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Optimization of Onshore Base and Hub Location Supplying Oil and Gas Installations in the Barents Sea

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Optimization of Supply Base and Hub Location Supplying Oil and Gas Installations in the Barents Sea

Background

Statoil is currently the leading oil and gas company on the Norwegian continental shelf, operating approximately 80 % of the production. All offshore installations require regular supply of cargo, which is transported by platform supply vessels. Optimization of the logistic concept can result in great costs savings.

Overall Aim and Focus

The objective is to generate a mathematical model in order to find the optimal location of Statoil's supply base serving three platforms in the Barents Sea. Optimal fleet size will be solved simultaneous.

The assignment should be prepared based on following points:

1) Generate a mathematical formulation for the supply concept
2) Complete various analyzes and collect essential data necessary for the mathematical model
3) Implement the mathematical model into Xpress IVE and find the optimal solution
4) Asses technical specifications associated with the optimal solution

Modus operandi

At NTNU, Professor Stein Ove Erikstad will be the responsible advisor.

The work shall follow the guidelines given by NTNU for the MSc Thesis work. The work load shall be in accordance with 30 ECTS, corresponding to 100% of one semester.

Stein Ove Erikstad

Professor/Responsible Advisor

Preface

This report presents my thesis for the degree of Master of Science in Marine Technology at the Norwegian University of Science and Technology, NTNU. The thesis is an integrated part of an academic specialization in marine design and logistics with focus on Operations Research. The work is conducted in its entirety by the author and has been carried out during the spring semester of 2014.

This report examines optimal base and hub location in a supply network for oil and gas installations in the Barents Sea. During the fall semester of 2013 I carried out my project thesis on the same topic. This master thesis builds up on the information and conclusions found during the project thesis. The literature review is in particular inspired by the project thesis. The hub-concept and the way of evaluate it, is in this thesis inspired by the idea presented in the master thesis of Henrik Nordbø (2013).

The topic has been developed in collaboration with Statoil ASA. Statoil has additionally provided data necessary for this thesis. During the spring of 2014 we have had one workshop and kept contact by e-mail and phone. Aspects and data that appeared during this communication channels are during the report referred to as "according to Statoil" or "in collaboration with Statoil".

I would like to thank my academic supervisor, Professor Stein Ove Erikstad for providing helpful guidance. I would not have managed this without your help and precious insight. Thank you very much. Thank you to my co-supervisor, Professor Kjetil Fagerholt, for valuable contributions to the mathematical model. In addition I would like to thank the employees I have been in contact with in Statoil for procuring necessary data and relevant information and suggestions. In particular, a great thank you to Endre Vik how has been my contact person during the project and master thesis.

Trondheim, June 2014

Cathrine Akselsen

Summary

This report present an academic study of a location-routing problem combined with the fleet size and mix vehicle routing problem. Operations research (OR) is utilized to examine a concept of Statoil's supply logistic for oil and gas installations in the Barents Sea where a hub-networks is included.

The aim of this thesis is to utilize OR to determine whether it is cost-efficient for Statoil to make use of a hub system in the Barents Sea to supply three offshore installations.

A simplified realistic problem is developed to define scope and limitations for the study. It comprise a set of three offshore installations and seven potential base locations. The optimal location of exactly one onshore supply base and one forward offshore base, hub, are determined. The installations are placed within given locations in the Barents Sea. The range of area span from 21°E to 36°E in longitudinal direction and from 71°N to 74°N in latitudinal direction. All facilities are open round the clock and the problem is assumed deterministic.

The report present a two stage solution approach. In Phase 1, all routes are generated and parameters are calculated. In Phase 2, a set partitioning problem is solved, where routes generated in Phase 1 constitute as the columns. For comparison reasons, Phase 1 defines parameters for two different logistical scenarios. A hub-network is included in Case 1 and excluded from Case 2. Both cases build on equal assumptions and simplifications. The results from the two cases are implemented separately in a integer programming model presented in Phase 2. Results from the model are finally compared. The process is repeated a number of times, varying in the location of the offshore installations.

The main results show that direct shuttle is more profitable than utilization of a hub-network for three installations. The optimum transportation costs are 6,8 million NOK and 2,2 million NOK for Case 1 and 2 respectively. Two PSVs are required for direct shuttle, where four different supply bases are optimal depending on the locations of the offshore installations. For Case 1, the Polarbase in Hammerfest is the optimal base location independent of the positions to the installations. The longest distance between optimal base and hub location is 160 [nm].

The results from the study indicate that logistic supply *with* hub-network is *not* profitable. Direct shuttle is more cost efficient for the given distances when three installations are supplied.

Sammendrag

Denne rapporten presenterer en akademisk studie av to typer optimerings grupper, nemlig «location-routing»-problemet og «fleet size and mix vehicle routing»-problemet. En kombinasjon av disse problemklassene har vært nødvendig for å undersøke et logistikkkonsept som angår leveranse til tre av Statoils olje- og gassinstallasjoner i Barentshavet. Målet med denne avhandlingen er å fastslå hvorvidt det er kostnadseffektivt for Statoil å benytte seg av fremskutt base når tre offshoreinstallasjoner skal betjenes.

I denne rapporten presenteres en forenklet problemstilling, basert på et reelt problem. Det består av tre offshoreinstallasjoner og sju mulige baselokasjoner. Plasseringen av nøyaktig én forsyningsbase og ett fremskutt baselager skal bestemmes. Mulige lokasjoner installasjonene kan ha er begrenset innenfor gitte koordinater i Barentshavet. Installasjonene kan plasseres på gitte lokasjoner nærmere bestemt mellom 21 og 36 grader øst og fra 71 til 74 grader nord. Alle fasiliteter er åpne døgnet rundt og problemet antas å være deterministisk

Rapporten presenterer en totrinns løsningstilnærming. I preprosesseringen genereres ruter og parametere. I den andre fasen løses et sett partisjonerings problem, der rutene som genereres i første steg utgjør kolonnene. Fase 1 definerer parametere for to logistikkscenarier. Scenario 1 omfatter transport av last med fremskutt base og scenario 2 ser på direkte leveranse mellom onshore basen og installasjonene. Utover dette bygger begge scenariene på like antakelser og forenklinger. Rutene og parameterne fra de to scenariene er implementert separat og løst i en heltallig programmeringsmodell. Resultatene fra modellen er til slutt sammenlignet opp mot hverandre. Prosessen gjentas et gitt antall ganger for forskjellige installation-lokasjoner.

Resultatene viser at direkte transport er mer lønnsomt enn bruk av fremskutt base når tre installasjoner betjenes. Optimale transportkostnader er henholdsvis 6,8 millioner kroner og 2,2 millioner kroner for scenario 1 og 2. For scenario 2 er det nødvendig å leie to PSVer, der fire forskjellige onshorebaser er optimale avhengig av plasseringen til offshoreinstallasjonene. For scenario 1, er Polarbasen i Hammerfest den optimale lokasjonen uavhengig av plasseringene til installasjonene.

Resultatene fra studiet tyder på at forsyning *med* fremskutt base *ikke* er lønnsomt. Direkte transport fra land er mer kostnadseffektivt for de gitte avstandene når tre installasjoner skal forsynes.

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List of Symbols

B&B	Branch and Bound
DC	Distribution Centre
FLP	Facility Location Problem
FSMVRP	Fleet Size and Mix Vehicle Routing Problem
GC	Great Circle route
HG	Hub-Grid
LRP	Location Routing Problem
MFSMVRP	Maritime Fleet Size and Mix Vehicle Routing Problem
MILP	Mixed Integer Linear Programming
MIP	Mixed Integer Programming
OR	Operation Research
OSV	Offshore Supply Vessel
PSV	Platform Supply Vessel
SAR	Search and Rescue
SOS2	Special Ordered Set 2
TSP	Travel Salesman Problem
VRP	Vehicle Routing Problem

Chapter 1

Introduction

Section 1.1 describes why there is a need to highlight the problem this report focuses on. Section 1.2 provides an overview of the objective of these thesis as well as assumptions and simplifications that have been done to solve the problem. Section 1.4 presents the structure of this report.

1.1. Background

The petroleum industry constituted 30 per cent of the state revenues and 23 per cent of the country's total value creation in 2012 (Bertelsen, 2013). Moreover, the sector is the largest industry in Norway. Today, Statoil is the leading oil and gas company on the Norwegian continental shelf, operating approximately 80 % of the production (ASA, 2013).

The Arctic continental shelf is anticipated to become the petroleum area with the highest potential of oil and gas (Barlindhaug, 2013). The Norwegian government has been given the right to distribute areas in the Barents Sea to interested stakeholders (Myhra & Gilje, 2014). Among others, Statoil is currently exploring for oil and gas in areas of the Barents Sea proposed during the 23. licensing round at the Ministry of Petroleum and Energy at the Norwegian Stortinget (Myhra & Gilje, 2014).

All offshore installations require regular supply of spare parts, equipment, commodities and other cargo. Special supply ships, platform supply vessels (PSVs), are designed to carry out necessary cargo to the oil and gas installations and return backload to the onshore bases. Adequate routes and a proper fleet is among other things important elements in upstream logistics. In offshore supply logistics, the fleet of supply vessels constitutes the major resources of costs (Statoil, 2013). By reducing the sailing distances as much as possible, transportation costs can be kept at a minimum.

Real logistic problems can be simplified and described as mathematical models. Such models can be exploited to improve logistic elements. Figure 1 (a) illustrates a traditional supply scenario between one onshore supply base and three offshore installations, where one or several PSVs shuttle between the units.

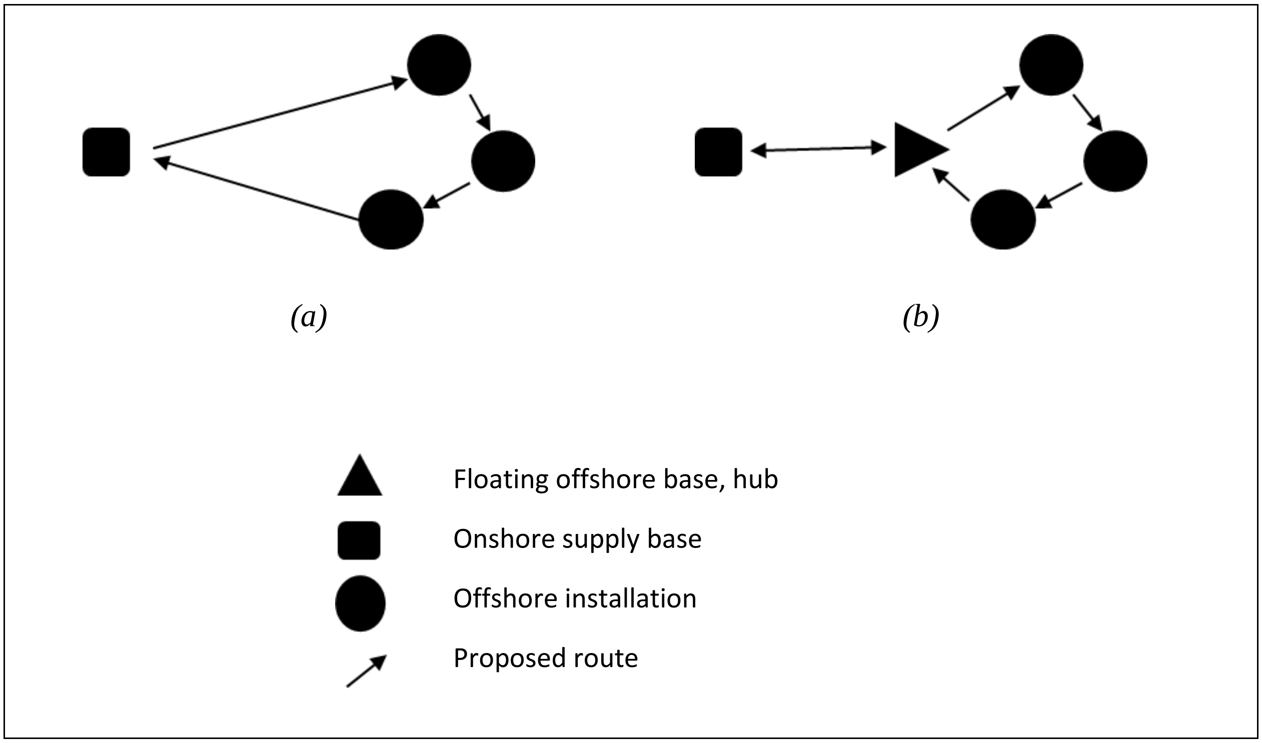

Figure 1 Offshore supply concepts. (a) illustrates a conventional offshore supply concept, while (b) suggests a offshore supply concept with a hub-network of one hub.

An extension of the conventional supply is to include a forward storage unit, a hub. A proposed system with a hub-network is illustrated in Figure 1 (b). A big hub-vessel shuttles between an onshore supply base and given offshore positions. From this positions, PSVs load cargo to supply the offshore installations. Optimizing supply logistics can result in potentially great cost savings (Fagerholt & Lindstad, 2000). A hub system can under the right circumstances reduce a firms total transportation cost.

1.2. Objective

The aim of this thesis is to utilize operations research to determine whether it is cost-efficient for Statoil to make use of a hub system in the Barents Sea when three offshore installations are to be serviced.

The main objective of this thesis, is to determine whether it is more cost efficient to utilize a hub-network than direct shuttle. Where is the optimal onshore base location? If hub-network is profitable, where should the hub-location and onshore base be located so that transportation costs are minimized? How is this decision influenced by the location of the offshore installations? Finally, how many vessels are required for the optimal solution?

1.3. Scope and Limitations

The specific tasks for this thesis are as follow:

1) Generate a mathematical model describing a simplified version of a real problem
2) Collect essential data necessary to run the mathematical model
3) Implement and solve the mathematical model in Xpress IVE
4) Asses the results and aspects related to the model

1.4. Maneuvering through the Report

The report is structured as follows:

Chapter 1 provide an introduction to the report. Background, objective, scope and limitations are presented

Chapter 2 explains the methods used to answer the questions stated in the introduction. Why and how these methods are implemented in software are also explained in this Chapter.

Chapter 3 provides an overview of existing theory and previous work. General information about onshore land depots, hubs, offshore installations and supply vessels is given.

Chapter 4 presents the mathematical model by words.

Chapter 5 presents the mathematical model.

Chapter 6 provides an overview of data input used to solve the mathematical model.

Chapter 7 assess and discuss the results from the mathematical model.

Chapter 8 presents the conclusion for the problems addressed inn this report.

Chapter 9 provides suggestions to further work.

Chapter 2

Method

This Chapter provides an overview of the methods that are used to answer the questions stated in the introduction. Why and how the methods are implemented in software are described in detail in section 2.1. General strengths and weaknesses with the methodology are discussed in section 2.2.

The report present a two-stage solution approach. In Phase 1, all routes are generated and parameters are calculated. In Phase 2, a set partitioning problem is solved, where the columns are the routes generated in Phase 1. Phase 1 defines the parameters for two different logistical scenarios. Case 1 includes a hub-network and Case 2 excludes a hub-network. Both cases build on equal assumptions and simplifications. The results from the two cases are implemented separately in the integer programming model. Results from the model are finally compared. A solution approach is illustrated in Figure 2.

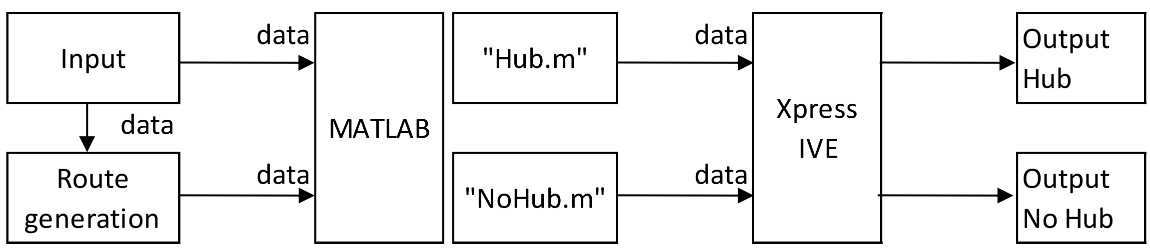

Figure 2 Flow chart of the solution method. "Hub.m" and "NoHub.m" represent case 1 and 2 of Phase 1 respectively. "Output hub" and "Output No Hub" represent the results from Phase 2, where columns from case 1 and 2 are implemented separately.

The method is performed a set of times for different locations of installations. This is done to study how the spreading of the installations' locations influence on the final results. Output from run 1 of Case 1 and 2 are attached in Appendix E. and 0. The corresponding MATLAB scripts can be found in Appendix B and C. The only factor distinguishing the various runs are location of the installations. These are given in Appendix A. The output from Phase 1 can be recaptured for all runs. Hence, it is found unnecessary to attach the output of Phase 1 from the remaining outputs.

2.1. Implementation in Commercial Software

Phase 1

"*MATLAB® is a high-level language and interactive environment for numerical computation, visualization and programming*" (Math Works, 2014, pp. 1-2). The commercial software is used to carry out Phase 1 of the problem described in this report. The MATLAB-version used is R2014a (8.3.0.532).

Two scripts are programmed during the preprocessing of the problem. "Hub.m" generates a hub-grid (HG) and calculates parameters in correspondence with Case 1. "NoHub.m" is the MATLAB script for Case 2, where direct shuttle is studied. All parameters are estimated forthright with the functions described in Chapter 5.1 with for- and while-loops. The hub-grid generation is programmed less forthright and are therefore described more in detail below. Furthermore, MATLAB's built-in mapping toolbox is utilized for distance calculations and map drawing. Pros and cons of this built-in function is discussed in Chapter 2.2.

Both MATLAB-scripts require a set of input. Some of the inputs are used as a basis for calculations of the parameters, others are simply displayed unprocessed in the output. The output includes a data file and a map which is displaying the bases, hubs and installations in the Barents Sea. It is a fully functional input file for the mathematical model in Phase 2.

Hub-grid-generation

A set of alternative hub locations is generated in Case 1 to provide the necessary input parameters to the mathematical model. The positions constitute a 4x3 array.

The grid is generated in two steps and is based on three input values; number of hubs in longitudinal and latitudinal direction and a geographical south-west location point, defining the corner hub of the grid. First, a three dimensional matrix is generated by a double for-loop. With the corner hub as starting point, nodes are created with regular intervals. The intervals between each position are chosen so the grid covers a desired area of the Barents Sea. One layer of the 3D matrix represent the hubs' geographical positions in latitudinal direction. Longitudinal positions are given by the other layer. Second, a built-in reshape-function is applied to flatten the matrix into a two-dimensional matrix. Consequently, the hub-matrix is displayed as a 12x2 array. Each row represents one hub location. The columns represent longitudinal and latitudinal locations respectively. This format is necessary to utilize the mapping-toolbox for calculations of durations in further scripting.

Case 2 requires no gridded hub generation as direct shuttle is evaluated. To exploit the same mathematical model for both Case 1 and 2, hub locations are still defined. Number of hubs and their respective locations are chosen similar to the onshore bases. To neglect the effect of hubs, the costs corresponding to shuttle between nearest hub and base are 0 NOK. A theoretical high value is selected for different placed bases and hubs.

Route generation

Due to limited number of installations described in this report, the routes are manually generated.

Phase 2

Operations research is a tool that can be utilized to find better ways of solving problems. It is a way of quantifying situations (Hiller & Lieberman, 2010). Phase 2 was implemented and solved in the commercial optimization software Xpress-IVE. The author has made use of Xpress IVE version 7.2.1. and Xpress Mosel as modelling language. The Xpress optimization suit is developed to solve mathematical models and optimization (Andersson, et al., 2013). This software was selected as it is suitable for mixed integer linear problems, MILP (FICO, 2012).

The solution process of Xpress IVE contains of three main phases. In a pre-solving phase, various numerical methods are applied to reduce the problem. Then the LP relaxation of the problem is found by use of the LP relaxation method. Finally, branch and bound (B&B) is performed to search for improved lower bounds and finally find the best feasible integer solution.

The integer programming model of Phase 2 is implemented in Xpress IVE. The same model is utilized for both of the described logistic scenarios. Consequently, two output files are generated. They present the optimal results based on parameters from Case 1 and 2 respectively.

Results for each run is compared by use of Microsoft Office Excel.

For comparable reasons, all runs are performed on the same computer. The computer is a Samsung with processor Intel® Core™ i5-3317U CPU @ 1.70 GHz and 4 GB RAM.

The implementation of the mathematical formulation, is presented in Appendix I.

2.2. Strengths and Weaknesses

General strengths and weaknesses for the methodology of Phase 1 and 2 are presented in the following. Comments specific to the model are discussed under Chapter 8.

Phase 1

Mapping Toolbox

"The mapping toolbox provides tools and utilities for analyzing geographic data and create map displays" (Math Works, 2012, pp. 1-2). The mapping toolbox has been used to calculate distances and display the map over the Barents Sea in the two MATLAB-scripts. The map is drawn with Mercator cylindrical projection. This projection contains parallel spacing, where the parallels define the latitude of true scale. The projection is according to Math Works (2012) good enough for navigational purposes.

