataFile
    Thr;
    CET;
    CbhEO;
    Cb;
    W;
    Si;
    Air;
    Qp;
    Di;
    M_p;
    M_r;
end-initializations

!Declare variables
declarations
    deltaH  :   dynamic array(Hubs)                                    of mpvar;
    gammaB  :   dynamic array(Bases)                                      of mpvar;
    alphaP  :   dynamic array(Psv)                                     of mpvar;
    rhoBH   :   dynamic array(Bases, Hubs)                             of mpvar;
    xPRH    :   dynamic array(Psv, Routes, Hubs)                       of mpvar;
    qIPRK   :   dynamic array(Installations, Psv, Routes, Times)       of mpvar;
    betaPRK :   dynamic array(Psv, Routes, Times)                      of mpvar;
end-declarations

!Generate the variables
forall (hh in Hubs) do
    create(deltaH(hh));
end-do

forall (bb in Bases) do         !Denne er itte aktiv, vil bare være en
    create(gammaB(bb));
end-do

forall (pp in Psv) do
    create(alphaP(pp));
```

```
end-do

forall (bb in Bases, hh in Hubs) do
    create(rhoBH(bb,hh));
end-do

forall (pp in Psv, rr in Routes, hh in Hubs) do
    create(xPRH(pp, rr, hh));
end-do

forall (ii in Installations, pp in Psv, rr in Routes, tt in Times) do
    create(qIPRK(ii,pp,rr,tt));
end-do

forall (pp in Psv, rr in Routes, tt in Times) do
    create(betaPRK(pp,rr,tt));
end-do

!Declare all restrictions (written under)
declarations
    TotalCost   :                                                    linctr; !objective function (5.1) in the report
    Service     :   dynamic array(Installations)                  of linctr; !Constraint 5.2 in the report
    HubLocation :                                                    linctr; !Constraint 5.3 in the report
    BaseLocation    :                                                linctr; !constraint 5.4 in the report
    CouplingA   :   dynamic array(Routes,Psv)                          of linctr;  !Constraint 5.5 in the report
    CouplingB   :   dynamic array(Bases)                          of linctr; !constraint 5.6 in the report
    CouplingC   :   dynamic array(Psv, Hubs)                      of linctr; !constraint 5.7 in the report
    ExistBase   :   dynamic array(Bases)                          of linctr; !constraint 5.8 in the report
    ExistHub    :   dynamic array(Hubs)                           of linctr; !constraint 5.9 in the report
    Duration     :   dynamic array(Psv,Hubs)                           of linctr;  !constraint 5.10 in the report
    Delivery    :   dynamic array(Installations)                  of linctr; !constraint 5.11 in the report
    CouplingD   :  dynamic array(Installations, Routes, Psv, Times)    of linctr; !constraint 5.12 in the report
    CouplingE   :   dynamic array(Routes,Psv)                     of linctr; !constraint 5.13 in the report
    CapacityVessel  :   dynamic array(Routes, Psv)                of linctr; !constraint 5.14 in the report
    AntiSym_p   :  dynamic array(Installations, Routes, Psv, Times)    of linctr; !constraint 5.15 in the report
```

```
    AntiSym_b   :   dynamic array(Psv, Routes, Times)                  of linctr;
!constraint 5.16 in the report
end-declarations

!-------Everything declared, mathematical model under ---------

! Define the objective function
TotalCost :=
    sum(pp in Psv) CET(pp) * alphaP(pp) +
    sum(bb in Bases, hh in Hubs) CbhEO(bb,hh) * rhoBH(bb,hh) +
    sum(bb in Bases, ii in Installations) Cb(bb) * Di(ii) * gammaB(bb);

!Constraint 5.2
forall(ii in Installations) do
    Service(ii) :=
        sum(hh in Hubs, pp in Psv, rr in Routes) Air(ii,rr) * xPRH(pp,rr,hh) >= Si(ii);
end-do

!constraint 5.3
HubLocation :=
    sum(hh in Hubs) deltaH(hh) = 1;