The distance between the hubs and installations can be calculated based on two tracking types. The Rhumb Line calculates distances with constant azimuth. This line type is a curve crossing each meridian at the same angle. The Great Circle (GC) estimates the shortest path between two nodes on the surface of a sphere. In accordance to Math Works (2012), this track type is suitable on cylindrical projections like Mercator. The Great Circle line is used in combination with the distance-function in mapping toolbox to calculate distances between all onshore bases and hubs, between hubs and installations and between all installations. An overview of all distances are embedded in Appendix G. The corresponding script is attached in Appendix F. In Figure 3 the difference between the two line types are depicted.

By making use of the mapping toolbox, the user get to draw a map with desirable geographical cut showing predefined cost line and onshore areas. By additionally illustrating bases, hubs and installations as given in the scripts' input, the map can be used to control that the input values seems correct in terms of each other.

The distance-function with Grate Circle lines do not consider shore areas. Each distance is calculated to be as short as possible between two points, independent of whether the shore is crossed. To correct for these inaccuracy one can make use of waypoints to one define one or several nodes that the route shall travel through. However, this has not been done in these thesis.

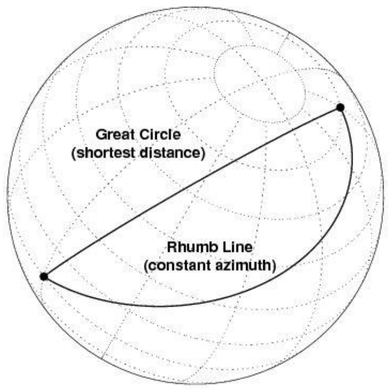

Figure 3 Great circle and Rhumb line. The figure is provided by (center, u.d.).

Route generation method

According to Fagerholt (2013), "*the route generation method is especially applicable for solving problems in maritime transportation".* By applying the method, one variable is defined per route rather than per edge or leg. By predefining multiple routes, the mathematical model may be defined as a set partitioning problem. This structure is easier to solve than applying direct formulation. A route generation can often easily include constraints for time window, maximum route duration, capacity and other practical restrictions. On the contrary, a two-step solving approach is required for the route generation method. All generated routes must be feasible to ensure optimal solution. Finally, the number of routes grow exponentially with problem size (Fagerholt, 2013).

Chapter 3

Literature Review

This chapter presents a literature survey on the location-routing problem and the fleet size and mix vehicle routing problem. Moreover, previous works and literature that are considered relevant, are presented to describe meteorological and oceanographic conditions of the Barents Sea.

To begin with, two types of optimization problems can be used to characterize the problem described in this report. One problem concerns optimal locations for a base and a hub. This may be seen as a facility location problem (FLP). According to Maranzana (1964, p. 261) *"the location of factories, warehouses and supply points in general… is often influenced by transport costs."* Hence, it may be smart to study literature combining these two elements.

The other problem involve determining the optimal size and mix of fleet of vessels. This report assume a homogeneous fleet of vessels. Nevertheless, the mathematical model is programmed to function for heterogeneous vessels. In the literature, this type of problem class can be considered as the maritime fleet size and mix vehicle routing problem (MFSMVRP).

Relevant literature applicable for these two problem categories are considered in the following. Section 3.1 presents written works pertinent for the location-routing problem. Section 3.2 provides an overview of relevant literature available for the fleet size and mix vehicle routing problem. Section 3.3, presents literature relevant for the meteorological and oceanographic conditions in the Barents Sea.

3.1. The Location-Routing Problem

"Location-routing problems (LRP) are vehicle routing problems (VRPs) in which the optimal depot locations and route design must be decided simultaneously" (Laporte, et al., 1988). The VRP finds the optimal set of routes for a fleet based on certain restrictions, such as minimized costs. This problem class do according to Jan Lundgren (2010) further consist of solving two problems simultaneously. First, customers are allocated vehicles. Secondly, the sequence of which customer

shall be visited per route, are determined. A sub-problem is in this relation solved, namely the travel salesman problem (TSP). (Jan Lundgren, 2010) presents a general mathematical model for the VRP with one depot. The model examine a set of given number of vehicles. No time window is considered.

Location-routing problems are not as well defined as the travel salesman problem or the vehicle routing problem. According to Nagy and Salhi (2006) it can rather be considered as an approach to modeling and solving location problems. Some heuristic solution strategies are developed. (Laporte, et al., 1988) reformulates the LRP into a TSP by graph transformation. B&B is used as solving method. (Laporte & Dejax, 1989) extends this model further to a dynamic LRP problem.

Perl and Daskin (1985) presented a heuristic solution method for simultaneously solving the distribution center (DC) location and vehicle routing problem. This type of problem is referred to as the warehouse location-routing problem (WLRP). The objective is to find the optimal location for the DC(s) while total costs are minimized. The model has a mixed integer programming formulation (MIP). The problem is decomposed into three subproblems. Each subproblem is solved sequentially, while the dependence between them are accounted for. The first subproblem constructs an initial set of routes that minimizes total delivery costs. It is assumed that all DCs are used. The second subproblem locates the warehouses. The routes generated in the first phase are allocated to the warehouses. The third subproblem solves two problems simultaneously. The costumers are reallocated to warehouses and a multi-depot routing problem for the warehouses selected in the previous subproblem are solved. The problem allows multiple depots.

3.2. The Fleet Size and Mix Vehicle Routing Problem

The fleet size and mix vehicle routing problem (FSMVRP) determines requisite size and number of vehicles in order to supply demanded devices at minimal cost (Golden, et al., 1984). Golden (1984) proposes a mathematical formulation with respect to optimizing both acquisition and routing costs. The paper suggests several analytic solution procedures with optimization of fleet composition and routing sub-problems. The supply of frequency is limited to one per costumer. It is assumed an infinite size of vessel fleet, where all vessels starts and terminate their routes at one depot. Both fixed and variable vehicle costs are considered.

Fagerholt (1999) presents a solution approach for a FSMWRP for a real liner shipping problem. It is a multi-trip VRP with weekly routes. A three stage solution process is suggested. The first to phases constitute a route generation algorithm. First, all feasible, single routes are found. Second, these routes are combined into multiple routes. The routes constitute as columns in the third stage. A set partition problem is considered. The problem addresses various opening hours of seven offshore installations. Heterogeneous vessels are considered. A second size and mix problem is addressed by (Fagerholt & Lindstad, 2000). The paper evaluates effect on supply costs when opening hours on offshore installations are limited. (Halvorsen-Weare, et al., 2012) present an alternative route generator for a FSMVRP. Voyages are generated by a one-step algorithm. Only feasible routes are generated. In a second step, the optimal fleet composition and periodic routing of offshore supply vessels are found by the presented mathematical model.

An extension of LRP problem from the aircraft industry is presented by (Aykin, 1991)**.** The paper consider hub location and routing problem. The elements are determined simultaneously. A set of two interacting hubs are considered. The vehicle may travel via one or two hubs. Direct shuttle between origin and destination nodes are additionally considered. The paper present a mathematical model and a two stage solution approach, where the hub locations and the routing subproblems are solved separately in an iterative manner.

(Nørdbø, 2013) studies optimal configuration of supply logistics for remote oil and gas fields. The report present a two-stage solution approach with a suggested set partitioning mathematical model with routes as columns. Nordbø (2013) claims that a minimum number of six offshore installations should be included in the logistical problem before a given hub-solution can be considered profitable.

(Norddal, 2013) proposes a solution method and three integer, linear, mathematical models for optimization of helicopter hub locations and fleet composition in the Brazilian pre-salt fields. Both arc and path flow formulations are presented. All models assess total investment and operational costs in addition to total accident risk aspects.

3.3. Meteorological and Oceanographic Conditions in the Barents Sea

According to Keghouche et al. (2010) icing does normally not represent a risks for maritime operations in the most southern part of the Barents Sea. Keghouche et al. (2010) carried out a study of iceberg drift characteristics in the Barents Sea from 1987 to 2005. The study was based on satellite observations monitoring extend of sea ice. According to this research, the presence of icebergs or drifting ice in the southern part of the Barents Sea is rare (Figure 13 in Appendix P). Figure 14 in Appendix Q illustrates the most common areas in which icebergs drifted up to year 2005.

Interpretation of Appendix P indicates iceberg encountering of maximum 20 % probability south from 74 degree north.

Various risk factors make logistics to and from offshore installations and search and rescue (SAR) operations challenging in the Barents Sea southeast. The risk factors can be icing on vessels or installations due to low air temperatures, fog, darkness, polar lows and lack of infrastructure especially related to search and rescue infrastructure capabilities. These factors appear to be more relevant for the northern part of the Barents Sea than in the south. The metrological conditions described above claim certain requirements for operation time and oil protection equipment (Eger, et al., 2012). Such standby parameters are not included in the problem described in this report. Nor have the above mentioned weather conditions been implemented as variable factors in the mathematical model. The model is deterministic and do not consider variety of temperature, precipitation, waves, etc. Nice weather and calm water are assumed. It is however assumed that the demanded characteristic for all vessels operating in the area meet minimum requirement, as ice classes.

According to the INTSOK report (Barlindhaug, 2013), it is difficult to get hold of data on environmental parameters in the Barents Sea. It is lack of empirical meteorological data on temperatures, darkness, snow, fog, icing, rapid weather changing, surface winds and polar lows. Due to local formation and small size, these conditions are difficult to forecast. It is however expected a decrease of polar lows in the Barents Sea, given that the ice edge moves further north and east in the future (Barlindhaug, 2013).

Chapter 4

Description of the Problem

This chapter explains the scope of the mathematical model presented in this report. The description is based on Chapter 3. Simplifications and assumptions that have been made are presented. Section 4.1 presents the current situation and the potential of the infrastructure in Finnmark. The hub system is elaborated in section 4.2, while the installations are described in section 4.3. Section 4.4 provides an overview of the vessels used to supply cargo to and from the installations.

Two supply scenarios of the problem are considered. Figure 4 illustrates the composition of the main elements in Case 1, where a hub-network is considered. It consists of a given set of offshore installations and onshore supply bases. A set of potential hub locations are generated in between the installations and bases. Supply vessels sails between an offshore hub and the installations (echelon 2). The hub is serviced by large vessels from the onshore base (echelon 1). A PSV can sail different routes or the same route various time during one period. Consequently, echelon 2 of the problem can be considered as a multitrip vehicle routing problem (VRP).

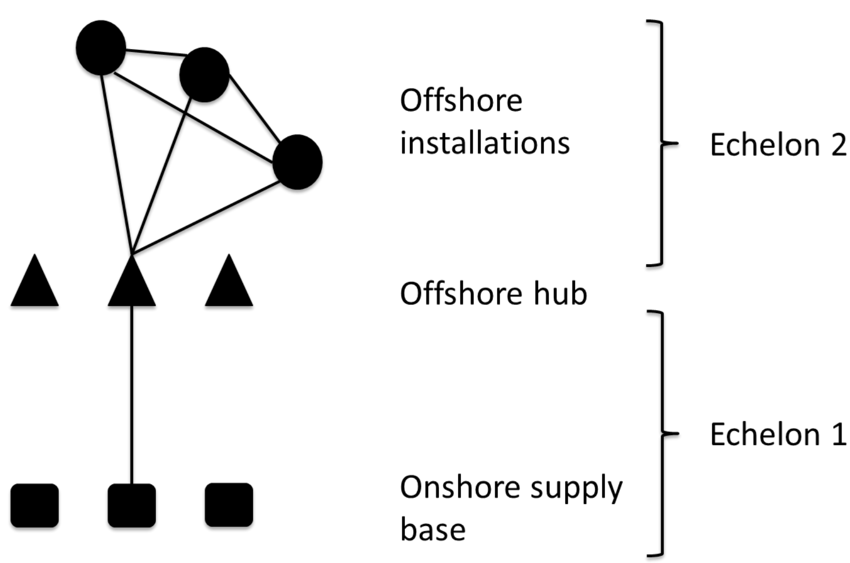

Figure 4 Composition of facilities including an intermediate storage unit

For comparison reasons a second version of the logistic supply concept is generated. Case 2 differs from Case 1 by excluding the hub network. It examines direct shuttle between shore and installations. All other assumptions and simplifications are equal for both cases. Case 2 can be illustrated by echelon 2 in Figure 8, where the hubs are drawn back to the base locations so the distances between two and two bases and hubs are neglected.

A route is in this report defined as a schedule. It starts and terminates at the same demand center. A route may visit one, two or all three installations. At least one installation is visited per route. The problem is assumed deterministic.

4.1. Onshore Supply Base

A certain number of bases and their locations are given by Statoil. All bases are restricted to be on Norwegian shore and only one base can be used as the supply base. The bases are assumed to be open twenty-four-seven, year round. Each supply base delivers cargo demanded by the installations. Depending on the two supply scenarios, only PSVs or hub-vessels load cargo at the current base. The variable leasing cost bases on amount of cargo transported over wharfside.

The logistic system described in this report is handled isolated from prospective, former Phases of the total logistic chain. Hence, onshore or offshore transportation to and from the base is not considered.

The objective is to find the onshore base location such as total transportation costs are minimized.

4.2. Hub

In this thesis, a hub is considered an offshore storage base working as an intermediate storage unit. It can be a container carrier or another type of big vessel. Number and location for hubs are not given. A grid of possible hub locations are assumed for Case 1. In case 2, location and number of hubs are assumed equal with the onshore supply bases. Consequently, it is no distance between nearest base-hub-pair and the corresponding costs are thus zero for echelon 1.

Each hub-vessel load commodities at an onshore supply base. Further, it sails to a given location to supply the PSVs in echelon 2. The hub-vessel is assumed fixed at a given location until empty stock. A second well-stocked hub will then take over, while vacant hub-vessel returns to shore for reload. Furthermore, the storage unit is fixed at a current position at all time, either moored or on dynamic positioning. It is for example not possible for a hub to change its position towards an installation with greater demand for periods.

The opening hours are assumed twenty-four-seven. In order to have an available hub at all time, at least two vessels must shuttle between the base and hub location. When the storage at one hub is empty, a new hub is ready to take over. Time to swap places is not taken into account. Time for maintenance of hubs are not considered.

Emergency hospital, route landing for helicopter, among other things are additional functions a hub could have. The hub in this report is handled as a pure storage unit, where only transshipment of cargo is handled.

Each hub-vessel is assumed hired on a time charter contract. All costs are assumed included in the contract, including maintenance, crew costs and operational costs as fuel etc.

Based on a set of predefined locations, the objective is to determine whether it is profitable to make use of an intermediate storage unit, and furthermore to decide the optimal location of the hub so that all transportation costs are minimized.

4.3. Offshore Installations

A set of offshore exploration installations are given. Each unit is presented by a location in the Barents Sea, where one installation is placed per location. Different locations are assessed. The installations are localized north from the supply bases but not further north than 74 degrees, and from 21 to 36 degree east. Cargo demand and number of services per period are given and assumed not to vary by time and/or unforeseen events. Capacity constraints are intact for each cargo delivery per period. All delivery of commodity is carried out by the PSVs. Supply from other units as helicopter or other vessels are not considered.

In similarity with the supply bases and hubs, the installations are assumed to operate 24/7.

4.4. Platform Supply Vessels

Platform supply vessels (PSV) shuttle between two facilities to supply cargo. Two supply scenarios are considered. First, a set of PSVs shuttle between a hub locations and installations. Commodity is loaded at a hub. The supply vessels are located in echelon 2 at all time. Costs and time for sailing or transporting the PSVs to and from their onshore base is not considered. For the second supply scenario, a set of PSVs are stationed at the onshore base. In theory, these vessels transport cargo from a hub location. The practical interpretation is however direct shuttle from onshore base, as the fictive geographical locations are similar as for the bases. The fleet of vessels in both scenarios can visit one, two or three installations per route. One route starts and terminates at same hub/base location. Transshipment to and from supply vessels happen at similar unit. An upper boundary for number of supply vessels are given.

The fleet of vessel is homogeneous, with given values for deck load capacity and service speed. It is assumed that the PSVs are able to deliver deck load and floating bulk goods after demand from the installations. The cargo capacity is measured by ton cargo transported. Constraints on maximum cargo capacity per route stays intact for all vessels. No further restrictions on cargo are specified.

The PSVs are assumed to be ice classed. This assumption is based on the literature review of Chapter 3.3. Extra equipment or fittings necessary to meet the required ice class are assumed installed on the hired vessels.

The offshore supply vessels are hired on long-term time charter contracts where all costs are assumed included. The costs are given. It is assumed that the vessels use dynamic positioning whenever waiting for an assigned route. For simplicity sake, fuel consumption for utilizing the DP system is assumed similar to sailing. Furthermore the costs for all hired vessels are equal. The charter contract includes both maintenance costs, crew costs, additional costs due to ice class, operational costs as fuel and so on. Time for inspection and maintenance are however not considered.

Approximately 70% of the cargo delivered to installations return as backload. This appeared from the workshop with Statoil March 6. According to Statoil, the volume of backload vary from day to day. It is here assumed that a supply vessel visiting an installation, returns backload. Time consumption for loading backload is included in turn time for hubs and installations. Further considerations, as volume and frequency, are not considered.

All vessels are assumed to be provided with clean hulls. Increased cost and time consumption due to friction and saturation resistance are not taken into consideration.

The objective is to determine size of the PSV fleet such as the total transportation costs are minimized.

Chapter 5

Mathematical Formulation

This Chapter presents a suggestion to a two-Phase solution approach of the problem presented in Chapter 1. The preprocessing Phase provides input for the mathematical model and is described in section 5.1. Section 5.2 explains the structure of the mathematical model, presented as a column generation model.

5.1. Phase 1: Preprocessing

The preprocessing Phase comprises generation of routes and determines parameters used as input in Phase 2. Calculations and assumptions for all the parameters are explained.

Route generation:

The route generation for echelon 2 represents all possible combinations of sailing distances between a hub and a set of installations in the Barents Sea. The routes are generated manually due to a relatively small problem of three offshore installations. Potentially one has 36 different combination of routes per hub location. Symmetric travel distances are assumed. Additionally, each offshore installation is visited at most once on each route and all routes are restricted to start and terminate at the same hub location. Consequently, the different route combinations reduce to eight. All routes composite of one or several arcs illustrated in Figure 5. Table 1 provides an overview of the final routes from an arbitrary hub location.

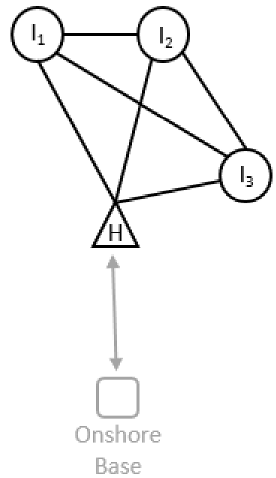

Figure 5 Combination of routes between one arbitrary hub and three installations. H represents a hub-location. The installations are symbolized by I and indexed by 1, 2 and 3. For Case 2, the distance between the hub and onshore base is removed.

Table 1 Overview of ordered routes in echelon 2 from an arbitrary hub location, where H describe an arbitrary hub location and the installations are represented by I.

Route number	**Route**
1	H-I1-H
2	H-I1-I2-H
3	H-I1-I2-I3-H
4	H-I1-I3-H
5	H-I2-H
6	H-I2-I3-H
7	H-I3-H
8	H-I3-I1-I2-H

Hub grid generation:

For Case 1, a set of potential hub locations are assumed based on a HG generation. 12 locations are developed with regular intervals. The method for how the grid of possible hub locations are programmed are described in Chapter 2.1. The programmed code for the HG generation is only current for Case 1 and is presented in Appendix B. For Case 2, the hubs are defined directly by the supply base input values (Appendix C).

Duration of each route from all possible hub locations, T_{hr}:

The length of all the routes presented in Table 1, are calculated from each potential hub location. The duration of each route is determined based on the distances and a given service. As long as the PSVs sail, it is assumed that the service speed is constant. No route is checked up against any time or capacity restrictions. Infeasible routes, if any, are handled in Phase 2. Turn time at the hubs and installations are included in the route durations. Turn time is here defined as time for load and unload cargo. It is assumed that backload is taken into account of the loading/unloading procedures. Finally, ideal weather conditions are assumed and unforeseen events are neglected. The duration of each route is therefore deterministic and the same for each vessel. The calculations of the T_{hr}-parameter is annexed in Appendix E and 0 for the first run of Case 1 and 2. The code is similar for both cases.

A_{ir}-matrix:

The routes given in Table 1 describes which installations are visited on each route. By manually translating this information to a binary format, the A_{ir} matrix is generated. Elements of the matrix is one when an installation i is visited on route r, and zero otherwise. The matrix is embedded in Appendix E and 0 for the first run of Case 1 and 2.

Cost for serving hub-vessels in Echelon 1, C_{bh}^{EO}:

The total costs for echelon 1 are found in the preprocessing phase. It varies with the number of hub-vessels. Given a base b and a hub h, series of hubs times chartering cost for a chosen period, constitute the cost for echelon 1. C_{bh}^{EO} is calculated for all possible base and hub combination. This means (7*12=) 84 cost calculations for echelon 1 in the first supply scenario. The calculations are made after the function presented in Table 2.

Table 2 Cost function for using hubs, Echelon 1

$C_{bh}^{EO} = nVessel * \frac{CYearEO}{52} * W$	
$where$	
C_{bh}^{EO}	$is\ the\ cost\ for\ chartering\ one\ hub - vessel\ per\ period\ [NOK]$
$nVessel$	$is\ the\ number\ of\ chartered\ hub - vessels$ shuttling $between\ each\ base\ b\ and\ hub\ h\ in\ echelon\ 1\ [-]$
$CYearEO$	$is\ the\ cost\ for\ hiring\ one\ hub - vessel\ per\ year\ [NOK]$
W	$is\ the\ period\ for\ which\ the\ model\ is\ limited\ to\ [weeks]$

The yearly cost is given. Time value of money is not taken into account in the cost calculations. The costs are simply determined by dividing yearly charter cost by number of weeks in one year. The crucial parameter for the problem described in this report is first of all number of chartered vessels. The accuracy of the cost estimations are assumed sufficient without present value calculations.

Period, W:

The period W is given directly as an input parameter. It appears from the following description of nVessel that W influences on how many times each route maximally can be sailed.

nVessel-generation:

nVessel is the minimum number of hub-vessels required for echelon 1. Initially a zero matrix is generated. The size depends on number of hubs and installations. All elements are then given a value two, due to the assumption of twenty-four-seven opening hours. If a hub-vessel breaks with time or capacity constraints, a third intermediate unit is added to the fleet. Conditions belonging to the algorithm is described more in detail in the following.

Let the dotted line in Figure 6 illustrate vessel A, while vessel B is illustrated by the orange line. At the start of a period (T0), vessel A is located at a given hub-location. PSVs load cargo from the hub until time T1, half way through the period. By time T1 the storage is empty. Vessel A sails to an onshore base, reloads and returns to the hub location between time T1 and T2. By T1 vessel B has already reloaded its storage, so that it is ready to change position with hub-vessel A. It appears from the illustration that the PSVs are supplied by two fully loaded hub-vessel per period. The second change of hub-vessel, T2, will serve PSVs the next period.

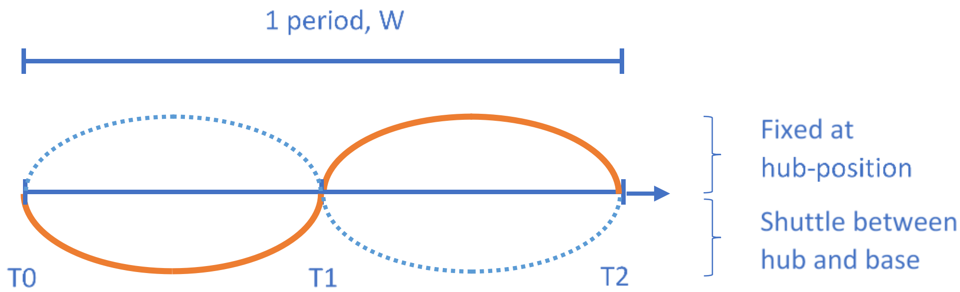

Figure 6 Concept behind nVessel generation. nVessel is here two, meaning that the fleet consist of two hub-vessel. Hub-vessel A and B sail one roundtrip.each. A roundtrip starts at a certain hub-location, goes via an onshore base and terminates at the same hub-location.

If the total demand at the installations exceeds the capacity of the two hub-storage supplyes, it is possible for vessel A to sail one extra roundtrip. This will then increas the hub-delivery capacity by one additional unit. Figure 7 illustrates the case where vessel A sails two round trips and vessel B one.

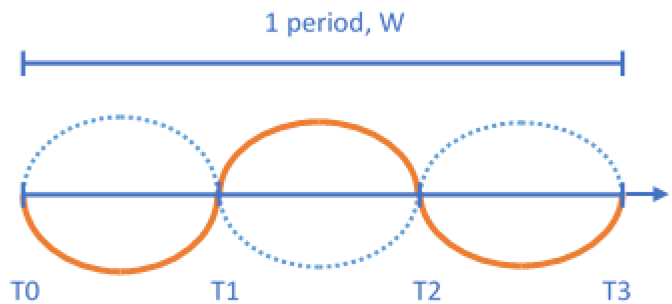

Figure 7 Concept behind nVessel generation. nVessel is two. Hub-vessel A sails two trips. Hub-vessel B sails one trip.

This solution is feasible as long as the sailing duration is still within given boundarys. Under the same condition, vessel B may additionally make two roundtrips if necessary. If the fleet of hub-vessels violate from feasible sailing durations and do not meet the required amount of cargo, an additional vessel is added to the fleet. The nVessel-algorithm do not include the scenario illustrated in Figure 7. The hubs sail same number of times.

C^{ET}:

The unit cost for using one PSV in echelon 2 is based on a given, yearly chartering cost. The calculations are performed with the same argumentation as used for the costs in echelon 1 (Table 2). The cost for chartering one PSV per period is calculated by the cost function in Table 3.

Table 3 Cost function for using one PSV, Echelon 2

$C^{ET} = \frac{CYearET}{52} W$	
$where$	
$CYearET$	$is\ the\ yearly\ chartering\ cost\ per\ PSV, echelon\ 2$
W	$is\ the\ period$

C_b:

The base cost C_b, is given per ton cargo shipped over wharfside. It is given directly by input values for each base. Time value of money is not taken into consideration.

S_i:

S_i is the required number of weekly services at each installation. This value is given as input directly. To ensure correct scaling, S_i is multiplyed by the number of periods.

Table 4 Frequency of service at installations per period

$S_i = S_i^{inp} * W$	
$where$	
S_i	$is\ the\ required\ number\ of\ services\ at\ each\ installation\ per\ period$
S_i^{inp}	$is\ the\ input\ value\ for\ weekly\ demand\ of\ services\ at\ each\ installation$
W	$is\ the\ period$

Q_p:

The capazity for all PSVs are the same as the fleet is assumed homogeneous. The value is given as input directly.

Big M values:

The three coupling constraints (4.9), (4.10) and (4.15) in the mathematical model presented in section 5.2, require two big M values. M^p represent the big M value for the former two constraints. M^r belongs to the latter constraints. M^p is determined by the maximum number of trips one PSV can sail on one route in echelon 2. Hence, it is calculated by dividing the period W [hours] by the minimum duration of all routes as described in Table 5.

Table 5 Determination of big-M value, M^p

$M^p = \frac{PeriodHours}{\min(min(T_{hr}))}$	
$where$	
M^p	$is\ the\ big\ M\ value\ for\ constraints\ (4.9)\ and\ (4.10)\ in\ phase\ 2$
$PeriodHours$	$is\ the\ period\ W\ in\ hours, no\ slack\ included$
T_{hr}	$is\ the\ duration\ on\ route\ r\ from\ hub\ h$

The min(min(T_{hr}))-function selects the shortest duration of all considered routes. PeriodHours is converted from the duration W in weeks to hours. No slack is considered. Hence, PeriodHours is found as described in Table 6.

Table 6 Unit conversion of period, W

$PeriodHours = W * 24 * 7$

M^r is determined based on the amount of cargo a PSV delivers to each installation on a route. The calculation builds on the assumption of that delivered cargo is equal to the demand of the installation. The maximum required cargo delivery for all installations rule as the big M value. The function is given by Table 7.

Table 7 Determination of big-M value, M^r

$M^r = \max(D_i)$	
where	
M^r	*is the big M value for constraints* (4.15)
D_i	*is demanded cargo for each installation i per period*

5.2. Phase 2: Mathematical Model

In Phase 2, the optimization model for a single hub allocating problem is presented. The parameters from Phase 1 is used as columns in the following set partition problem. The problem is to determine the location of the hub and onshore supply base, so the sum of the transportation costs are minimized. In addition, the fleet size of PSVs and hubs is to be determined.

The fundament of the mathematical model is based on Fagerholt and Lindstad's (2000) formulation with minor modifications. The paper do not consider hub-network, but direct shuttle between a set of demand and destination nodes. By considering the hubs as onshore bases, echelon 2 is initially treated as the routing problem described in (Fagerholt & Lindstad, 2000).

The mathematical model describing echelon 2 is descried as follows:

<u>Sets</u>

H	*set of different hub locations, indexed by h*
R	*set of routes between hub and installation(s), echelon 2, indexed by r*
P	*fleet of possible PSV's p that can be used on echelon 2, indexed by p*

<u>Parameters</u>

T_{hr}	*duration on route r originating and ending at hub location h, echelon* 2 (*calculated in phase* 1)
C^{ET}	*cost for hiring and using a PSV per period, echelon* 2. *Including operational and chartering costs*
W	*constant, limit on sailing hours per period*

S_i $\quad$ $required\ number\ of\ demanded\ weekly\ services\ for\ installation\ i$

A_{ir} $\quad$ $if\ installation\ i\ is\ visited\ on\ route\ r, 0\ otherwise\ (from\ phase\ 1)$

M^p $\quad$ $constant, big\ number$

Variables

$\alpha_p =$ $\quad$ $1\ if\ PSV\ p\ is\ used, echelon\ 2$
$0\ otherwise$

$x_{prh} =$ $\quad$ $Integer\ varialbe, number\ of\ times\ PSV\ p\ sails\ on\ route\ r\ starting\ and\ ending\ in\ hub\ h\ each\ period, echelon\ 2$

$$\min Z = \sum_{p \in E} C^{ET}\,\alpha_p \tag{4.1}$$

$$\sum_{h \in H} \sum_{p \in P} \sum_{r \in R} A_{ir} x_{prh} \geq S_i \qquad i \in I \tag{4.6}$$

$$\sum_{r \in R} T_{hr} x_{prh} \leq W \qquad p \in P, h \in H \tag{4.13}$$

$$\sum_{h \in H} x_{prh} - M^p\,\alpha_p \leq 0 \qquad p \in P, r \in R \tag{4.10}$$

$$\alpha_p \in [0,1] \qquad p \in P \tag{4.22}$$

$$x_{prh} \geq 0\ integer, \qquad p \in P, r \in R, h \in H \tag{4.24}$$

The objective function (4.1) minimizes the sum of transportation costs in echelon 2. In Chapter 4 Description of the Problem it was assumed that all costs where included in the chartering cost. Hiring costs are the main cost component (Fagerholt & Lindstad, 2000). Hence, operational costs given as fuel etc. are not handled as a separate element in the objective function. Consequently, the number of hired vessels is the deceive factor to the cost element.

The objective function (4.1) is defined for a heterogeneous fleet of vessels. The fleet of vessels evaluated in this problem is homogenous. The model is however indexed over vessels to increase the degree of usability. If the model should work for a homogenous fleet only, the variable α_p would instead of being binary, been defined as an integer variable describing number of chartered vessels. The objective function would further be a product of number of vessels times the unit cost of chartering one vessel.

Each offshore installation is serviced a minimum number of times. This is ensured by constraints (4.5). The sign of inequality, '$\geq$' can be changed to '$=$'. If an installation is serviced more frequently, the objective function will either increase or remain the same. The objective function is to be minimize, so the number of visits will be kept at a minimum. Furthermore, number of services will not be chosen higher than what is demanded. On this basis, the choice of sign of inequality was concluded.

Restrictions (4.13) ensure that the duration of all routes sailed by each PSV are within a given period. It is here possible to introduce some slack to the problem. Given for example a period of one week. By choosing W to be 80% of 168 hours, one increase the ruggedness of the time aspect in the model (Fagerholt & Lindstad, 2000). In case of delay due to for instance bad weather, one could still spend some extra time on the route without getting consequences beyond the longer sailing time. Doing so would on the other hand restrict the feasible region of the problem even more. Furthermore, one could potential lose a feasible solution that is better than the optimal solution without slack.

Coupling constraints (4.10) ensure that if a PSV sails a certain route, the PSV is hired. (4.22) and (4.24) claim binary and integer restrictions on the variables, respectively.

With this as a starting point, the model is further developed by connecting echelon 1 and base costs to the problem. The objective function is extended to include the cost from echelon 1 and the bases.

$$\min Z = \sum_{p \in P} C^{ET} \alpha_p + \sum_{b \in B} \sum_{H \in H} C_{bh}^{EO} \rho_{bh} + \sum_{b \in B} \sum_{i \in I} C_b D_i \gamma_b \tag{4.5}$$

The first term is the transportation costs from echelon 2. The second segment corresponds to the hub-costs in echelon 1. The base cost are described by the third element. C_{bh}^{EO} is the total cost for hiring and using hub-vessels. ρ_{bh} is a binary variable. It is one if a hub-vessel shuttle between a base b and a hub h, zero otherwise. Only if a hub-vessel sails on an arc between a base b and hub h, the corresponding cost is added to the objective value. The choice of base and hub location is simultaneous given indirectly. The third term consists of three factors. γ_b is a variable equal to one if base b is optimal and zero otherwise. C_b is a variable cost per unit throughput at base b. Restrictions for demanded cargo at all offshore installations are assumed intact. Consequently, the total demand from the installations are multiplied with base costs to estimate the total base costs. Note that the base variable γ_b is an auxiliary variable, as the same information is given implicit by the ρ_{bh} variable. Nevertheless, it provides a clear overview of which base location that is chosen.

In the preprocessing Phase of Fagerholt et al. (2000) all routes that breaks with vessel capacity are removed. As mentioned in section 5.1, this capacity aspect is not dealt with in Phase 1 of this thesis. Capacity constraints could alternatively remove such infeasible routes. This becomes specially important for a problem counting several number of installations, as the combinations of routes increase exponentially (Fagerholt, 1999, p. 11). Suggested capacity constraints for the route generation in this thesis could be as restrictions (4.2).

$$Q_p \alpha_p \geq D_i \qquad p \in P, i \in I \qquad (4.2)$$

Such constraints are not included in the model described in this thesis. With three installations, the total demand of cargo delivery is much smaller than the capacity on each vessel. The capacity holds for all routes.

Existence of only one operating hub and onshore supply base is assumed. To ensure this, two constraints are added to the mathematical model.

$$\sum_{h \in H} \delta_h = 1 \qquad (4.7)$$

$$\sum_{b \in B} \gamma_b = 1 \qquad (4.8)$$

δ_h is a binary variable equal to one if a hub location h is chosen in the optimal solution and zero otherwise. Constraints (4.7) ensures that only one of all potential hub locations are selected in the optimal solution. The problem is restricted to one onshore base by (4.8). Both the binary variables δ_h and γ_b are implicit given by the binary arc variable ρ_{bh} from echelon 1. As a consequence of this equality it is necessary to make sure that the three variables are square. Hence, constraints (4.11) and (4.12) are added to the model.

$$\gamma_b = \sum_{h \in H} \rho_{bh} \qquad b \in B \qquad (4.11)$$

$$\delta_h = \sum_{b \in B} \rho_{bh} \qquad h \in H \qquad (4.12)$$

Restrictions (4.11) force the two variables γ_b and $\rho_{bh}$to take value one or zero for the same base locations. Correspondingly, this is done for the hub locations by constraints (4.12). These two restrictions work as long as the problem is limited to choose one hub and one base location. If constraints (4.7) allowed the system to choose more than one hub location, constraints (4.11) must be defined differently. If for example the optimal solution is to use two hubs and one onshore base, the sum of ρ_{bh} over the optimal base location would be two. As γ_b only can take the value one or zero, constraints (4.11) would not work as defined here.

Moreover, it is necessary to connect the two segments of the logistic system, echelon 1 and echelon 2. Restrictions (4.10) make sure that the hub position chosen from echelon 1 is the same that is used in echelon 2.

$$\sum_{r \in R} x_{prh} - M^p \, \delta_h \leq 0 \qquad p \in P, h \in H \qquad (4.10)$$

x_{prh} is an integer variable describing how many times a PSV p sails on a route r from a hub h. M^p is a constant, a big number. Constraints (4.10) ensure that if a PSV sails on a route originating and ending at a given hub location, the specific hub location should be used in the optimal solution. If no PSV sails from a hub, the hub will not be used.

Without these constraints, one could risk that the optimization model chooses two hub locations. One hub located closest to the installations, such as the distance for the PSV(s) in echelon 2 where minimized. Another location located in minimal distance from the optimal onshore base. These constraints are necessary in despite of the presence hub constraints (4.7) that define that number of hubs are exactly one.

Further, it is assume that all demand at each installation must be met. It is desirable to claim that all delivered cargo at least correspond to what is required from each installation. In mathematical terms, this can be described by the non linear constraints (4.3).

$$\sum_{r\in R}\sum_{p\in P} q_{irp}x_{prh} \geq D_i \qquad i \in I, h \in H \qquad (4.3)$$

Product of two variables breaks with linearity. Certain routes can be sailed several times and it is therefore not enough to make use of the quantum variable alone. To linearize constraints (4.3) and still keep track of number of times each route is sailed, a new index, k, is introduced. A route can be sailed several times within a given time period, W. The k-index report that a PSV sails a route r the k-th time. Hence, the quantum variable is indexed by k. In addition a new binary variable is introduced.

$$\beta_{\mathrm{prk}} = \begin{matrix} 1\ if\ PSV\ p\ sails\ on\ route\ r\ time\ number\ k \\ 0\ otherwise \end{matrix}$$

The correlation between β_{prk} and the integer variable describing how many times a PSV p sails a route r from hub h is described by constraints (4.16).

$$\sum_{k\in K} \beta_{prk} = \sum_{h\in H} x_{prh} \qquad r \in R, p \in P \qquad (4.16)$$

The sum of all times a PSV p sails a route r is equal to the total number of times a route r is sailed. These constraints work since only one hub is used (ref. constraints (4.5)). By swapping $x_{prh}$with β_{prk} in (4.3) we get the following restrictions:

$$\sum_{p\in P}\sum_{r\in R}\sum_{k\in K} q_{irpk}\beta_{prk} \geq D_i \qquad i \in I \qquad (4.4)$$

By use of special ordered set, SOS2, (4.4) are split into two linear constraints as follows:

$$\sum_{p \in P} \sum_{r \in R} \sum_{k \in K} q_{iprk} \geq D_i \qquad i \in I \qquad (4.14)$$

D_i is the demand at installation i per period. Restrictions (4.14) ensure that total delivered cargo at least meet requested amount from each offshore installation.

$$q_{iprk} - M^r \beta_{prk} \leq 0 \qquad i \in I, r \in R, p \in P, k \in K \qquad (4.15)$$

Constraints (4.24) are coupling constraints. If a PSV do not sail on a route r, no cargo is delivered to any installations. Furthermore, cargo capacity stay intact for all PSVs that deliver cargo on a route r. This is ensured by constraints (4.17).

$$Q_p \geq \sum_{k \in K} \sum_{i \in I} q_{iprk} \qquad r \in R, p \in P \qquad (4.17)$$

Q_p is the deck load capacity for PSV p in echelon 2. Constraints (4.17) ensure that the total cargo delivered on a route do not exceed the vessel's capacity.

At this point of time, the run time for solving the optimization problem in Xpress IVE is three hours. In an attempt to reduce the solving time, anti-symmetry restrictions are added.

$$q_{ipr,k+1} \leq q_{iprk} \qquad i \in I, \;\; p \in P, r \in R, k \in (K-1) \qquad (4.18)$$

$$\beta_{pr,k+1} \leq \beta_{prk} \qquad p \in P, r \in R, k \in (K-1) \qquad (4.19)$$

The constraints are made for k-indexed variables. They make sure that the indices are used in chronological order. First k=1 is used, then k=2, etc.