!Constraint 5.4
BaseLocation :=
    sum(bb in Bases) gammaB(bb) = 1;        !bare en base blir valgt

!Constraint 5.5
forall(pp in Psv, rr in Routes) do
    CouplingA(rr,pp) :=
        sum(hh in Hubs) xPRH(pp,rr,hh) - (M_p * alphaP(pp)) <= 0;
end-do

!Constraint 5.6
forall (bb in Bases) do
    CouplingB(bb) :=
        sum(hh in Hubs) rhoBH(bb,hh) - gammaB(bb) <= 0;
end-do

!Constraint 5.7
forall (pp in Psv, hh in Hubs) do
    CouplingC(pp,hh) :=
```

```
        sum(rr in Routes) xPRH(pp,rr,hh) - (M_p * deltaH(hh)) <= 0;
end-do

!Constraint 5.8
forall (bb in Bases) do
    ExistBase(bb) :=
        gammaB(bb) = sum(hh in Hubs) rhoBH(bb,hh);
end-do

!Constraint 5.9
forall (hh in Hubs) do
    ExistHub(hh) :=
        deltaH(hh) = sum(bb in Bases) rhoBH(bb,hh);
end-do

!Constraint 5.10
forall (pp in Psv, hh in Hubs) do
    Duration(pp,hh) :=
        sum(rr in Routes) Thr(hh,rr) * xPRH(pp,rr,hh) <= W;
end-do

!Constraint 5.11
forall (ii in Installations) do
    Delivery(ii) :=
        sum(pp in Psv, rr in Routes, tt in Times) qIPRK(ii,pp,rr,tt) >= Di(ii);
end-do

!Constraint 5.12
forall (ii in Installations, rr in Routes, pp in Psv, tt in Times) do
    CouplingD(ii,rr,pp,tt) :=
        qIPRK(ii,pp,rr,tt) - M_r * betaPRK(pp,rr,tt) <= 0;
end-do

!Constraint 5.13
forall (rr in Routes, pp in Psv) do
    CouplingE(rr,pp) :=
        sum(tt in Times) betaPRK(pp,rr,tt) = sum(hh in Hubs) xPRH(pp,rr,hh);
end-do

!Constraint 5.14
forall (rr in Routes, pp in Psv) do
```

```
    CapacityVessel(rr,pp) :=
        Qp(pp) >= sum(ii in Installations, tt in Times) qIPRK(ii,pp,rr,tt);
end-do

!Constraint 5.15
forall (ii in Installations, pp in Psv, rr in Routes, tt in Times | tt  <= (nTimes-1) ) do
    AntiSym_p(ii,rr,pp,tt) :=
        qIPRK(ii,pp, rr, tt+1) <= qIPRK(ii,pp, rr, tt);
end-do

!Constraint 5.16
forall (pp in Psv, rr in Routes, tt in Times | tt <= (nTimes-1) ) do
    AntiSym_b(pp,rr,tt) :=
        betaPRK(pp, rr, tt+1) <= betaPRK(pp,rr, tt);
end-do

!Defines binary restriction of variables

forall(hh in Hubs) deltaH(hh) is_binary;

forall(bb in Bases) gammaB(bb) is_binary;

forall (pp in Psv) alphaP(pp) is_binary;

!Defines integer variables
forall (bb in Bases, hh in Hubs) rhoBH(bb,hh) is_integer;

forall (pp in Psv, rr in Routes, hh in Hubs) xPRH(pp,rr,hh) is_integer;

forall (ii in Installations, pp in Psv, rr in Routes, tt in Times) qIPRK(ii,pp,rr,tt) is_integer;

forall (pp in Psv, rr in Routes, tt in Times) betaPRK(pp,rr,tt) is_binary;

setparam('xprs_maxtime',LIMIT);
minimize (TotalCost);