The implementation of these anti-symmetry-restrictions reduces the run time to approximately 3 seconds, depending on supply scenario. The final mathematical model is summarized in the following:

<u>Sets</u>

H $\quad set\ of\ alternative\ hub\ locations, indexed\ by\ h$

B $\quad set\ of\ alternative\ base\ locations, indexed\ by\ b$

R $\quad set\ of\ routes\ between\ hub\ and\ installation(s), echelon\ 2, indexed\ by\ r$

P $\quad fleet\ of\ possible\ PSVs\ p\ used\ for\ supply\ in\ echelon\ 2, indexed\ by\ p$

I $\quad set\ of\ offshore\ installations, indexed\ by\ i$

K $\quad set\ of\ times\ a\ route\ r\ can\ be\ sailed\ per\ period, indexed\ by\ k$

<u>Parameters</u>

T_{hr} $\quad duration\ of\ route\ r\ originating\ and\ ending\ at\ hub\ location\ h, echelon\ 2\ (calculated\ in\ phase\ 1)$

C^{ET} $\quad cost\ per\ unit\ chartered\ and\ used\ PSV\ per\ period, echelon\ 2$

C_{bh}^{EO} $\quad cost\ per\ unit\ chartered\ and\ used\ hub - vessel\ h\ per\ period, echelon\ 1.\ (calculated\ in\ phase\ 1)$

C_b $\quad cost\ of\ making\ use\ of\ supply\ base\ b\ per\ ton\ cargo\ transported\ from\ base$

W $\quad constant, limit\ on\ sailing\ hours\ per\ period$

S_i $\quad required\ number\ of\ demanded\ weekly\ services\ for\ installation\ i$

A_{ir} $\quad if\ installation\ i\ is\ visited\ on\ route\ r, 0\ otherwise\ (generated\ in\ phase\ 1)$

Q_p $deck\ load\ capacity\ for\ PSV\ p, echelon\ 2$

D_i $demand\ at\ installation\ i\ per\ period$

M^p $constant, big\ number, restriction\ (4.9)\ and\ (4.10)$

M^r $constant, big\ number, restriction\ (4.15)$

Variables

$\delta_h =$ $1\ if\ hub\ location\ h\ us\ used$
$0\ otherwise$

$\gamma_b =$ $1\ if\ base\ location\ b\ is\ used$
$0\ otherwise$

$\alpha_p =$ $1\ if\ PSV\ p\ is\ used, echelon\ 2$
$0\ otherwise$

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

$x_{prh} =$ $Integer\ variable, number\ of\ times\ PSV\ p\ sails\ on\ route\ r\ starting\ and\ ending\ in\ hub\ h\ each\ period, echelon\ 2$

$q_{iprk} =$ $Integer\ variable, volume\ of\ cargo\ delivered\ to\ installation\ i\ on\ route\ r\ by\ PSV\ p$ time $number\ k\ the\ route\ issailed, echelon\ 2$

$\beta_{prk} =$ $1\ if\ PSV\ p\ sails\ on\ route\ r\ time\ number\ k$
$0\ otherwise$

Mathematical model

$$\min Z = \sum_{p \in P} C^{ET} \alpha_p + \sum_{b \in B} \sum_{H \in H} C^{EO}_{bh} \rho_{bh} + \sum_{b \in B} \sum_{i \in I} C_b D_i \gamma_b \qquad (4.5)$$

$$\sum_{h \in H} \sum_{p \in P} \sum_{r \in R} A_{ir} x_{prh} \geq S_i \qquad i \in I \qquad (4.6)$$

$$\sum_{h \in H} \delta_h = 1 \qquad (4.7)$$

$$\sum_{b \in B} \gamma_b = 1 \qquad (4.8)$$

$$\sum_{h \in H} x_{prh} - M^p \alpha_p \leq 0 \qquad p \in P, r \in R \qquad (4.9)$$

$$\sum_{h \in H} \sum_{r \in R} x_{prh} - M^p \delta_h \leq 0 \qquad p \in P, h \in H \qquad (4.10)$$

$$\gamma_b = \sum_{h \in H} \rho_{bh} \qquad b \in B \qquad (4.11)$$

$$\delta_h = \sum_{b \in B} \rho_{bh} \qquad h \in H \qquad (4.12)$$

$$\sum_{r \in R} T_{hr} x_{prh} \leq W \qquad p \in P, h \in H \qquad (4.13)$$

$$\sum_{p \in P} \sum_{r \in R} \sum_{k \in K} q_{iprk} \geq D_i \qquad i \in I \qquad (4.14)$$

$$q_{iprk} - M^r \beta_{prk} \leq 0 \qquad i \in I, r \in R, p \in P, k \in K \qquad (4.15)$$

$$\sum_{k \in K} \beta_{prk} = \sum_{h \in H} x_{prh} \qquad r \in R, p \in P \qquad (4.16)$$

$$Q_p \geq \sum_{k \in K} \sum_{i \in I} q_{iprk} \qquad r \in R, p \in P \qquad (4.17)$$

$$q_{ipr,k+1} \leq q_{iprk} \qquad i \in I, \; p \in P, r \in R, k \in (K-1) \qquad (4.18)$$

$$\beta_{pr,k+1} \leq \beta_{prk} \qquad p \in P, r \in R, k \in (K-1) \qquad (4.19)$$

$$\delta_h \in [0,1] \qquad h \in H \qquad (4.20)$$

$$\gamma_b \in [0,1] \qquad b \in B \qquad (4.21)$$

$$\alpha_p \in [0,1] \qquad p \in P, r \in R \qquad (4.22)$$

$$\rho_{bh} \in [0,1] \qquad h \in H, b \in B \qquad (4.23)$$

$$x_{prh} \geq 0 \; integer, \qquad p \in P, r \in R \qquad (4.24)$$

$$q_{iprk} \geq 0 \; integer, \qquad i \in I, r \in R, \; p \in P \qquad (4.25)$$

$$\beta_{prk} \in [0,1] \qquad p \in P, r \in R, \; k \in K \qquad (4.26)$$

The objective function (4.5) minimizes the total costs of chartering and using supply vessels and bases in a logistic hub network. Service constraints (4.6) assure that each platform is serviced at least the number of times required per period. From constraints (4.7) one assures that only one hub is used. Exactly one onshore service base is ensured by constraints (4.8). The coupling constraints (4.9) ensure that if at least one route r is selected, then the corresponding binary variable is used. They ensure vessel existence for the vessels that are given a route. (4.10) assure that the same hub is used both in echelon 1 and 2. Base existence constraints (4.11) impose that if a base b does not exist, no vessel sails from the given location. Additional it ensure that if there exists a connection between a base b and a hub h, the given base is chosen. Correspondingly, the hub existence constraints (4.12) assure that if a given hub is not used, no shuttle vessel shall sail to the hub. Restrictions (4.13) ensure that the duration on all routes sailed by each PSV are within the given time period. Constraints (4.14) ensure that each installation is delivered at least the amount of cargo it requires. Constraints(4.15) and (4.16) are coupling constraints. Capacity constraints (4.17) ensure that for each route, the total supply delivered at the installation(s) does not exceed the capacity on the vessel. (4.14) together with (4.17) secure consistency between demand at installations and capacity at vessels. (4.18) and (4.19) are anti-symmetry constraints used on variables indexed by k. (4.20) to (4.26) impose binary and integer restrictions on the variables.

Chapter 6

Data Assembling

This Chapter presents all the input data used in this study. Data concerning onshore supply bases are presented in section 6.1. Section 6.2 presents an overview of hub specifications and geographical locations. Offshore installation data are provided in section 6.3. Section 6.4 contribute with data regarding the PSVs.

Based on the length of the route durations calculated in the preprocessing, the period W is 1 week. Statoil has provided all data, unless otherwise is specified.

6.1. Onshore Supply Base

Based on the report by Karlstrøm et al. (2011), seven different base locations are assessed as potential for the logistic problem described during these thesis. An overview of the base locations are shown in Table 8.

Table 8 Geographical coordinates for onshore supply base locations. The locations are base on the work performed by (Karlstrøm, et al., 2011)

Base number	Base name	Geographical coordinates	
		Latitude [°] N	Longitude [°] E
1	Hammerfest	70,38	70,38
2	Honningsvåg	70,58	70,58
3	Kifjord in Lebesby	70,54	70,54
4	Båtsfjord	70,38	70,38
5	Vadsø	70,04	70,04
6	Kirkenes	69,51	69,51
7	Vardø	70,22	70,22

The Polarbase in Hammerfest is at this point of time the only adequate base that can be used as a supply base without major changes. It is assumed that neither of the bases are in Statoil's possession. The rental cost for the Polarbase is 1000 NOK per ton cargo transported over wharfside. The remaining base locations require in varying degree improvement. Some of the bases do not exist today, but the port conditions are considered appropriate for base development. To some extent it may also be necessary to rectify some of the harbor entrances. This appeared during the workshop with Statoil March 6, 2014 at Sandsli in Bergen. Wherever improvements of bases where found necessary, additional costs were counted for in the assumed base cost. The costs are estimated 150% of the utilization cost of the Polarbase. An overview of all base costs are presented in Table 9. The costs are given in thousand NOK per ton cargo transported from base.

Table 9 Base costs per ton cargo throughput

Base cost [10^3 NOK / ton]	**Base number**						
	1	2	3	4	5	6	7
C_b	1,0	1,5	1,5	1,5	1,5	1,5	1,5

6.2. Hub

As described in Chapter 2.1, the hub-grid generation in Case 1 requires inputs that define the matrix- size and an initial hub location (south-west corner). The corner hub is positioned at 70.5°N and 22°E. Furthermore, number of hubs in longitudinal and latitudinal direction are four and three respectively. Consequently, the HG constitute a 4x3 array. These values are made so that the grid covers the main area between the bases and installations in the Barents Sea. The final geographical coordinates for all alternative hub locations are presented in Table 10.

For the MATLAB-script "NoHub.m", no HG is generated. All hub locations are defined with same location as the onshore supply bases. The geographical locations are presented in Table 11.

Table 10 Geographical coordinates for alternative hub locations of Case 1. The hub locations are generated in the MATLAB-script "Hub.m" and is based on three input values: number of hubs in latitudinal and longitudinal direction and an initial corner point.

Hub location	**Geographical coordinates**	
	Latitude [°] N	Longitude [°] E
1	71,00	26,00
2	71,50	26,00
3	72,00	26,00
4	72,50	26,00
5	71,00	30,00
6	71,50	30,00
7	72,00	30,00
8	72,50	30,00
9	71,00	34,00
10	71,50	34,00
11	72,00	34,00
12	72,50	34,00

Table 11 Geographical coordinates for hubs in Case 2. The locations correspond to the MATLAB-script "NoHub.m". Number and position are in accordance with the onshore bases.

Hub location	**Geographical coordinates**	
	Latitude [°] N	Longitude [°] E
1	70,38	23,40
2	70,58	25,58
3	70,54	27,23
4	70,38	29,43
5	70,04	29,44
6	69,51	29,48
7	70,22	31,06

Data for yearly charter cost, capacity and service speed per hub-vessel are not provided by Statoil directly. However, a source is given and used as basis for the assumption, namely (Cooper's Mechanical Oilfield Services Pte Ltd, u.d.). CMOS is a Singapore registered company established in 1982. These data are additionally seen in context with dimensions and costs belonging to the PSVs. A scaling factor of 1,9 is utilized for determining the yearly hub-vessel charter cost. It is furthermore assumed that the maritime company Wilhelmsen can deliver a solution fitting the desirable hub-concept. According to (Wilhelmsen, u.d.), the firm offers tailor made hub agency solutions.

Table 12 Chartering costs, capacity and service speed for the fleet of hub-vessels. The table presents an overview of assumed data for chartering one hub-vessel per year, as well as the capacity and service speed of the hub-vessels.

	Value	**Unit**
Yearly cost per hub	120 000	[103 NOK]
Capacity	750	[knot]
Service speed	12	[ton]

Based on the same cost function and assumptions presented in Section 5.1 in Table 2, the cost of utilizing one hub-vessel per week is calculated to be 2 307 000 NOK. All costs concerning hubs are assumed included in the time charter contract. Consequently, the total hub-vessel costs vary exclusively by the number of chartered units. Hence, the hub costs can be illustrated as a step function in similar way as described in the following for the PSVs (Figure 9).

6.3. Offshore Installations

All potential locations for the offshore installation are based on a hearing at the Norwegian Ministry of Petroleum and Energy (Myhra & Gilje, 2014). The hearing concerns the 23rd licensing round regarding announced oil and gas blocks. A map of these areas are presented in Figure 8. Seven of these positions are evaluated for the offshore installations. The positions are presented in Table 13. Among these, three different locations are chosen for each run/ analyze of Case 1 and 2.

Table 13 Geographical coordinates for alternative locations of offshore installations.Three locations are assessed at a time.

Location of offshore installation	**Geographical coordinates**	
	Latitude [°] N	**Longitude [°] E**
A	74,00	36,00
B	72,00	35,00
C	73,00	32,00
D	71,00	32,00
E	72,00	28,00
F	72,00	21,00
G	73,00	23,00

The demand per offshore installation is provided by Statoil. The demand represents the amount of cargo [ton] that each installation requires per period. An overview is provided by Table 14.

Table 14 Demand per installation per period

Demand per installation i per period [ton]	**Installation number**		
	1	2	3
D_i	230	230	230

In addition, a minimum number of services per installation per period is required. These service parameters are presented in Table 15.

Table 15 Required number of services per installation per period

Required number of services per installation i per period [-]	**Installation number**		
	1	2	3
S_i	3	3	3

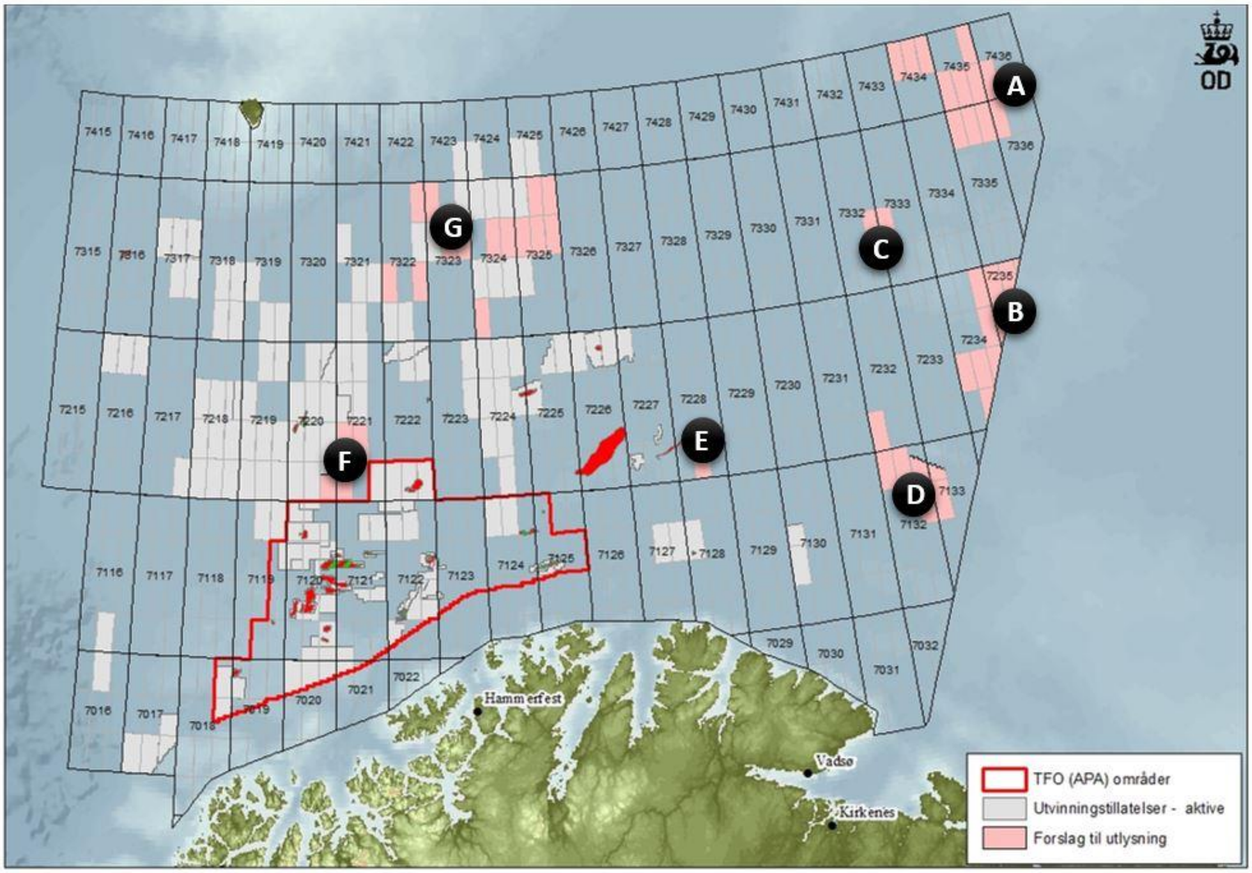

Figure 8 The 23rd licensing round at the Norwegian Ministry of Petroleum and Energy. The 23rd licensing round regarding announced oil and gas blocks. The figure illustrate the seven installation locations that have been assessed during the theses. These are presented by the black clots. The pink areas are the announced blocks for the current licensing round. The white/grey are active blocks with already given production licence. The red framed areas are areas for petroleum (APA) activity. Source: (Myhra & Gilje, 2014)

6.4. Platform Supply Vessel

Table 16 provides an overview of data concerning the PSVs in echelon 2.

Table 16 Data for PSVs: yearly cost, capacity, service speed and maximum size of fleet

	Value	**Unit**
Yearly charter cost per PSV	80 000	[10^3 NOK]
Capacity	450	[ton]
Service speed	15	[knot]
Maximum fleet size	10	[-]

The data is provided from Statoil and are based on real numbers, except for the maximum fleet size. The fleet size is an arbitrary chosen value that are assumed to cover the need of vessels. It is a necessary parameter to run the optimization model in Phase 2.

All costs concerning the PSVs are in this report assumed to be included in the time charter contract. In resemblance with the hub costs, the PSV hiring costs are determined by number of necessary supply vessels. The cost function may be any non-decreasing function. It may be illustrated as a step function as shown in Figure 9.

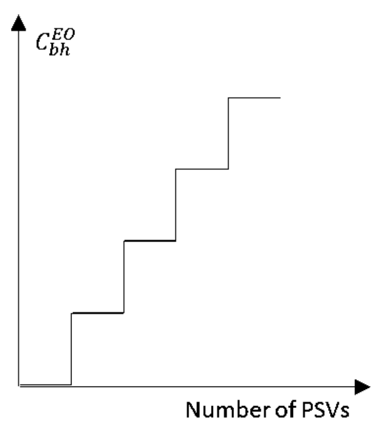

Figure 9 Cost-step function for hubs C_{bh}^{EO}, echelon 1

Chapter 7

Results

In this Chapter the results obtained from the mathematical model are presented. During this study, the locations of the three offshore installations were combined in 35 ways. For each run, the model was solved for two input variants. Case 1 includes a grid of potential hub location and Case 2 considers direct shuttle between shore and offshore installations. The main results from Case 1 and 2 are presented in the following. The different locations of the installations are presented in Appendix A. The programmed MATLAB-scripts for Case 1 and 2 are annexed in Appendix B and Appendix C respectively.

Among the 35 runs, the maximum distance between two installations was calculated as 288 [nm]. The longest distance between a base and an offshore installation was calculated as 316 [nm].

The optimal value ρ_{bh}* is 1 for optimal b* and h* per run and 0 for all other base and hub locations.

Table 17 presents the optimal transportation cost and optimal base and hub locations for all runs of Case 1 and 2. The optimal weekly transportation cost for the first case is 6, 8 million NOK. Among the 35 runs, the optimal hub locations are 1, 2, 3, 4, 5, 6 and 7 depending on how the three installations are located. The hubs from 8 an up to 10 are never optimal. Base 1, the Polarbase in Hammerfest, are optimal for all analysis of this case. Maximum distance between base and hub location are according to Table 32 in Appendix G 160 [nm].

The optimal transportation cost for the second case is 2,9 million NOK per week. Among the set of runs for Case 2, all bases, except for base 5 and 6, are optimal at least once. The optimal base depends on the locations of the installations. If installations are located on positions C-D-E, C-E-F or D-E-G, base 2 minimize total transportation costs. Base location 3 is optimal when installations are localized at B-C-D, B-C-E or D-F-G. If oil and gas explorations areas are relevant for installation-positions A-C-D base number 4 is optimal. The supply base in Kirkenes should be chosen if installations are located at locations A-B-D or B-D-E. For the remaining locations, base 1 is optimal. In contrary of Case 1, the Polarbase do not conduce to minimal transportation cost for Case 2. Geographical coordinates for the locations were presented in Table 13 in Section 6.3.

Table 17 Results of study 1, case 1 and 2. Optimal base location, hub location and objective value for all runs are given for case 1 and 2 respectively.

Run number	Case 1 hub-network			Case 2 – no hub-network		
	Base, b*	**Hub, h***	**Z*[10^3 NOK]**	**Base, b***	**Hub, h***	**Z*[10^3 NOK]**
1	1	5	6 843	1	1	3 766
2	1	6	6 843	3	3	2 918
3	1	1	6 843	2	2	2 918
4	1	1	6 843	1	1	2 228
5	1	1	6 843	1	1	2 228
6	1	6	6 843	7	7	2 918
7	1	6	6 843	1	1	3 766
8	1	1	8 381	1	1	3 766
9	1	1	8 381	1	1	3 766
10	1	5	6 843	4	4	2 918
11	1	3	6 843	1	1	3 766
12	1	4	6 843	1	1	3 766
13	1	4	6 843	1	1	3 766
14	1	7	6 843	1	1	3 766
15	1	1	8 381	1	1	3 766
16	1	1	8 381	1	1	3 766
17	1	1	8 381	1	1	3 766
18	1	4	6 843	1	1	3 766
19	1	1	8 381	1	1	3 766
20	1	7	6 843	3	3	2 918
21	1	7	6 843	1	1	3 766
22	1	3	6 843	1	1	3 766
23	1	7	6 843	7	7	2 918
24	1	6	6 843	1	1	3 766
25	1	6	6 843	1	1	3 766
26	1	6	6 843	1	1	3 766
27	1	7	6 843	1	1	3 766
28	1	4	6 843	1	1	3 766
29	1	3	6 843	1	1	3 766
30	1	3	6 843	1	1	3 766
31	1	2	6 843	2	2	2 918
32	1	3	6 843	1	1	3 766
33	1	2	6 843	1	1	3 766
34	1	3	6 843	2	2	2 918
35	1	4	6 843	3	3	2 918

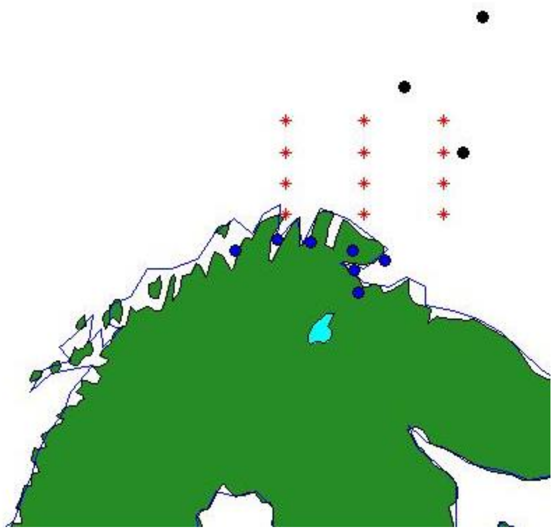

Figure 10 Illustration of hub-grid, Case 1 Map over the Barents Sea with hub grid. The red stars illustrate the potential hub locations. The black clots illustrate the offshore installations, while the onshore bases are represented by the blue circles. The figure is generated in the MATLAB-script "Hub.m"

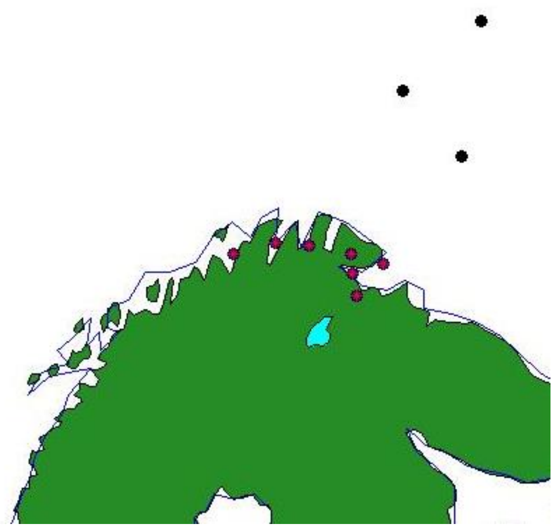

Figure 11 Illustration of base-hub-pair, Case 2. Map over the Barents Sea without hubs. Equally many hubs as onshore bases are generated with the same locations. The hubs in red are placed on top of one base each (blue circles) so there is no distance between each hub-base-pair. The black circles in the Barents Sea symbolize three offshore installations. The figure is generated in the MATLAB-script "NoHub.m"

Figure 10 and Figure 11 present the visual output from the preprocessing Case 1 and 2 respectively.

Table 18 and Table 19 present the optimal value for x_{prk}* for the first run of Case 1 and 2. x_{prk} counts how many times k PSV p sails a route r. An overview of the results for all 35 runs for Case 1 and 2 are attached in Appendix L and M respectively.

For the first run of Case 1, route nr 3 is sailed twice, while route number 2 and 7 are sailed once. Only one PSV is necessary. For the second Case, two PSVs are required to meet all restrictions. Route number 3, 4 and 6 are sailed by PSV 1 once. Route 2, 3 and 5 are sailed once by PSV 3. (Note: as the fleet of PSVs are assumed homogeneous, type of PSV is irrelevant in this report.)

Table 18 Optimal x_{prk} Case 1 Run 1*

Run	**(p,r,k)**	**x_{prk}***
1	(1,2,5) :	1
	(1,3,5) :	2
	(1,7,5) :	1

Table 19 Optimal x_{prk} Case 2 Run 1*

Run	**(p,r,k)**	**x_{prk}***
1	(1,3,1) :	1
	(1,4,1) :	1
	(1,6,1) :	1
	(3,2,1) :	1
	(3,3,1) :	1
	(3,5,1) :	1

Table 20 and Table 21 present the optimal values of q_{iprk}* for Case 1 and 2 respectively. q_{iprk} specifies how much cargo PSV p can deliver to the installation i the k-th time route r is sailed. Among all routes, one route is at the most sailed three times. The results for all runs are enclosed in Appendix J and K respectively. A common trend points at little or no distribution in cargo delivery per installation. Normally all demanded cargo is delivered on one supply. Often, only one installation receives cargo on a route, despite that several installations are visited on the same route.

*Table 20 Optimal q_{iprk}** Case 1 Run 1

Run	**(i,p,r,k)**	**q_{iprk}***
1	(1,1,7,1) :	230
	(2,1,3,1) :	230
	(3,1,2,1) :	230

Table 21 Optimal q_{iprk} Case 2 Run 1*

Run	**(i,p,r,k)**	**q_{iprk}***
1	(1,1,3,1) :	230
	(2,1,4,1) :	230
	(3,1,6,1) :	230

Table 22 presents the results for optimal β_{prk}* for the first run of Case 1 and 2. β_{prk} is one if PSV p sails on route r the k-th time and zero otherwise. The non-optimal variables are not displayed in this table. A collection of the results corresponding to all 35 runs for Case 1 and 2 are presented in Appendix N and N respectively.

Table 22 Optimal β_{prk} Case 1 and 2 Run 1*

Case 1		Case 2	
(p, r, k)	$\boldsymbol{\beta_{prk}}$*****	**(p, r, k)**	$\boldsymbol{\beta_{prk}}$*****
(1,3,1) :	1	(1,2,1) :	1
(1,4,1) :	1	(1,3,1) :	1
(1,6,1) :	1	(1,3,2) :	1
(3,2,1) :	1	(1,7,1) :	1
(3,3,1) :	1		
(3,5,1) :	1		

Table 23 provides an overview of optimal number of supply vessels for both cases. Moreover, the results provide information about the number of PSVs necessary to deliver the required amount of cargo. The minimum number of required PSVs are at the most two for both scenarios. One PSV is required for Case 1 in 83% of the cases.

Table 23 Optimal $\boldsymbol{\alpha}$**for case 1 and 2*for all 35 cases. In addition, the table illustrates the minimum number of required PSVs for each run.

Run number	**Vessel α_p***	
	Optimal PSV p Case 1	**Optimal PSV p for Case 2**
1	1	1,3
2	1	1
3	1	1
4	1	1
5	1	1
6	1	1
7	1	1,5
8	1,2	1,3
9	1,2	1,10
10	1	1
11	1	1,2
12	1	1,9
13	1	1,2
14	1	1,6
15	1,2	1,2
16	1,2	1,5
17	1,2	1,6
18	1	1,6
19	1,2	1,7
20	1	1
21	1	1,2
22	1	1,2
23	1	1
24	1	1,3
25	1	1,6
26	1	1,6
27	1	1,3
28	1	1,10
29	1	1,2
30	1	1,5
31	1	1
32	1	1,4
33	1	1,9
34	1	1
35	1	1

Table 24 provides an overview of the required number of hubs for each base-hub combination. From the first base, minimum two hub-vessels are required for hub-location 1 up to and including 7. The remaining hub locations necessitate at least three hub-vessels. In general, depending on the distances between shore and hub-locations, two or three hub-vessels are required. Only base 4 and 7 are located within reach of all hub-locations with two hub-vessels The hub positions 1, 2, 3, 5, 6 and 7 are reachable with to hub vessels from all the bases. These results originated from the preprocessing and are presented in Table 24.

Table 24 Results from Phase 1 Case 1: Number of vessels necessary to supply the PSVs of echelon 2 with required cargo 24/7. Base locations are presented in rows and hub locations are given in columns.

Base/ Hub	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	2	2	2	2	2	2	2	3	3	3	3	3
2	2	2	2	2	2	2	2	2	3	3	3	3
3	2	2	2	2	2	2	2	2	2	2	2	3
4	2	2	2	2	2	2	2	2	2	2	2	2
5	2	2	2	2	2	2	2	2	2	2	2	3
6	2	2	2	3	2	2	2	3	2	2	3	3
7	2	2	2	3	2	2	2	2	2	2	2	2

In addition to the 35 runs, two additional analysis have been performed as a part of this thesis. First, the installations were located far outside the defined boundaries used in this report. The geographical coordinates are attached in Appendix 0. The hub-locations remained the same. It appeared that even for theoretical long distances from shore, hub-network is not profitable for the three installations. This result bases is based on the assumptions and simplifications made in this report. Second, the value of required supply, S_i, was reduced from 3 to 2, for the first run of case 2. All other assumptions that commensurate with the problem description were retained. The results show a curtail in number of PSVs from two to one.

Chapter 8

Discussion

This Chapter discusses the results presented in Chapter 7. Ideas and observations are considered. Furthermore, elements of the mathematical model are discussed.

The optimal objective value for Case 2 points at lower total transportation costs compared to Case 1. This is shown for all 35 input variations. These results match with the conclusion of Henrik Nordbø's master thesis (2013) for three installations. For direct shuttle between shore and installations, the results from Table 23 claims that maximum two PSVs are required. With basis in the assumed time charter cost, one can charter $2{,}99 \approx 2$ PSVs per two hub-vessels. When at most two PSVs are sufficient to serve the given problem, combined with higher charter costs per hub than for each PSV, it is clear that direct shuttle is more cost efficient.

It appears from the results presented in Table 17, that direct shuttle is profitable independent of how the installations are located in the Barents Sea. For Case 1, the first base, the Polarbase in Hammerfest, is optimal for all combinations of locations of installations. The hub-vessel costs are the most costly among the cost parameters. These costs are minimized after first priority. At least two hub-vessels are assumed necessary. The cost function for echelon 1 is furthermore described as a step wise function. The costs of echelon 1 depends on number of exclusively of chartered hub-vessels. Hence, as long as for instance two hub-vessels manage to shuttle between given positions and serve the PSVs with required cargo to all time, the sailing distance is insignificant. For some runs, other bases than the Polarbase is placed closer, but since two hub-vessels still manage to sail to base 1 within the given period and the base in Hammerfest offer the lowest rental costs, this base is chosen to be optimal.

Moreover, the hub-costs overrule the costs of echelon 2. The assumed charter costs for one hub-vessel is 2 307 000 NOK per week in comparison to 1 540 000 NOK for one PSV. One can based on these costs observe that 4 PSVs can be chartered before it becomes less costly to charter a third hub-vessel. According to the results of Table 23, the maximum number of required PSVs for direct shuttle is two. Hence, for Case 1, only one or two PSVs are required. Consequently, the base with lowest variable costs are chosen. This is related to the following observation.

From the results presented in Table 17, one can observe that the five most faraway hubs, seen from base 1, are never optimal in Case 1. Faraway hubs, refer to hub location 8, 9, 10, 11 and 12. This can be interpret in two ways. First, as discussed on the previous paragraph the model chooses hub locations such as number of hub-vessels are kept at a minimum. It requires for example three hub-vessels for serving hub position 10 from base 1. This is verified from the preprocessing data of Table 24. Second, the mean longitudinal location of the seven installations, are located west for the faraway hubs. The most eastern location for an installation is 36°E. The most western location is 21°E. The latitude coordinates considered for the hub values are 26, 30 and 34°E. The hub-grid is not localized in center of the installations.

For direct shuttle between base and installations, a greater range of bases are optimal among the 35 runs. Observations from Case 2 (Table 17), illuminate that all bases except from 5 and 6, are optimal at least once. The bases in Vadsø and Kirkenes are localized relatively south compared to the other five bases. The two bases are localized on approximately the same latitude as the fourth base, Båtsfjord, but more south. Consequently, the bases are not desirable to use.

The optimal base is not necessarily chosen due to shortest distances between the facilities. The following point is discussed with bases in results from the first run of Case 2. For this run, two PSVs are required (Table 23). Routes 3, 4 and 6 and 2, 3 and 5 are sailed once by PSV number 1 and 3 respectively (Table 19). Furthermore, installation 1 is visited by PSV 1 (Table 21). All demanded cargo is delivered to the installation via route number 3. No other installations are supplied with cargo on this roundtrip. Since only one installation is supplied with cargo on this route, a shorter route could just as well been chosen, for example route 1 which include only installation 1 on the roundtrip. If no other reason exists for visiting the remaining installations, it is reasonable to believe that a shorter route would be desired. This is a limitation of the model, as the optimal route choice not necessarily is the shortest route. This cohere to the assumption regarding operational costs being included in the fixed time charter costs. On the contrary, the core aim of this report is not to determine optimal schedules, but rather to determine the size of fleet. Fleet size affects the charter costs and moreover the total transportation cost. This is reflected for all 35 runs.

The reason for why the model chooses vessel 1 to sail route 3 instead of a shorter route, needs to be seen in another context. Two PSVs are required hired, but only one of them delivers cargo. This appear from Table 19 and Table 22 respectively. On the other hand both PSVs are dedicated routes to sail (Table 19 and Table 22). According to Statoil, all installations require a minimum number of visits per period. Results from the additional analyze show that only one supply vessel is necessary when the number of services, S_i, are curtailed from 3 to 2. Control of the optimal values for Case 2 run 1, verify that the time restrictions (4.13) and capacity constraints (4.17) are met for each vessel. Based on the additional analyze, it is reasonable to believe that number of required PSVs depend on requested services.

Further, the importance of having exactly three services per installation per period can be discussed. How important is the frequency of visits for Statoil? Perhaps the installations necessitate regular supply of consumables or spare parts. Maybe the installations have to dismiss certain backload. Given that the frequency of supply remains as stated in the data assembling, distribution in cargo may be achieved by extending or changing the model. The model presented in this report do not include any distribution constraints. A proposed solution is presented in further work.

For all runs of Case 2, one can observe that the optimal base and hub are equal for each run. This is expected as all hub locations are given the same geographical positions as the supply bases.

It is assumed that all costs are included in the time charter costs. It can be discussed whether this is a realistic assumption. It is likely to believe, that the fuel cost to some extent will influence on the operational costs. Moreover, it is reasonable to presume that the operational cost as fuel is tried kept at a minimum. It is however likely to believe that the final optimal solution would remain the same notwithstanding that variable fuel costs were included in the model. The additional fuel cost for sailing the longer distance would probably be negligible due to higher hub time charter costs.

The p index in the optimization model imply a heterogeneous fleet of supply vessels. The vessels in this report are assumed to be homogeneous. A homogeneous fleet is characterized by equal properties, service speed and capacity, etc. for all vessels. The interesting factor for being able to answer the objectives of this thesis is the number of vessels. Furthermore, the p index is here indeed redundant. The model is made more complex by utilize the index, as it gains more variables. By using the p index, the model is on the other hand held at a higher generic level. One can with simple justifications in the preprocessing phase, run the optimization model for a heterogenic fleet. The duration on each route, T_{hr}, is however calculated based on equal service speed for all vessels. This would require changes in case of a heterogenic fleet. As the size of the problem is a relatively limited, the solving time is not too affected by the p index.

AS an alternative to introduce k as an index in the mathematical model, it could be included in the preprocessing as a part of the route generation. This would save the model for denary number of constraints. Furthermore, it would positively influence on the solving time, of a problem with more installations than described in this report.

A suggestion to how this could be implemented in the route generation is described in the following. Given an arbitrary route r* that potentially can be sailed three times per period W. Based on the route r* three different route editions could be defined. To sail route r* one time only is one route. A second route is to sail route r* two times and the third route is to sail r* three times. Instead of implementing route r* alone as a parameter, one could implement the three versions as three different routes. This would increase the number of inputs, but the number of variables would decrease. For the problem described in this thesis, saved run time would be relatively confined due to the size of the problem. However, the k index provide the optimal results with lucidity. With a set of many enough routes, one would have to return to the route generation to interpret which route combination a given route hails from. Due to the k index, optimal routes are displayed directly.

It can be discussed whether the approach to the quantum variable, q_{iprk}, is reasonable. Alternatively, it can be defined as a parameter. One can assume regular cargo delivery by dividing the total demand by the number of services per installation per period. Similar is done by (Andersson, et al., 2011). A benefit of this methodology is that one secure a certain distribution on how much cargo is delivered each installation per visit. The frequency, amount and type of cargo is in reality regulated by the offshore installations. The consequences of an installation not receiving required commodities can be of a much greater extent than hiring one additional PSV. By not defining q_{iprk} as a variable, but rather as a parameter, one can potentially loose a better optimal solution. On the contrary, it might be more realistic. It is likely to believe that the quantum variable is more crucial on an operational planning level. The intention of the mathematical model described in these thesis is to be used as a strategic decision tool. The motive is to disclose whether a hub network is more cost efficient than direct shuttle between onshore and installations. The consequences of using the quantum variable has however a negative influence on the model's solving time.

By not removing infeasible routes in Phase 1, one risk to feed unnecessary input into the mathematical model. It appears from Phase 2 that infeasible routes are rejected as potential solutions due to time and/or capacity constraints and are trivial for the final optimal solution. By removing infeasible routes in the preprocessing the model would on the other hand be presented with fewer columns. Given existence of infeasible routes, the model would then have less parameters to check for optimality and the solving time would decrease.

Chapter 9

Conclusion

In this report, optimization of onshore base and hub location supplying oil and gas installations in the Barents Sea has been studied. Based on the discussion of the results presented in Chapter 8 a final conclusion is presented.

It appears from the result that it is *not* cost efficient to utilize a hub-network compared to direct shuttles when three offshore installations are served. The minimum transportation cost for supply scenario including hub-network is 6,8 million NOK. Sufficient reduction in hub charter cost and/or increased number of installations are necessary before hubs ca be considered lucrative.

The optimal transportation cost for supply scenario of direct shuttle is 2,2 million NOK per week. Two PSVs are required and four bases emerge as optimal, depending on the location of the installations. This is summarized in Table 25.

Table 25 Optimal base for given locations of installations

Optimal base location	Geographical coordinates for installations (lat, lon)		
	Installation 1	Installation 2	Installation 3
2	(73°N, 32°E)	(71°N, 32°E)	(72°N, 28°E)
2	(73°N, 32°E)	(72°N, 28°E)	(72°N, 21°E)
2	(71°N, 32°E)	(72°N, 28°E)	(73° N, 23°E)
3	(72°N, 35°E)	(73°N, 32°E)	(71°N, 32°E)
3	(72°N, 35°E)	(73°N, 32°E)	(72°N, 28°E)
3	(71°N, 32°E)	(72°N, 21°E)	(73° N, 23°E)
4	(74°N, 36°E)	(73°N, 32°E)	(71°N, 32°E)
7	(74°N, 36°E)	(72°N, 35°E)	(72°N, 28°E)
7	(72°N, 35°E)	(71°N, 32°E)	(72°N, 28°E)

Chapter 10

Further work

The work that has been carried out in this report has improvements in view of being more realistic. Further work can be done by vary the input parameters and keeping the model as it is defined in this report, or the model can be expanded or changed. This chapter provides suggestions to how the work can continue and which aspects that could be interesting to study further.

First, the structure of the mathematical model presented in this report can be run with different inputs and used to assess different scenarios. The model can be used to find the mean distance between bases and installations, where hub-network becomes profitable. This can be detected by vary the number of and the location for the installations. Similarly, for a specific number of installations, the model can be used to determine the point of intersection where the spreading of installations makes it lucrative to utilize hub-network. Furthermore, the model can be used to assess how many PSVs that are necessary to charter if a given hub location is determined. This can be examined by changing the input. A hub location can be selected by assign it a sufficient low charter cost and simultaneous provide the remaining hubs with theoretical high costs.

From an operations research point of view, one could additionally study the effect of small changes in the mathematical model's parameters. One could for instance allow at most two hubs to operate. Similar could be done for number of supply bases. This would require changes at the right hand side in constraints (4.7) and/or (4.8). As a consequence of this operation, constraints (4.11) and/or (4.12) would additionally require some changes. This brings us into the next point of further work.

The mathematical model could be expand or changed. By validating the programming model, one can gain insight to whether or not the important aspects of the transportation system have been taken into consideration. Introduce restrictions on the opening hours of one or several offshore installations, bases and/or hubs could be considered. This would make the model more realistic. Fagerholt & Lindstad (2000) provides a suggestion on how this can be solved by use of tabu search heuristics.

To avoid all the cargo from being delivered simultaneously, distribution of cargo could improve the degree of realism. Two suggestions are proposed in the following. First, the model could be changed to treat q_{iprk} as a parameter rather than a variable. Delivered cargo per installation can be predetermined by assuming regular supply. For example, the delivered amount per supply can be the ratio of total demand and frequency of services. (Andersson, et al., 2011) can be a relevant paper for this problem. Second, the model could be extended by adding constraints. Such a constraints could be formulated in a way that the volume variable for each vessel and on each route is less or equal to demanded cargo multiplied by a factor k. The k-factor could for instance be a function of service frequency and a chosen number. For example, $k = \frac{1}{s_i} k_1$, where k_1 is decimal between zero and one. Such constraints would restrict the cargo delivery per vessel per route.

The model could be extend to include the logistics Phases before the cargo reaches the onshore supply base. Given that the different cargo is transported from other bases before reaching the supply base, it could be of interest to include these related costs into the model. In addition to the locations of the installations, the optimal supply base location would be considered in relation to these former nodes. An increased overall picture of the total logistic costs would be achieved. This would complicate the model. This pre-phase of the logistic system could be defined as a sub problem of the model described in this thesis. By iterating between the two models, one could achieve a near optimal or an optimal solution.

By validate the logistic system further, one could evaluate whether certain elements require to be stochastically described. This could result in a more realistic model. The demand of cargo varies in reality from time to time. Bad weather conditions influences on route durations. This could be interpret as stochastic elements. One would then have to define the model stochastically and not deterministic. If such changes were added, it could moreover be of interest to study consequences of delay. One could gain information by study sensitivity analysis or perform what if analysis. Specifically, one could introduce slack in constraints (4.13), namely on parameter W. By reducing W with for example 10%, one would gain an extra time buffer.