!Write to output
writeln;
writeln(getobjval);
writeln;
```

```

! Displays number of PSVs in use by this solution
writeln( sum(pp in Psv) getsol(alphaP(pp)) );

writeln;
writeln('xPRH int - number of times PSV p sails on route r starting and ending in hub h each period');
!writeln(' ');
forall(pp in Psv, rr in Routes ,hh in Hubs) do
    if (getsol(xPRH(pp, rr, hh)) <> 0 ) then
        write('xPRH(',pp,',', rr,',', hh,') : ');
        writeln(getsol(xPRH(pp, rr, hh)));
    end-if
end-do


end-model
```

Appendix D Example of input file from Matlab

```
! Input file from matlab Script - Tore Stangs Master Thesis

nHubs : 1
nBases : 1
nRoutes : 31
nPsv : 8
nInstallations : 5
nTimes : 11

Thr : [
49    34    37    29    31    57    71    60    68    53    42    50    44
      41    41    75    64    72    75    76    72    57    58    54    49
      80    80    76    80    62    84
]

CET : [
3077  3077  3077  3077  3077  3077  3077  3077
]
CbhEO : [
0
]

Cb : [
1
]
W : 336

Si : [
6     6     6     6     6
]

Di : [
460   460   460   460   460
]

Air : [
1     0     0     0     0     1     1     1     1     0     0     0     0
      0     0     1     1     1     1     1     1     0     0     0     0
      1     1     1     1     0     1
0     1     0     0     0     1     0     0     0     1     1     1     0
      0     0     1     1     1     0     0     0     1     1     1     0
      1     1     1     0     1     1
0     0     1     0     0     0     1     0     0     1     0     0     1
      1     0     1     0     0     1     1     0     1     1     0     1
      1     1     0     1     1     1
0     0     0     1     0     0     0     1     0     0     1     0     1
      0     1     0     1     0     1     0     1     1     0     1     1
      1     0     1     1     1     1
0     0     0     0     1     0     0     0     1     0     0     1     0
      1     1     0     0     1     0     1     1     0     1     1     1
      0     1     1     1     1     1
]
```

```
Qp : [
450   450   450   450   450   450   450   450
]