Thirdly, the hub-concept requires further research. During this report, the hub concept and the hub time charter costs build on assumptions only. More detailed cost estimates could with advantage be assessed. A study on whether or not the described hub-system is executable realistic should be specified. Other hub-design should be evaluated. A system containing a barge and small supply vessels could be less costly and a more realistic concept to charter. For Case 1, it could be interesting to include other logistic challenges such as SAR operations and helicopter shuttle.

It could finally be of interest to carry out a cost benefit analysis of utilizing a hub-network. Although hub-network under certain conditions appear to be more expensive than direct shuttle, other aspects could be of importance. In case of an unforeseen event, two aspects could be interesting to considered: “safety first”-aspects like for instance SAR and increased frequencies of cargo delivery to installations.

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Appendix

A Definition of Locations for Offshore Installations per 35 Run

Table 26 Definition of Locations for offshore installations

Run number	Location of offshore installation						
	A: (74°N, 36°E)	B: (72°N, 35°E)	C: (73°N, 32°E)	D: (71°N, 32°E)	E: (72°N, 28°E)	F: (72°N, 21°E)	G: (73° N, 23°E)
1	1	2	3				
2		1	2	3			
3			1	2	3		
4				1	2	3	
5					1	2	3
6	1	2		3			
7	1	2			3		
8	1	2				3	
9	1	2					3
10	1		2	3			
11	1		2		3		
12	1		2			3	
13	1		2				3
14	1			2	3		
15	1			2		3	
16	1			2			3
17	1				2	3	
18	1				2		3
19	1					2	3
20		1	2		3		
21		1	2			3	
22		1	2				3
23		1		2	3		
24		1		2		3	
25		1		2			3
26		1			2	3	
27		1			2		3
28		1				2	3
29			1	2		3	
30			1	2			3
31			1		2	3	
32			1		2		3

33			1			2	3
34				1	2		3
35				1		2	3

B MATLAB-Script “Hub.m”

```
clear all
close all

%-INPUT-----------------------------------------------------------------
%----------------------------------------------------------------------

%Geographical coordinates for supply bases and installations
bases = [70.38, 23.40; 70.58, 25.58; 70.54, 27.23; 70.38, 29.43; 70.04, 29.44;
69.65, 29.68; 70.22, 31.06];
inst = [74, 36; 72, 35; 73, 32];

%Yearly cost for chartering one vessel [10^3 NOK]
CYearEO = 120000;           %Echelon 1
CYearET = 80000;            %Echelon 2

%Cost for making use of supply base per ton cargo transported from base [10^3
NOK / ton]
Cb=[1.0, 1.5, 1.5, 1.5, 1.5, 1.5, 1.5];

%Capacity per vessel [ton]
Q_Hub=750;                  %Echelon 1
Q_PSV=450;                  %Echelon 2

%Service speed on vessels [knot]
vShuttle=12;                %Echelon 1
vPSV=15;                    %Echelon 2

%Number of PSVs in the fleet, echelon 2
nPSV = 10;

%Demand per installation [ton]
Di=[230, 230, 230];

%Required number of services per installation per week
Si=[3, 3, 3];

%Hub-grid
nLong = 4;                  %No of hub-locations, longitudinal direction
nLat = 3;                   %No of hub-locations, latitudinal direction
SW = [70.5, 22];            %Soth-West corner of hub grid

%Period [weeks]:
W = 1;

%-END-INPUT-------------------------------------------------------------
%----------------------------------------------------------------------

%% Create hub-grid
hg = zeros(nLong,nLat,2);   %Keep the grid points in a 3-dim matrix (hg=hub-
Grid)
stepLat = 0.5;              %Latitudinal distance between hub grid locations
stepLong = 4;               %Longitudinal distance between hub grid locations
```

```
for i=1:nLong
    for j=1:nLat
        hg(i,j,1) = SW(1)+stepLat*i;
        hg(i,j,2) = SW(2)+stepLong*j;
    end
end

%% Map

%Draw map with all positions and lines
ha = axesm('mapproj', 'mercator', 'maplatlim', [65,78], 'maplonlim', [10,40]);
setm(ha, 'MLineLocation', 5, 'PLineLocation', 5);
axis on, gridm off, framem on;
load('coast');
gc = geoshow(lat,long,'displaytype','line','color','b');
geoshow('landareas.shp', 'FaceColor', [0.15 0.55 0.15])
geoshow('worldlakes.shp', 'FaceColor', 'cyan')
textm(inst(1,1)+0.5, inst(1,2), 'P1')
textm(inst(2,1)+0.5, inst(2,2), 'P2')
textm(inst(3,1)+0.5, inst(3,2), 'P3')

% Draw bases
for i=1:length(bases)
    geoshow(bases(i,1), bases(i,2),'DisplayType','point',  'markeredgecol-
or','k', ...
    'markerfacecolor', 'b', 'marker', 'o');
end

%Draw platforms
for i=1:length(inst)
    geoshow(inst(i,1), inst(i,2),'DisplayType','point',  'markeredgecol-
or','k', ...
    'markerfacecolor', 'k', 'marker', 'o');
end

%Draw gridded hubs
for j=1:size(hg,2)
    for i=1:size(hg,1)
        geoshow(hg(i,j,1), hg(i,j,2),'DisplayType','point',  'markeredgecol-
or','r', ...
        'markerfacecolor', 'k', 'marker', '*');
    end
end

%% Calculate durations, and write to tab delimited file

fid = fopen('InputHUB.dat', 'w');
fprintf(fid, '\n\n!Input file for Xpress IVE, generated in MATLAB R2014a
\n\n');
fprintf(fid, '\n\n!Master thesis, NTNU, Marine Technology by Cathrine Aksel-
sen\n\n');
fprintf(fid, '\n\n!"Optimization of supply base location and hub location sup-
plying oil and gas installations in the Barents Sea"\n\n');
fprintf(fid, '\n\n \n\n');
fprintf(fid, '\n\n!All durations given in [hours]\n\n');
fprintf(fid, '\n\n!All costs given in [10^3 NOK]\n\n');
```

```
fprintf(fid, '\n\n \n\n');
fprintf(fid, '\n\n!Inst : [');
fprintf(fid,'%3.0f\t', inst);
fprintf(fid, ']');
fprintf(fid, '\n\n \n\n');

%Flatten hub matrix (lat, long, 2) to a 2-by-N matrix
hgList = reshape(hg, nLong*nLat,2);

fprintf(fid, '\n');
fprintf(fid, '\n\nnHubs : ');
nHubs = length(hgList);
fprintf(fid,'%3.0f\t', nHubs);
fprintf(fid, '\n\nnBases : ');
nBases = length(bases);
fprintf(fid,'%3.0f\t', nBases);
fprintf(fid, '\n\nnRoutes : ');
nRoutes=8;
fprintf(fid,'%3.0f\t', nRoutes);
fprintf(fid, '\n\nnPsv : ');
fprintf(fid,'%3.0f\t', nPSV);
fprintf(fid, '\n\nnInstallations : ');
nInst = length(inst);
fprintf(fid,'%3.0f\t', nInst);

%Calculate the duration from base b to hub h (one way)[hours]
bhDuration = zeros(length(bases),length(hgList));
for i=1:length(bases)
    for j=1:length(hgList)
        bhDuration(i,j) = 8+round(deg2nm(distance('gc',[bases(i,1),ba-
ses(i,2)],...
                [hgList(j,1),hgList(j,2)]))/vShuttle);
    end
end

%Calculate the duration from hub h to installation i [hours]
hiDuration = zeros(length(inst),length(hgList));
for i=1:length(inst)
    for j=1:length(hgList)
        hiDuration(i,j) = 4+round(deg2nm(dis-
tance('gc',[inst(i,1),inst(i,2)],...
                [hgList(j,1),hgList(j,2)])/vPSV));
    end
end

%Calculate the duration between the platforms [hours]
earthRadiusInMeters=6371000;
ppDuration = zeros (3,1);
    ppDuration(1,1)=4+round((rad2nm(distance(inst(1,1), inst(1,2), inst(2,1),
inst(2,2), earthRadiusInMeters)/earthRadiusInMeters)/vPSV));
    ppDuration(2,1)=4+round((rad2nm(distance(inst(1,1), inst(1,2), inst(3,1),
inst(3,2), earthRadiusInMeters)/earthRadiusInMeters)/vPSV));
    ppDuration(3,1)=4+round((rad2nm(distance(inst(2,1), inst(2,2), inst(3,1),
inst(3,2), earthRadiusInMeters)/earthRadiusInMeters)/vPSV));

%Calculate the duration on route r from each hub h, echelon 2 [hours]
```

```
Thr = zeros(nRoutes, length(hgList));
for i = 1:length(hgList)
        Thr(1,i) = 2*hiDuration(1,i);
        Thr(2,i) = hiDuration(1,i) + ppDuration(1,1) + hiDuration(2,i);
        Thr(3,i) = hiDuration(1,i) + ppDuration(1,1) + ppDuration(3,1)+hiDura-
tion(3,i);
        Thr(4,i) = hiDuration(1,i) + ppDuration(2,1) + hiDuration(3,i);
        Thr(5,i) = 2*hiDuration(2,i);
        Thr(6,i) = hiDuration(2,i) + ppDuration(3,1) + hiDuration(3,i);
        Thr(7,i) = 2*hiDuration(3,i);
        Thr(8,i) = hiDuration(3,i) + ppDuration(2,1) + ppDuration(1,1) + hiDu-
ration(2,i);
end

periodHours = W * 24 * 7; %Period in [hours], no slack
fprintf(fid, '\n\nnTimes : ');
nTimes = floor(periodHours/min(min(Thr)));
fprintf(fid,'%3.0f\t', nTimes);
fprintf(fid, '\n\n \n\n');

fprintf(fid, '\n\nThr : [ \n\n');
T_hr = zeros(length(hgList), nRoutes);
for i = 1 : length(hgList)
    for j = 1: nRoutes
        T_hr(i,j) = Thr(j,i);
        fprintf(fid,'%3.0f\t', T_hr(i,j));
    end
        fprintf(fid, '\n');
end
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');

%Number of vessels needed to serve each hub from each base
nVessel= zeros(length(bases), length(hgList));

for i = 1: length(bases)
    for j = 1:length(hgList)
       nVessel(i,j)= nVessel(i,j)+2;
    end
end

DiTot=sum(Di);%Total demand from all installations
nTrips=ones(length(bases), length(hgList));%No of round trips per hub-vessel
per period, echelon 1

%Total delivery capacity per hub-location per period
CapEO = zeros(length(bases), length(hgList));
for i = 1: length(bases)
    for j = 1:length(hgList)
        CapEO(i,j)=(nVessel(i,j)*nTrips(i,j))*Q_Hub;
    end
end

for i = 1: length(bases)
    for j = 1:length(hgList)
```

```
        if ( (2*bhDuration(i,j) > (periodHours/(2*nTrips(i,j)))) && (nVes-
sel(i,j)* Q_Hub < DiTot) ) %Logisk betingelse for duration er galt og kapasi-
tet er galt
            nVessel(i,j) = nVessel(i,j) + 1; %(2*bhDuration) fordi NoTrips re-
presenterer antall rundturer hub-base-hub
        elseif ((nVessel(i,j)* Q_Hub >= DiTot) && (2*bhDuration(i,j) > (pe-
riodHours/(2*(nTrips(i,j)+1))))) %Kapasitet er galt og økt varighet er galt
                nVessel(i,j) = nVessel(i,j) + 1;
                nTrips(i,j)=nTrips(i,j)+1;
        end
    end
end
%nVessel = 2 otherwise

%Unit cost for chartering & operating one PSV p per period, echelon 2
fprintf(fid, '\n\nCET : ');
CET = ( CYearET / 52 ) * W ;
fprintf(fid,'%3.0f\t', CET);
fprintf(fid, '\n\n \n\n');

%Unit cost for chartering & operating the fleet of hub-vessels per period,
echelon 1
CbhEO = zeros(length(bases), length(hgList));
fprintf(fid, '\n\nCbhEO : [ \n\n');
for i = 1:length(bases)
    for j = 1:length(hgList)
        CbhEO(i,j) = nVessel(i,j)* ((CYearEO / 52) * W);
        fprintf(fid,'%3.0f\t', CbhEO(i,j));
    end
    fprintf(fid, '\n');
end
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');

%Write to file, various
%Base costs, Cb
fprintf(fid, '\n\n\nCb : [ \n\n');
fprintf(fid,'%3.0f\t', Cb);
fprintf(fid, '\n');
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');

%Period, W [weeks]
fprintf(fid, '\n\n\nW : ');
fprintf(fid,'%3.0f\t', periodHours);
fprintf(fid, '\n');
fprintf(fid, '\n\n \n\n');

SiW=Si*W;
%Number of services at installations, Si
fprintf(fid, '\n\n\nSi : [ \n\n');
fprintf(fid,'%3.0f\t', SiW);
fprintf(fid, '\n');
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');
```

```
%Air-matrix (fixed due to predefined routes & nInstallations)
fprintf(fid, '\n\n\nAir : [ \n\n');
Air=[1,1,1,1,0,0,0,0;0,1,1,0,1,1,0,1;0,0,1,1,0,1,1,1];
A_ir = zeros(nInst, nRoutes);
for j = 1 : nInst
    for k = 1 : nRoutes
        A_ir(j,k) = Air(j,k);
        fprintf(fid,'%3.0f\t', A_ir(j,k));
    end
    fprintf(fid, '\n');
end
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');

%Capacity PSV, echelon 2, Qp
fprintf(fid, '\n\n\nQp : ');
fprintf(fid,'%3.0f\t', Q_PSV);
fprintf(fid, '\n');
fprintf(fid, '\n\n \n\n');

%Demand at installations, Di

fprintf(fid, '\n\n\nDi : [ \n\n');
D_i = zeros(1, length(Di));
for j = 1 : length(Di)
    D_i(j) = Di(j);
    fprintf(fid,'%3.0f\t', D_i(j));
end
fprintf(fid, '\n');
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');

%Big M: M_p
fprintf(fid, '\n\n\nM_p : ');
M_p = ceil(periodHours / min(min(Thr)));
fprintf(fid,'%3.0f\t', M_p);
fprintf(fid, '\n');
fprintf(fid, '\n\n \n\n');

%Big M: M_r
fprintf(fid, '\n\nM_r : ');
M_r = max(Di);
fprintf(fid, '%3.0f\t', M_r);
fprintf(fid, '\n');

fclose(fid);
```

C MATLAB-Script "NoHub.m"

```
clear all
close all

%-INPUT------------------------------------------------------------------------
%-----------------------------------------------------------------------------

%Geographical coordinates for supply bases and installations
bases = [70.38, 23.40; 70.58, 25.58; 70.54, 27.23; 70.38, 29.43; 70.04, 29.44;
69.65, 29.68; 70.22, 31.06];
inst = [74, 36; 72, 35; 73, 32];

%Yearly cost for chartering one vessel [10^3 NOK]
CYearEO = 0;                %Echelon 1
CYearET = 80000;            %Echelon 2

%Cost for making use of supply base per ton cargo transported from base [10^3
NOK / ton]
Cb=[1.0, 1.5, 1.5, 1.5, 1.5, 1.5, 1.5];

%Capacity per vessel [ton]
Q_Hub=750;                  %Echelon 1
Q_PSV=450;                  %Echelon 2

%Service speed on vessels [knot]
vShuttle=12;                %Echelon 1
vPSV=15;                    %Echelon 2

%Number of PSVs in the fleet, echelon 2
nPSV = 10;

%Demand per installation [ton]
Di=[230, 230, 230];

%Required number of services per installation per week
Si=[3, 3, 3];

%Period [weeks]:
W = 1;

%-END-INPUT--------------------------------------------------------------------
%-----------------------------------------------------------------------------

%%Draw

%Draw map with all positions and lines
ha = axesm('mapproj', 'mercator', 'maplatlim', [65,78], 'maplonlim', [10,40]);
setm(ha, 'MLineLocation', 5, 'PLineLocation', 5);
axis on, gridm off, framem on;
load('coast');
gc = geoshow(lat,long,'displaytype','line','color','b');
geoshow('landareas.shp', 'FaceColor', [0.15 0.55 0.15])
geoshow('worldlakes.shp', 'FaceColor', 'cyan')
```

```
% Draw bases
for i=1:length(bases)
    geoshow(bases(i,1), bases(i,2),'DisplayType','point',  'markeredgecol-
or','k', ...
    'markerfacecolor', 'b', 'marker', 'o');
end

%Draw platforms
for i=1:length(inst)
    geoshow(inst(i,1), inst(i,2),'DisplayType','point',  'markeredgecol-
or','k', ...
    'markerfacecolor', 'k', 'marker', 'o');
end

%Draw gridded hubs
for i=1:length(bases)
        geoshow(bases(i,1), bases(i,2),'DisplayType','point',  'markeredgecol-
or','r', ...
        'markerfacecolor', 'k', 'marker', '*');
end

%% Calculate durations, and write to tab delimited file

fid = fopen('InputNoHUB.dat', 'w');
fprintf(fid, '\n\n!Input file for Xpress IVE, generated in MATLAB R2014a
\n\n');
fprintf(fid, '\n\n!Master thesis, NTNU, Marine Technology by Cathrine Aksel-
sen\n\n');
fprintf(fid, '\n\n!"Optimization of supply base location and hub location sup-
plying oil and gas installations in the Barents Sea"\n\n');
fprintf(fid, '\n\n!No hub-network \n\n');
fprintf(fid, '\n\n \n\n');
fprintf(fid, '\n\n!All durations given in [hours]\n\n');
fprintf(fid, '\n\n!All costs given in [10^3 NOK]\n\n');
fprintf(fid, '\n\n \n\n');
fprintf(fid, '\n\n!Inst : [');
fprintf(fid,'%3.0f\t', inst);
fprintf(fid, ']');
fprintf(fid, '\n\n \n\n');

%"Hub-network" transformed to base locations
hgList = zeros(size(bases));
for i = 1 : size(bases,1)
    for j = 1 : size(bases, 2)
    hgList(i,j) = bases(i,j);
    end
end

fprintf(fid, '\n');
fprintf(fid, '\n\nnHubs : ');
nHubs = length(hgList);
fprintf(fid,'%3.0f\t', nHubs);
fprintf(fid, '\n\nnBases : ');
nBases = length(bases);
fprintf(fid,'%3.0f\t', nBases);
```

```
fprintf(fid, '\n\nnRoutes : ');
nRoutes=8;
fprintf(fid,'%3.0f\t', nRoutes);
fprintf(fid, '\n\nnPsv : ');
fprintf(fid,'%3.0f\t', nPSV);
fprintf(fid, '\n\nnInstallations : ');
nInst = length(inst);
fprintf(fid,'%3.0f\t', nInst);

%Calculate the duration from base b to hub h (one way)[hours]
bhDuration = zeros(length(bases),length(hgList));
for i=1:length(bases)
    for j=1:length(hgList)
        bhDuration(i,j) = round(deg2nm(distance('gc',[bases(i,1),ba-
ses(i,2)],...
                [hgList(j,1),hgList(j,2)]))/vShuttle);
    end
end

%Calculate the duration from hub h to installation i [hours]
hiDuration = zeros(length(inst),length(hgList));
for i=1:length(inst)
    for j=1:length(hgList)
        hiDuration(i,j) = 4+round(deg2nm(dis-
tance('gc',[inst(i,1),inst(i,2)],...
                [hgList(j,1),hgList(j,2)])/vPSV));
    end
end

%Calculate the duration between the platforms [hours]
earthRadiusInMeters=6371000;
ppDuration = zeros (3,1);
    ppDuration(1,1)=4+round((rad2nm(distance(inst(1,1), inst(1,2), inst(2,1),
inst(2,2), earthRadiusInMeters)/earthRadiusInMeters)/vPSV));
    ppDuration(2,1)=4+round((rad2nm(distance(inst(1,1), inst(1,2), inst(3,1),
inst(3,2), earthRadiusInMeters)/earthRadiusInMeters)/vPSV));
    ppDuration(3,1)=4+round((rad2nm(distance(inst(2,1), inst(2,2), inst(3,1),
inst(3,2), earthRadiusInMeters)/earthRadiusInMeters)/vPSV));

%Calculate the duration on route r from each hub h, echelon 2 [hours]
Thr = zeros(nRoutes, length(hgList));
for i = 1:length(hgList)
        Thr(1,i) = 2*hiDuration(1,i);
        Thr(2,i) = hiDuration(1,i) + ppDuration(1,1) + hiDuration(2,i);
        Thr(3,i) = hiDuration(1,i) + ppDuration(1,1) + ppDuration(3,1)+hiDura-
tion(3,i);
        Thr(4,i) = hiDuration(1,i) + ppDuration(2,1) + hiDuration(3,i);
        Thr(5,i) = 2*hiDuration(2,i);
        Thr(6,i) = hiDuration(2,i) + ppDuration(3,1) + hiDuration(3,i);
        Thr(7,i) = 2*hiDuration(3,i);
        Thr(8,i) = hiDuration(3,i) + ppDuration(2,1) + ppDuration(1,1) + hiDu-
ration(2,i);
end

periodHours = W * 24 * 7; %Period in [hours], no slack
fprintf(fid, '\n\nnTimes : ');
```

```
nTimes = floor(periodHours/min(min(Thr)));
fprintf(fid,'%3.0f\t', nTimes);
fprintf(fid, '\n\n \n\n');

fprintf(fid, '\n\nThr : [ \n\n');
T_hr = zeros(length(hgList), nRoutes);
for i = 1 : length(hgList)
    for j = 1: nRoutes
        T_hr(i,j) = Thr(j,i);
        fprintf(fid,'%3.0f\t', T_hr(i,j));
    end
        fprintf(fid, '\n');
end
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');

DiTot=sum(Di);

%Unit cost for chartering & operating one PSV p per period, echelon 2
fprintf(fid, '\n\nCET : ');
CET = ( CYearET / 52 ) * W ;
fprintf(fid,'%3.0f\t', CET);
fprintf(fid, '\n\n \n\n');

%Unit cost for chartering & operating the fleet of hub-vessels per period,
echelon 1
CbhEO = zeros(length(bases), length(hgList));
fprintf(fid, '\n\nCbhEO : [ \n\n');
for i = 1:length(bases)
    for j = 1:length(hgList)
        if i == j
            CbhEO(i,j) = 0;
        else
            CbhEO(i,j) = 10^4;
        end
    end
end

for i = 1 : size(CbhEO,1)
    for j = 1 : size(CbhEO,2)
                fprintf(fid,'%3.0f\t', CbhEO(i,j));
    end
    fprintf(fid, '\n');
end

fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');

%Write to file, various
%Base costs, Cb
fprintf(fid, '\n\n\nCb : [ \n\n');
fprintf(fid,'%3.0f\t', Cb);
fprintf(fid, '\n');
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');
```

```
%Period, W [weeks]
fprintf(fid, '\n\n\nW : ');
fprintf(fid,'%3.0f\t', periodHours);
fprintf(fid, '\n');
fprintf(fid, '\n\n \n\n');

SiW=Si*W;
%Number of services at installations, Si
fprintf(fid, '\n\n\nSi : [ \n\n');
fprintf(fid,'%3.0f\t', SiW);
fprintf(fid, '\n');
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');

%Air-matrix (fixed due to predefined routes & nInstallations)
fprintf(fid, '\n\n\nAir : [ \n\n');
Air=[1,1,1,1,0,0,0,0;0,1,1,0,1,1,0,1;0,0,1,1,0,1,1,1];
A_ir = zeros(nInst, nRoutes);
for j = 1 : nInst
    for k = 1 : nRoutes
        A_ir(j,k) = Air(j,k);
        fprintf(fid,'%3.0f\t', A_ir(j,k));
    end
    fprintf(fid, '\n');
end
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');

%Capacity PSV, echelon 2, Qp
fprintf(fid, '\n\n\nQp : ');
fprintf(fid,'%3.0f\t', Q_PSV);
fprintf(fid, '\n');
fprintf(fid, '\n\n \n\n');

%Demand at installations, Di
fprintf(fid, '\n\n\nDi : [ \n\n');
D_i = zeros(1, length(Di));
for j = 1 : length(Di)
    D_i(j) = W*Di(j);
    fprintf(fid,'%3.0f\t', D_i(j));
end
fprintf(fid, '\n');
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');

%Big M: M_p
fprintf(fid, '\n\n\nM_p : ');
M_p = ceil(periodHours / min(min(Thr)));
fprintf(fid,'%3.0f\t', M_p);
fprintf(fid, '\n');
fprintf(fid, '\n\n \n\n');

%Big M: M_r
fprintf(fid, '\n\nM_r : ');
M_r = max(D_i);
```

```
fprintf(fid, '%3.0f\t', M_r);
fprintf(fid, '\n');

fclose(fid);
```

D Output Phase 1: A_{ir}-matrix

Table 27 Air-matrix, describing whether an installation is visited on a route. A_{ir} is 1 if installation i is visited on route r and zero otherwise. The matrix is necessary input for Phase 2 of the problem

r / i	1	2	3	4	5	6	7	8
1	1	1	1	1	0	0	0	0
2	0	1	1	0	1	1	0	1
3	0	0	1	1	0	1	1	1

E Output “Hub.m” Phase 1 Run 1

Table 28 Output from "Hub.m" Phase 1 Run 1

!Input file for Xpress IVE, generated in MATLAB R2014a											
!Master thesis, NTNU, Marine Technology by Cathrine Akselsen											
!"Optimization of supply base location and hub location supplying oil and gas installations in the Barents Sea"											
!All durations given in [hours]											
!All costs given in [10^3 NOK]											
!Inst : [74	72	73	36	35	32	]					
nHubs : 12											
nBases : 7											
nRoutes : 8											
nPsv : 10											
nInstallations : 3											
nTimes : 16											
Thr : [											
42	49	57	46	32	40	30	53				
38	46	53	42	30	37	26	50				
36	45	51	40	30	36	24	49				
34	44	49	38	30	35	22	48				
36	42	51	40	24	33	24	46				
32	39	47	36	22	30	20	43				
30	37	45	34	20	28	18	41				
26	35	41	30	20	26	14	39				
32	36	49	38	16	29	24	42				
28	32	45	34	12	25	20	38				
24	29	42	31	10	23	18	36				
20	28	38	27	12	22	14	35				
]											
CET : 1538											
CbhEO : [											
4615	4615	4615	4615	4615	4615	4615	6923	6923	6923	6923	6923
4615	4615	4615	4615	4615	4615	4615	4615	6923	6923	6923	6923
4615	4615	4615	4615	4615	4615	4615	4615	4615	4615	4615	6923
4615	4615	4615	4615	4615	4615	4615	4615	4615	4615	4615	4615
4615	4615	4615	4615	4615	4615	4615	4615	4615	4615	4615	6923
4615	4615	4615	6923	4615	4615	4615	6923	4615	4615	6923	6923

4615	4615	4615	6923	4615	4615	4615	4615	4615	4615	4615	4615
]											
Cb : [											
1	1,5	1,5	1,5	1,5	1,5	1,5					
]											
W : 168											
Si : [											
3	3	3									
]											
Air : [											
1	1	1	1	0	0	0	0				
0	1	1	0	1	1	0	1				
0	0	1	1	0	1	1	1				
]											
Qp : 450											
Di : [											
230	230	230									
]											
M_p : 17											

F Output "NoHub.m" Phase 1 Run 1

Table 29 Output from "NoHub.m" Phase 1 Run 1

!Input file for Xpress IVE, generated in MATLAB R2014a							
!Master thesis, NTNU, Marine Technology by Cathrine Akselsen							
!"Optimization of supply base location and hub location supplying oil and gas installations in the Barents Sea"							
!No hub-network							
!All durations given in [hours]							
!All costs given in [10^3 NOK]							
!Inst : [74	72	73	36	35	32	]	
nHubs : 7							
nBases : 7							
nRoutes : 8							
nPsv : 10							
nInstallations : 3							
nTimes : 6							
Thr : [							
50	57	65	54	40	48	38	61
46	52	61	50	34	43	34	56
42	49	58	47	32	41	32	54
42	47	57	46	28	38	30	51
44	49	59	48	30	40	32	53
46	51	62	51	32	43	36	56
40	45	56	45	26	37	30	50
]							
CET : 1538							
CbhEO : [							
0	10000	10000	10000	10000	10000	10000	
10000	0	10000	10000	10000	10000	10000	
10000	10000	0	10000	10000	10000	10000	
10000	10000	10000	0	10000	10000	10000	
10000	10000	10000	10000	0	10000	10000	
10000	10000	10000	10000	10000	0	10000	
10000	10000	10000	10000	10000	10000	0	
]							
Cb : [							

1	1,5	1,5	1,5	1,5	1,5	1,5	
]							
W : 168							
Si : [							
3	3	3					
]							
Air : [							
1	1	1	1	0	0	0	0
0	1	1	0	1	1	0	1
0	0	1	1	0	1	1	1
]							
Qp : 450							
Di : [							
230	230	230					
]							
M_p : 7							
M_r : 230							

G MATLAB-Script for Distance Calculations

```
%% Calculate distances[nm]
base = [70.38, 23.40; 70.58, 25.58; 70.54, 27.23; 70.38, 29.43; 70.04, 29.44;
69.65, 29.68; 70.22, 31.06];
inst = [74, 36; 72, 35; 73, 32; 71, 32; 72, 28; 72, 21; 73, 23]; %Location A,
B, C, D, E, F and G respectively
hub = [
71,26;71.5,26;72,26;72.5,26;71,30;71.5,30;72,30;72.5,30;71,34;71.5,34;72,34;72
.5,34]; %From hgList

%Distance from base to installations [nm]
biDist = zeros(length(base),length(inst));
for i=1:length(base)
    for j=1:length(inst)
        biDist(i,j) = round(deg2nm(distance('gc',[base(i,1),base(i,2)],...
                [inst(j,1),inst(j,2)])));
    end
end

%Distance between installations [nm]
bhDist = zeros(length(inst), length(inst));
for i = 1:length(inst)
    for j= 1:length(inst)
        bhDist(i,j) = round(deg2nm(distance('gc',[inst(i,1),inst(i,2)],...
                [inst(j,1),inst(j,2)])));
    end
end

%Distance between base and hub-locations [nm]
bhDist = zeros(length(base), length(hub));
for i = 1:length(base)
    for j= 1:length(hub)
        bhDist(i,j) = round(deg2nm(distance('gc',[base(i,1),base(i,2)],...
                [hub(j,1),hub(j,2)])));
    end
end
```

H Output Distance Calculations

Table 30 Distances between bases and installations [nm]

Base/ Installation	A	B	C	D	E	F	G
1	316	244	226	175	132	108	157
2	279	200	189	129	97	123	153
3	262	173	173	98	89	149	168
4	248	145	165	63	101	190	198
5	267	160	184	77	121	202	216
6	286	176	206	94	145	221	238
7	244	131	168	50	122	222	226

Table 31 Distances between installations [nm]

Installation/ Installation	A	B	C	D	E	F	G
A	0	121	91	194	185	288	229
B	121	0	81	83	130	259	224
C	91	81	0	120	94	207	158
D	194	83	120	0	97	218	205
E	185	130	94	97	0	130	108
F	288	259	207	218	130	0	70
G	229	224	158	205	108	70	0

Table 32 Distances between bases and hub-locations [nm]

Base/ Hub	1	2	3	4	5	6	7	8	9	10	11	12
1	64	84	109	137	136	146	160	179	213	218	227	239
2	27	56	86	116	91	102	120	143	168	173	183	197
3	37	62	91	120	61	79	103	129	137	144	157	174
4	78	95	118	143	39	68	98	128	98	112	131	154
5	90	111	135	162	59	88	118	148	108	126	147	172
6	110	133	159	185	81	111	141	171	119	141	165	191
7	111	126	145	168	51	80	109	138	75	96	121	148

The distances are calculated with great circle route

I Implementation of the Mathematical Model, Phase 2, in Xpress IVE

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

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

parameters
	DataFile = '1Hub.txt';
end-parameters
! Get the data file

declarations
	nHubs		:	integer;
	nBases		:	integer;
	nRoutes		:	integer;
	nPsv		:	integer;
	nInstallations	:	integer;
	nTimes		:	integer;
end-declarations
! Data describing the size of the problem:

initializations from DataFile
	nHubs;
```

```
	nBases;
	nRoutes;
	nPsv;
	nInstallations;
	nTimes;
end-initializations
! The data is read from the file DataFile

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 sets

Hubs := 1 .. nHubs;
Bases := 1 .. nBases;
Routes := 1 .. nRoutes;
Psv := 1 .. nPsv;
Installations := 1 .. nInstallations;
Times := 1 .. nTimes;
! Define the sets based on the number of facilities

finalize(Hubs);
finalize(Bases);
finalize(Routes);
```

```
finalize(Psv);
finalize(Installations);
finalize(Times);
! All sets are finalized. It is no longer possible to add or remove elements from the sets

writeln('Hubs : ', Hubs);
writeln('Bases : ', Bases);
writeln('Routes : ', Routes);
writeln('PSV : ', Psv);
writeln('Installations : ', Installations);
writeln('Times : ', Times);
! Write to screen

declarations
    Thr     :   array(Hubs, Routes)             of integer;
    CET     :                                   integer;
    CbhEO   :   array(Bases, Hubs)              of integer;
    Cb      :   array(Bases)                    of integer;
    W       :                                   integer;
    Si      :   array(Installations)            of integer;
    Air     :   array(Installations, Routes)    of integer;
    Qp      :   array(Psv)                      of integer;
    Di      :   array(Installations)            of integer;
    M_p     :                                   integer;
    M_r     :                                   integer;
end-declarations
! Data describing the rest of the problem

initializations from DataFile
```

```
        Thr;
        CET;
        CbhEO;
        Cb;
        W;
        Si;
        Air;
        Qp;
        Di;
        M_p;
        M_r;
end-initializations
! Read data from "DataFile"

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
! Declare all variables

forall (hh in Hubs) do
        create(deltaH(hh));
end-do
```

```
forall (bb in Bases) do
	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, kk in Times) do
	create(qIPRK(ii,pp,rr,kk));
end-do

forall (pp in Psv, rr in Routes, kk in Times) do
	create(betaPRK(pp,rr,kk));
end-do
! Generate all variables

declarations
	TotalCost:						linctr;
	Service:		dynamic array(Installations)		of linctr;
	HubLocation:						linctr;
```

```
    BaseLocation:                                                              linctr;
    CouplingA:        dynamic array(Psv)                                       of linctr;
    CouplingC:        dynamic array(Psv, Hubs)                                 of linctr;
    ExistBase:        dynamic array(Bases)                                     of linctr;
    ExistHub:         dynamic array(Hubs)                                      of linctr;
    Duration:         dynamic array(Psv)                                       of linctr;
    Delivery:         dynamic array(Installations)                             of linctr;
    CouplingD:        dynamic array(Installations, Routes, Psv, Times)         of linctr;
    CouplingE:        dynamic array(Routes, Psv)                               of linctr;
    CapacityVessel:   dynamic array(Routes, Psv)                               of linctr;
    AntiSym_p:        dynamic array(Installations, Psv, Routes, Times)         of linctr;
    AntiSym_b:        dynamic array(Psv, Routes, Times)                        of linctr;
end-declarations
! Declare the objective function (4.5) in the report
! Declare constraints (4.6) in the report
! Declare constraints (4.7) in the report
! Declare constraints (4.8) in the report
! Declare constraints (4.9) in the report
! Declare constraints (4.10) in the report
! Declare constraints (4.11) in the report
! Declare constraints (4.12) in the report
! Declare constraints (4.13) in the report
! Declare constraints (4.14) in the report
! Declare constraints (4.15) in the report
! Declare constraints (4.16) in the report
! Declare constraints (4.17) in the report
! Declare constraints (4.18) in the report
! Declare constraints (4.19) in the report
```

```
TotalCost:=
	sum(pp in Psv) CET * 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);
! Defines the objective function

forall(ii in Installations) do
	sum(hh in Hubs, pp in Psv, rr in Routes) Air(ii,rr) * xPRH(pp,rr,hh) >= Si(ii);
end-do
! Defines constraints (4.6) in the report



HubLocation :=
	sum(hh in Hubs) deltaH(hh) = 1;
! Defines constraints (4.7) in the report

BaseLocation :=
	sum(bb in Bases) gammaB(bb) = 1;
! Defines constraints (4.8) in the report

forall(pp in Psv, rr in Routes) do
	sum(hh in Hubs) xPRH(pp, rr, hh) - (M_p * alphaP(pp)) <= 0;
end-do
! Defines constraints (4.9) in the report



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

```
! Defines constraints (4.10) in the report

forall(bb in Bases) do
        gammaB(bb) = sum(hh in Hubs) rhoBH(bb,hh);
end-do
! Defines constraints (4.11) in the report

forall(hh in Hubs) do
        deltaH(hh) = sum(bb in Bases) rhoBH(bb,hh);
end-do
! Defines constraints (4.12) in the report

forall(pp in Psv, hh in Hubs) do
        sum(rr in Routes) Thr(hh,rr) * xPRH(pp,rr,hh) <= W;
end-do
! Defines constraints (4.13) in the report

forall(ii in Installations) do
        sum(pp in Psv, rr in Routes, kk in Times) qIPRK(ii,pp,rr,kk) >= Di(ii);
end-do
! Defines constraints (4.14) in the report

forall(ii in Installations, rr in Routes, pp in Psv, kk in Times) do
        qIPRK(ii,pp,rr,kk) - M_r * betaPRK(pp,rr,kk) <= 0;
end-do
! Defines constraints (4.15) in the report

forall(rr in Routes, pp in Psv) do
        sum(kk in Times) betaPRK(pp,rr,kk) = sum(hh in Hubs) xPRH(pp,rr,hh);
```

```
end-do
! Defines constraints (4.16) in the report

forall(rr in Routes, pp in Psv) do
	Qp(pp) >= sum(ii in Installations, kk in Times) qIPRK(ii,pp,rr,kk);
end-do
! Defines constraints (4.17) in the report

forall(ii in Installations, pp in Psv, rr in Routes, kk in Times | kk <= (nTimes-1) ) do
	qIPRK(ii, pp, rr, kk+1) <= qIPRK(ii, pp, rr, kk);
end-do
! Defines constraints (4.18) in the report

forall(pp in Psv, rr in Routes, kk in Times | kk <= (nTimes-1) ) do
	betaPRK(pp, rr, kk+1) <= betaPRK(pp, rr, kk);
end-do
! Defines constraints (4.19) in the report

forall(hh in Hubs) deltaH(hh) is_binary;
! Defines binary restriction on variable. Constraints (4.20) in the report

forall(bb in Bases) gammaB(bb) is_binary;
! Defines binary restriction on variable. Constraints (4.21) in the report

forall(pp in Psv) alphaP(pp) is_binary;
! Defines binary restriction on variable. Constraints (4.22) in the report

forall(bb in Bases, hh in Hubs) rhoBH(bb,hh) is_integer;
! Defines binary restriction on variable. Constraints (4.23) in the report
```

```
forall(pp in Psv, rr in Routes, hh in Hubs) xPRH(pp,rr,hh) is_integer;
! Defines integer restriction on variable. Constraints (4.24) in the report

forall(ii in Installations, pp in Psv, rr in Routes, kk in Times) qIPRK(ii,pp,rr,kk) is_integer;
! Defines integer restriction on variable. Constraints (4.25) in the report

forall(pp in Psv, rr in Routes, kk in Times) betaPRK(pp,rr,kk) is_binary;
! Defines binary restriction on variable. Constraints (4.26) in the report

minimize(TotalCost);

writeln;
writeln('----------------------------------------');
writeln('"Optimal objective value : " ');
writeln(getobjval);

writeln;
writeln('deltaH is 1 if hub location h is used, o otherwise');
forall(hh in Hubs) do
writeln('deltaH(',hh,') :', getsol(deltaH(hh)));
end-do

writeln;
writeln('gammaB is 1 if base b is used, 0 otherwise');
forall(bb in Bases) do
writeln('gamaB(',bb,') : ',getsol(gammaB(bb)));
end-do
```

```
writeln;
writeln('alphaP');
forall(pp in Psv) do
writeln('alphaP(',pp,') : ', getsol(alphaP(pp)));
end-do

writeln;
writeln('betaPRK');
forall(pp in Psv, rr in Routes ,kk in Times) do
writeln('betaPRK(',pp,',', rr,',', kk,') : ', getsol(betaPRK(pp, rr, kk)));
end-do

writeln;
writeln('qIPRK');
writeln(' ');
forall(ii in Installations, pp in Psv, rr in Routes ,kk in Times) do
writeln('qIPRK(',ii,',',pp,',', rr,',', kk,') : ',getsol(qIPRK(ii,pp, rr, kk)));
end-do

writeln;
writeln('rhoBH');
forall(bb in Bases, hh in Hubs) do
writeln('rhoBH(',bb,',', hh,') : ', getsol(rhoBH(bb,hh)));
end-do

writeln;
writeln('xPRH');
forall(pp in Psv, rr in Routes ,hh in Hubs) do
writeln('xPRH(',pp,',', rr,',', hh,') : ', getsol(xPRH(pp, rr, hh)));
```

```
end-do
end-model
```