M_p : 12
M_r : 460

FuelCost : [
126   77    84    59    65    140   187   152   176   128   93    118   99
      90    89    191   156   181   191   193   181   132   134   122   105
      195   197   185   197   138   201
]
```

Appendix E Measurements saved in results vector

In addition to the lowest possible cost for each run (optimal solution), several parameters are saved in the result vector. Some of these parameters are analyzed against optimal solution.

Table 10 - List of measurements saved in result vector

Measurement/ parameters	**Obtained from**
Objective function value	Xpress IVE
Number of installations	From scenario
Geographical constraints of installation locations	From Scenario
Relative hub position	From Scenario
Sum of all distances between installations	Pre-Processing
Sum of distance from centroid to installations	Pre-Processing
Sum of all route durations	Pre-Processing
Mean of all route durations	Pre-Processing
Shortest route covering all installations	Pre-Processing
Distance from base to south west hub	Pre-Processing
Sum of installation demand	Pre-Processing
Mean of installation demand	Pre-Processing
Cost of chartering shuttle	Pre-Processing
Shuttle capacity	Pre-Processing
PSV capacity	Pre-Processing
Sum of installation service need	Pre-Processing
Mean of installation service need	Pre-Processing
Run time for Xpress IVE	Xpress IVE

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Appendix F SWOT-Analysis of Hub-Solution

SWOT analysis was developed by Albert Humphrey in the 1960s, when he led a convention at the Stanford Research Institute. The analysis is a very structured way to evaluate the Strengths,Weaknesses, Opportunities and threats regarding a hub solution.(Mindtools, 2014)

Strengts	
Cost Effective	The hub solution could be cost effective under certain conditions. In Nordbø's case study, he concluded that a hub solution was cost effective when serving six or more installations around Jan Mayen (Nordbø, 2013). For different charter costs than used in this thesis, could the solution become cost efficient.
Lead-time on Commodities	When using a hub close to the fields, the storage of commodities is closer to the installations, and thereby the lead-time on these items are shorter than for a conventional solution.
Weaknesses	
Complexity	The upstream logistics chain gets more complex in a hub solution, and the logistics management will therefore be more challenging. The economic consequences of bad planning will increase, due to less visits to shore. In a conventional solution, vessels are visiting the base more often, and equipment forgotten on one voyage, can be brought on the next voyage departing from the base.
Lead-time on specialized goods	The lead-time on specialized goods might be high if an order is placed just after a hub vessel leaves the onshore base. The order has to be picked up on next visit to shore, which will be longer than for a conventional solution, due to the bigger capacity and lower speed.
Opportunities	
Safety	The emergency response to accidents can potentially be reduced quite a lot

	with a standby rescue-helicopter on board the hub vessels.
Helicopter Depot	For long helicopter trips to remote fields, a hub vessel can function as a re-fuel station for the helicopters, increasing their reach.
Oil Recovery Base	A hub vessel will have a central location close to several installations, and can function as a storage for oil spill equipment. This can ensure quick response if oil spills occur.
Capacity Utilization	Benefit of hub in the airline industry is capacity utilization on long routes. In our model, a hub could prevent smaller PSVs sailing long routes with a small amount of cargo.
Threats	
Harsh Conditions	The hub vessels will experience the same harsh environment as the permanent installations when standing stand by (if operated in arctic), but without the same anchor system. This introduce technical challenges.
Unproven Technology	The hub solution introduce new challenges and uncertainty for the vessel owners. A long contract will probably be needed to reduce economical uncertainty to go for a hub solution
Ancchor Management	Anchor management in Arctic is placed as a threat in this SWOT analysis, because of the challenges related to making a solution where a hub can easily switch between being a movable and fixed unit.

Appendix G Distances in the Barents Sea

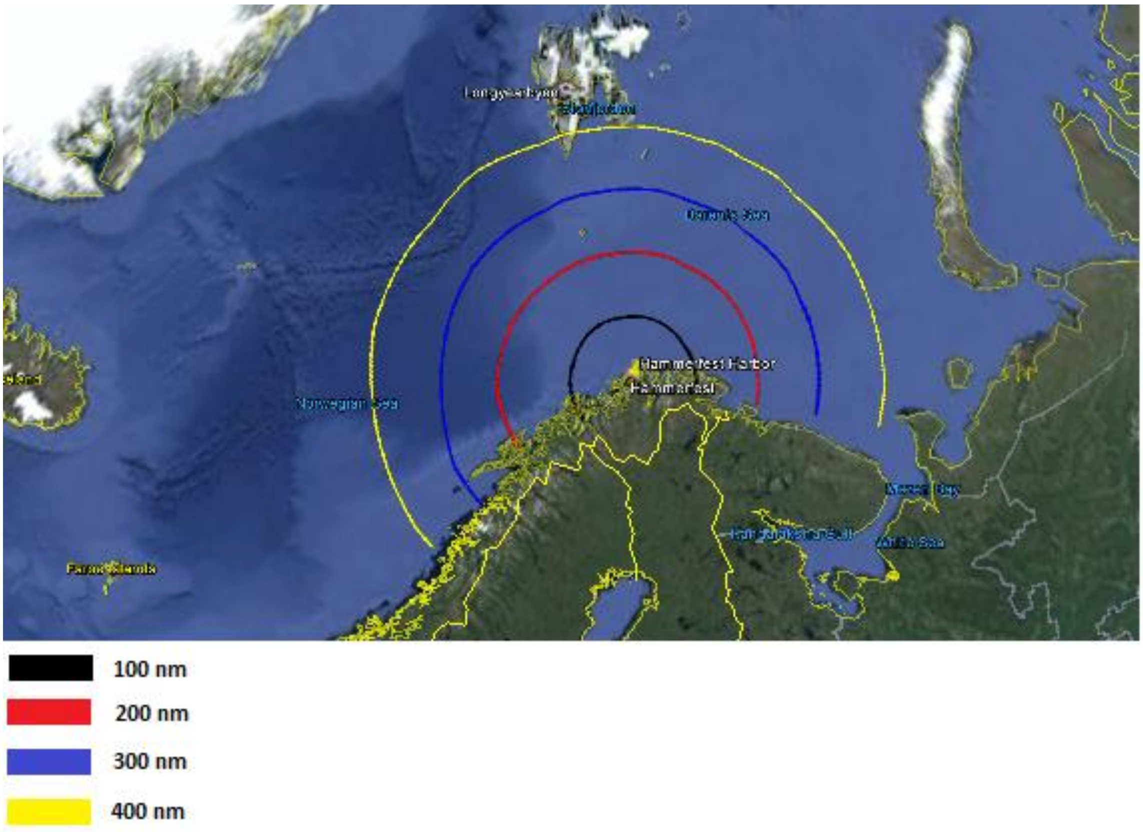

Figure 23 - Illustration of distances from Hammerfest

Table 11 - Time [h] as function of distance [nm] and speed [kn]

		Distance [nm]						
	9	**100**	**150**	**200**	**250**	**300**	**350**	**400**
Speed [kn]	**9**	11	17	22	28	33	39	44
	10	10	15	20	25	30	35	40
	11	9	14	18	23	27	32	36
	12	8	13	17	21	25	29	33
	13	8	12	15	19	23	27	31
	14	7	11	14	18	21	25	29
	15	7	10	13	17	20	23	27

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Appendix H Oil&Gas resources in the High North

Arctic Mean Estimated Undiscovered Technically Recoverable, Conventional Oil and Natural Gas Resources By Arctic Province, Ranked by Total Oil Equivalent Resources

USGS Petroleum Province	Crude Oil (billion Barrels)	Natural Gas (trillion cubic feet)	Natrual Gas Liquids 1/ (billion barrels)	Total resources, Oil Equicalent (billion Barrels)
West Siberian Basin	3.66	651.5	20.33	132.57
Arctic Alaska	29.96	221.4	5.9	72.77
East Barents Basin	7.41	317.56	1.42	61.76
East Greenland Rift Basins	8.9	86.18	8.12	31.39
Yenisey-Khatanga Basin	5.58	99.96	2.68	24.92
Amerasia Basin	9.72	56.89	0.54	19.75
West Greenland-East Canada	7.27	51.82	1.15	17.06
Laptev Sea Shelf	3.12	32.56	0.87	9.41
Norwegian Margin	1.44	32.28	0.5	7.32
Barents Platform	2.06	26.22	0.28	6.7
Eurasia Basin	1.34	19.48	0.52	5.11
North Kara Basinsand Platforms	1.81	14.97	0.39	4.69
Timan-Pechora Basin	1.67	9.06	0.2	3.38
North Greenland Sheared Margin	1.35	10.21	0.27	3.32
Lomonosov-Makarov	1.11	7.16	0.19	2.49
Sverdrup Basin	0.85	8.6	0.19	2.48
Lena-Anabar Basin	1.91	2.11	0.06	2.32
North Chukchi-Wrangel Foreland Basin	0.09	6.07	0.11	1.2
Vilkitskii Basin	0.1	5.74	0.1	1.16
Northwest Laptev Sea Shelf	0.17	4.49	0.12	1.04
Lena-Vilyui Basin	0.38	1.34	0.04	0.64
Zyryanka Basin	0.05	1.51	0.04	0.34
East Siberian Sea Basin	0.02	0.62	0.01	0.13
Hope Basin	0.002	0.65	0.01	0.12
Northwest Canadian Interior Basins	0.02	0.31	0.02	0.09
Total	**89.98**	**1,668.66**	**44.06**	**412.16**

Source: U.S. Geological Survey, “Circum-Arctic Resource Appraisal: Estimates of Undiscovered Oil and Gas North of the Arctic Circle,” USGS Fact Sheet 2008-3049 Washington, DC (2008), Table 1, page 4. Note: The column totals do not equal the sum of the rows due to rounding. USGS website URL is: http://pubs.usgs.gov/fs/2008/3049/. The relative location of these provinces is identified in Appendix B. 1/ Natural gas liquids are composed of ethane, propane, and butane. 2/ The USGS uses a natural gas to oil conversion factor in which 6 thousand cubic feet of natural gas equals 1 barrel of crude oil.