J Results Phase 2 Case 1 Optimal q_{iprk}* all runs

Table 33 Optimal q_{iprk} Phase 2 Case 1 for all runs*

Run	(i,p,r,k)	**q(i,p,r,k)***	Run	(i,p,r,k)	**q(i,p,r,k)***	Run	(i,p,r,k)	**q(i,p,r,k)***
1	(1,1,7,1) :	230	13	(1,1,1,1) :	230	25	(1,1,7,1) :	230
	(2,1,3,1) :	230		(2,1,6,1) :	230		(2,1,3,1) :	230
	(3,1,2,1) :	230		(3,1,3,1) :	230		(3,1,2,1) :	230
2	(1,1,1,1) :	230	14	(1,1,2,1) :	220	26	(1,1,3,1) :	230
	(2,1,8,1) :	230		(1,1,7,1) :	10		(2,1,2,1) :	230
	(3,1,2,1) :	230		(2,1,7,1) :	230		(3,1,2,1) :	10
				(3,1,2,1) :	230		(3,1,3,1) :	220
3	(1,1,2,1) :	220	15	(1,1,3,1) :	12	27	(1,1,1,1) :	220
	(1,1,7,1) :	10		(1,1,3,2) :	12		(1,1,2,1) :	10
	(2,1,7,1) :	230		(1,1,7,1) :	206		(2,1,1,1) :	230
	(3,1,2,1) :	230		(2,1,3,1) :	230		(3,1,2,1) :	230
				(3,1,7,1) :	230			
4	(1,1,1,1) :	230	16	(1,1,3,1) :	12	28	(1,1,3,1) :	230
	(2,1,7,1) :	230		(1,1,3,2) :	12		(2,1,6,1) :	230
	(3,1,2,1) :	230		(1,1,7,1) :	206		(3,1,2,1) :	230
				(2,1,3,1) :	230			
				(3,1,7,1) :	230			
5	(1,1,1,1) :	230	17	(1,1,3,1) :	230	29	(1,1,7,1) :	115
	(2,1,7,1) :	230		(2,1,7,1) :	230		(1,1,7,2) :	115
	(3,1,2,1) :	230		(3,1,2,1) :	230		(2,1,3,1) :	10
							(2,1,7,1) :	110
							(2,1,7,2) :	110
							(3,1,3,1) :	230
6	(1,1,1,1) :	220	18	(1,1,1,1) :	230	30	(1,1,7,1) :	230
	(1,1,2,1) :	10		(2,1,6,1) :	230		(2,1,2,1) :	230
	(2,1,1,1) :	230		(3,1,2,1) :	230		(3,1,3,1) :	230
	(3,1,2,1) :	230						
7	(1,1,1,1) :	220	19	(1,1,1,1) :	220	31	qIPRK(1,1,1,1) :	230
	(1,1,2,1) :	10		(1,1,2,1) :	10		(2,1,7,1) :	230
	(2,1,1,1) :	230		(2,1,1,1) :	230		qIPRK(3,1,2,1) :	230
	(3,1,2,1) :	230		(3,1,2,1) :	230			

8	(1,1,1,1) :	220	20	(1,1,1,1) :	220	32	(1,1,8,1) :	230
	(1,1,2,1) :	10		(1,1,2,1) :	10		(2,1,2,1) :	10
	(2,1,1,1) :	230		(2,1,1,1) :	230		(2,1,8,1) :	220
	(3,1,2,1) :	230		(3,1,2,1) :	230		(3,1,2,1) :	230
9	(1,1,1,1) :	220	21	(1,1,2,1) :	230	33	(1,1,4,1) :	220
	(1,1,2,1) :	10		(2,1,3,1) :	230		(1,1,5,1) :	10
	(2,1,1,1) :	230		(3,1,7,1) :	230		(2,1,5,1) :	230
	(3,1,2,1) :	230					qIPRK(3,1,4,1) :	230
10	(1,1,6,1) :	230	22	(1,1,7,1) :	230	34	(1,1,1,1) :	230
	(2,1,3,1) :	230		(2,1,1,1) :	230		qIPRK(2,1,7,1) :	230
	(3,1,2,1) :	230		(3,1,2,1) :	230		(3,1,2,1) :	230
11	(1,1,3,1) :	230	23	(1,1,1,1) :	220	35	(1,1,3,1) :	230
	(2,1,7,1) :	230		(1,1,2,1) :	10		(2,1,7,1) :	230
	(3,1,2,1) :	230		(2,1,1,1) :	230		(3,1,2,1) :	230
				(3,1,2,1) :	230			
12	(1,1,2,1) :	220	24	(1,1,3,1) :	230			
	(1,1,3,1) :	10		(2,1,7,1) :	230			
	(2,1,3,1) :	230		(3,1,2,1) :	230			
	(3,1,2,1) :	230						

K Results Phase 2 Case 2 Optimal q_{iprk}* all runs

Table 34 Optmal q_{iprk} Phase 2 Case 2 for all runs*

Run	(i,p,r,k)	**q(i,p,r,k)***	Run	(i,p,r,k)	**q(i,p,r,k)***	Run	(i,p,r,k)	**q(i,p,r,k)***
1	(1,1,3,1) :	230	13	(1,1,3,1) :	230	25	(1,1,2,1) :	230
	(2,1,4,1) :	230		(2,1,4,1) :	230		(2,1,3,1) :	230
	(3,1,6,1) :	230		(3,1,7,1) :	230		(3,1,4,1) :	230
2	(1,1,4,1) :	230	14	(1,1,3,1) :	103	26	(1,1,2,1) :	96
	(2,1,5,1) :	230		(1,1,3,2) :	2		(1,1,3,1) :	67
	(3,1,3,1) :	230		(1,1,5,1) :	125		(1,1,3,2) :	67
				(2,1,3,1) :	230		(2,1,3,1) :	230
				(3,1,5,1) :	230		(3,1,2,1) :	230
3	(1,1,3,1) :	230	15	(1,1,3,1) :	140	27	(1,1,3,1) :	230
	(2,1,6,1) :	230		(1,1,3,2) :	2		(2,1,3,1) :	2
	(3,1,1,1) :	230		(1,1,7,1) :	88		(2,1,3,2) :	2
				(2,1,3,1) :	230		(2,1,6,1) :	226
				(3,1,7,1) :	230		(3,1,3,1) :	3
							(3,1,3,2) :	3
							(3,1,6,1) :	224
4	(1,1,3,1) :	230	16	(1,1,3,1) :	72	28	(1,1,3,1) :	110
	(2,1,7,1) :	230		(1,1,4,1) :	158		(1,1,3,2) :	2
	(3,1,3,1) :	10		(2,1,3,1) :	230		(1,1,6,1) :	118
	(3,1,7,1) :	220		(3,1,4,1) :	230		(2,1,3,1) :	110
							(2,1,3,2) :	110
							(2,1,6,1) :	10
							(3,1,6,1) :	230
5	(1,1,6,1) :	230	17	(1,1,3,1) :	230	29	(1,1,3,1) :	230
	(2,1,4,1) :	230		(2,1,6,1) :	230		(2,1,5,1) :	230
	(3,1,1,1) :	230		(3,1,3,1) :	167		(3,1,7,1) :	230
				(3,1,3,2) :	48			
				(3,1,6,1) :	15			
6	(1,1,4,1) :	230	18	(1,1,3,1) :	230	30	(1,1,4,1) :	230
	(2,1,6,1) :	230		(2,1,4,1) :	230		(2,1,3,1) :	230
	(3,1,2,1) :	230		(3,1,6,1) :	230		(3,1,6,1) :	230
7	(1,1,3,1) :	230	19	(1,1,3,1) :	230	31	(1,1,7,1) :	230
	(2,1,4,1) :	230		(2,1,4,1) :	230		(2,1,3,1) :	230
	(3,1,6,1) :	230		(3,1,6,1) :	230		(3,1,2,1) :	230

8	(1,1,3,1) :	230	20	(1,1,1,1) :	92	32	(1,1,3,1) :	230
	(2,1,4,1) :	230		(1,1,3,1) :	138		(2,1,6,1) :	230
	(3,1,7,1) :	230		(2,1,3,1) :	230		(3,1,7,1) :	230
				(3,1,1,1) :	230			
9	(1,1,3,1) :	230	21	(1,1,2,1) :	165	33	(1,1,3,1) :	143
	(2,1,4,1) :	230		(1,1,3,1) :	65		(1,1,3,2) :	85
	(3,1,5,1) :	230		(2,1,2,1) :	230		(1,1,6,1) :	2
				(3,1,3,1) :	230		(2,1,3,1) :	142
							(2,1,6,1) :	88
							(3,1,6,1) :	230
10	(1,1,3,1) :	230	22	(1,1,3,1) :	146	34	(1,1,1,1) :	230
	(2,1,7,1) :	230		(1,1,3,2) :	2		(2,1,6,1) :	230
	(3,1,2,1) :	230		(1,1,6,1) :	82		(3,1,3,1) :	230
				(2,1,6,1) :	230			
				(3,1,3,1) :	230			
11	(1,1,3,1) :	230	23	(1,1,1,1) :	230	35	(1,1,1,1) :	230
	(2,1,6,1) :	230		(2,1,3,1) :	230		(2,1,3,1) :	230
	(3,1,3,1) :	147		(3,1,1,1) :	10		(3,1,6,1) :	230
	(3,1,3,2) :	2		(3,1,3,1) :	220			
	(3,1,6,1) :	81						
12	(1,1,3,1) :	122	24	(1,1,1,1) :	230			
	(1,1,3,2) :	2		(2,1,2,1) :	230			
	(1,1,7,1) :	106		(3,1,7,1) :	230			
	(2,1,3,1) :	230						
	(3,1,7,1) :	230						
1	(1,1,3,1) :	230	13	(1,1,3,1) :	230	25	(1,1,2,1) :	230

L Results Phase 2 Case 1 Optimal x_{prk}* all runs

Table 35 Optimal x_{prk} Phase 2 Case 1 for all runs*

Run	(p,r,k)	**x(p,r,k)***	Run	(p,r,k)	**x(p,r,k)***	Run	(p,r,k)	**x(p,r,k)***
1	(1,2,5) :	1	13	(1,1,4) :	1	25	(1,2,6) :	1
	(1,3,5) :	2		(1,3,4) :	2		(1,3,6) :	2
	(1,7,5) :	1		(1,6,4) :	1		(1,7,6) :	1
2	(1,1,6) :	1	14	(1,2,7) :	2	26	(1,2,6) :	1
	(1,2,6) :	2		(1,3,7) :	1		(1,3,6) :	1
	(1,4,6) :	1		(1,7,7) :	2		(1,4,6) :	1
	(1,7,6) :	1					(1,6,6) :	1
	(1,8,6) :	1						
3	(1,2,1) :	2	15	(1,3,1) :	2	27	(1,1,7) :	1
	(1,3,1) :	1		(1,7,1) :	1		(1,2,7) :	2
	(1,7,1) :	2		(2,2,1) :	1		(1,6,7) :	2
							(1,7,7) :	1
4	(1,1,1) :	1	16	(1,3,1) :	2	28	(1,2,4) :	1
	(1,2,1) :	1		(1,7,1) :	1		(1,3,4) :	1
	(1,3,1) :	1		(2,2,1) :	1		(1,4,4) :	1
	(1,5,1) :	1					(1,6,4) :	1
	(1,7,1) :	2						
5	(1,1,1) :	1	17	(1,2,1) :	1	29	(1,2,3) :	2
	(1,2,1) :	2		(1,3,1) :	1		(1,3,3) :	1
	(1,3,1) :	1		(1,7,1) :	2		(1,7,3) :	2
		2		(2,2,1) :	1			
6	(1,1,6) :	1	18	(1,1,4) :	1	30	(1,2,3) :	2
	(1,2,6) :	2		(1,2,4) :	1		(1,3,3) :	1
	(1,6,6) :	1		(1,3,4) :	1		(1,7,3) :	2
	(1,7,6) :	2		(1,6,4) :	1			
				(1,7,4) :	1			
7	(1,1,6) :	1	19	(1,1,1) :	1	31	(1,1,2) :	1
	(1,2,6) :	1		(1,2,1) :	1		(1,2,2) :	1
	(1,3,6) :	1		(1,6,1) :	2		(1,3,2) :	1
	(1,6,6) :	1		(2,3,1) :	1		(1,6,2) :	1
	(1,7,6) :	1					(1,7,2) :	1
8	(1,1,1) :	1	20	(1,1,7) :	1	32	(1,1,3) :	1
	(1,2,1) :	1		(1,2,7) :	3		(1,2,3) :	2
	(1,6,1) :	1		(1,6,7) :	2		(1,7,3) :	2

	(1,7,1) :	1		(1,7,7) :	1		(1,8,3) :	1
	(2,3,1) :	1						
9	(1,1,1) :	1	21	(1,2,7) :	1	33	(1,3,2) :	2
	(1,2,1) :	1		(1,3,7) :	2		(1,4,2) :	1
	(1,6,1) :	1		(1,7,7) :	1		(1,5,2) :	1
	(1,7,1) :	1						
	(2,3,1) :	1						
10	(1,2,5) :	1	22	(1,1,3) :	1	34	(1,1,3) :	1
	(1,3,5) :	2		(1,2,3) :	1		(1,2,3) :	1
	(1,6,5) :	1		(1,3,3) :	1		(1,3,3) :	2
				(1,6,3) :	1		(1,7,3) :	1
				(1,7,3) :	1			
11	(1,2,3) :	2	23	(1,1,7) :	2	35	(1,2,4) :	1
	(1,3,3) :	1		(1,2,7) :	1		(1,3,4) :	2
	(1,7,3) :	2		(1,6,7) :	2		(1,7,4) :	1
				(1,7,7) :	1			
12	(1,2,4) :	1	24	(1,2,6) :	1			
	(1,3,4) :	2		(1,3,6) :	2			
	(1,7,4) :	1		(1,7,6) :	1			

M Results Phase 2 Case 2 Optimal x_{prk}* all runs

Table 36 Optimal x_{prk} Phase 2 Case 2 for all runs*

Run	(p,r,k)	**x(p,r,k)***	Run	(p,r,k)	**x(p,r,k)***	Run	(p,r,k)	**x(p,r,k)***
1	(1,3,1) :	1	13	(1,3,1) :	1	25	(1,2,1) :	1
	(1,4,1) :	1		(1,4,1) :	1		(1,3,1) :	1
	(1,6,1) :	1		(1,7,1) :	1		(1,4,1) :	1
	(3,2,1) :	1		(2,2,1) :	1		(6,3,1) :	1
	(3,3,1) :	1		(2,3,1) :	1		(6,4,1) :	1
	(3,5,1) :	1		(2,6,1) :	1		(6,6,1) :	1
2	(1,3,3) :	2	14	(1,3,1) :	2	26	(1,2,1) :	1
	(1,4,3) :	1		(1,5,1) :	1		(1,3,1) :	2
	(1,5,3) :	1		(6,2,1) :	1		(6,1,1) :	1
				(6,3,1) :	1		(6,3,1) :	1
							(6,4,1) :	1
3	(1,1,2) :	1	15	(1,3,1) :	2	27	(1,3,1) :	2
	(1,3,2) :	2		(1,7,1) :	1		(1,6,1) :	1
	(1,6,2) :	1		(2,1,1) :	1		(3,1,1) :	1
				(2,2,1) :	1		(3,2,1) :	1
				(2,5,1) :	1		(3,6,1) :	1
				(2,7,1) :	1		(3,7,1) :	1
4	(1,2,1) :	1	16	(1,3,1) :	1	28	(1,3,1) :	2
	(1,3,1) :	2		(1,4,1) :	1		(1,6,1) :	1
	(1,7,1) :	1		(5,3,1) :	1		(10,2,1) :	1
				(5,5,1) :	1		(10,3,1) :	1
							(10,5,1) :	1
5	(1,1,1) :	1	17	(1,3,1) :	2	29	(1,3,1) :	1
	(1,2,1) :	1		(1,6,1) :	1		(1,4,1) :	1
	(1,4,1) :	1		(6,2,1) :	1		(1,5,1) :	1
	(1,6,1) :	2		(6,3,1) :	1		(1,7,1) :	1
				(6,7,1) :	1		(2,2,1) :	1
							(2,3,1) :	1
							(2,5,1) :	1
							(2,7,1) :	1
6	(1,2,7) :	1	18	(1,3,1) :	1	30	(1,3,1) :	1
	(1,3,7) :	1		(1,4,1) :	1		(1,4,1) :	1
	(1,4,7) :	1		(1,6,1) :	1		(1,6,1) :	1
	(1,6,7) :	1		(6,2,1) :	1		(5,2,1) :	1
				(6,4,1) :	1		(5,3,1) :	1

				(6,7,1) :	1		(5,5,1) :	1
7	(1,3,1) :	1	19	(1,3,1) :	1	31	(1,2,2) :	1
	(1,4,1) :	1		(1,4,1) :	1		(1,3,2) :	2
	(1,6,1) :	1		(1,6,1) :	1		(1,7,2) :	1
	(5,3,1) :	1		(7,2,1) :	1			
	(5,5,1) :	1		(7,6,1) :	1			
	(5,7,1) :	1		(7,7,1) :	1			
8	(1,3,1) :	1	20	(1,1,3) :	1	32	(1,3,1) :	1
	(1,4,1) :	1		(1,3,3) :	3		(1,6,1) :	1
	(1,7,1) :	1					(1,7,1) :	2
	(3,2,1) :	1					(4,2,1) :	1
	(3,5,1) :	1					(4,3,1) :	1
	(3,6,1) :	1					(4,7,1) :	1
9	(1,3,1) :	1	21	(1,2,1) :	1	33	(1,3,1) :	2
	(1,4,1) :	1		(1,3,1) :	1		(1,6,1) :	1
	(1,5,1) :	1		(1,7,1) :	1		(9,2,1) :	1
	(10,3,1) :	1		(2,3,1) :	2		(9,3,1) :	1
	(10,5,1) :	1					(9,7,1) :	1
	(10,6,1) :	1						
10	(1,2,4) :	1	22	(1,3,1) :	2	34	(1,1,2) :	1
	(1,3,4) :	2		(1,6,1) :	1		(1,3,2) :	2
	(1,7,4) :	1		(2,1,1) :	1		(1,6,2) :	1
				(2,2,1) :	1			
				(2,8,1) :	1			
11	(1,3,1) :	2	23	(1,1,7) :	1	35	(1,1,3) :	1
	(1,6,1) :	1		(1,3,7) :	3		(1,3,3) :	2
	(2,2,1) :	1					(1,6,3) :	1
	(2,5,1) :	3						
12	(1,3,1) :	2	24	(1,1,1) :	1			
	(1,7,1) :	1		(1,2,1) :	2			
	(9,2,1) :	1		(1,7,1) :	1			
	(9,6,1) :	1		(3,3,1) :	2			
	(9,7,1) :	1						

N Results Phase 2 Case 1 Optimal $\boldsymbol{\beta_{prk}}$* all runs

Table 37 Optimal β_{prk} Phase 2 Case 1 for all runs*

Run	(p,r,k)	**p(p,r,k)***	Run	(p,r,k)	**p(p,r,k)***	Run	(p,r,k)	**p(p,r,k)***
1	(1,2,1) :	1	13	(1,1,1) :	1	25	(1,2,1) :	1
	(1,3,1) :	1		(1,3,1) :	1		(1,3,1) :	1
	(1,3,2) :	1		(1,3,2) :	1		(1,3,2) :	1
	(1,7,1) :	1		(1,6,1) :	1		(1,7,1) :	1
2	(1,1,1) :	1	14	(1,2,1) :	1	26	(1,2,1) :	1
	(1,2,1) :	1		(1,2,2) :	1		(1,3,1) :	1
	(1,2,2) :	1		(1,3,1) :	1		(1,4,1) :	1
	(1,4,1) :	1		(1,7,1) :	1		(1,6,1) :	1
	(1,7,1) :	1		(1,7,2) :	1			
	(1,8,1) :	1						
3	(1,2,1) :	1	15	(1,3,1) :	1	27	(1,1,1) :	1
	(1,2,2) :	1		(1,3,2) :	1		(1,2,1) :	1
	(1,3,1) :	1		(1,7,1) :	1		(1,2,2) :	1
	(1,7,1) :	1		(2,2,1) :	1		(1,6,1) :	1
	(1,7,2) :	1					(1,6,2) :	1
							(1,7,1) :	1
4	(1,1,1) :	1	16	(1,3,1) :	1	28	(1,2,1) :	1
	(1,2,1) :	1		(1,3,2) :	1		(1,3,1) :	1
	(1,3,1) :	1		(1,7,1) :	1		(1,4,1) :	1
	(1,5,1) :	1		(2,2,1) :	1		(1,6,1) :	1
	(1,7,1) :	1						
	(1,7,2) :	1						
5	(1,1,1) :	1	17	(1,2,1) :	1	29	(1,2,1) :	1
	(1,2,1) :	1		(1,3,1) :	1		(1,2,2) :	1
	(1,2,2) :	1		(1,7,1) :	1		(1,3,1) :	1
	(1,3,1) :	1		(1,7,2) :	1		(1,7,1) :	1
	(1,7,1) :	1		(2,2,1) :	1		(1,7,2) :	1
	(1,7,2) :	1						
6	(1,1,1) :	1	18	(1,1,1) :	1	30	(1,2,1) :	1
	(1,2,1) :	1		(1,2,1) :	1		(1,2,2) :	1
	(1,2,2) :	1		(1,3,1) :	1		(1,3,1) :	1
	(1,6,1) :	1		(1,6,1) :	1		(1,7,1) :	1
	(1,7,1) :	1		(1,7,1) :	1		(1,7,2) :	1
	(1,7,2) :	1						

7	(1,1,1) :	1	19	(1,1,1) :	1	31	(1,1,1) :	1
	(1,2,1) :	1		(1,2,1) :	1		(1,2,1) :	1
	(1,3,1) :	1		(1,6,1) :	1		(1,3,1) :	1
	(1,6,1) :	1		(1,6,2) :	1		(1,6,1) :	1
	(1,7,1) :	1		(2,3,1) :	1		(1,7,1) :	1
8	(1,1,1) :	1	20	(1,1,1) :	1	32	(1,1,1) :	1
	(1,2,1) :	1		(1,2,1) :	1		(1,2,1) :	1
	(1,6,1) :	1		(1,2,2) :	1		(1,2,2) :	1
	(1,7,1) :	1		(1,2,3) :	1		(1,7,1) :	1
	(2,3,1) :	1		(1,6,1) :	1		(1,7,2) :	1
				(1,6,2) :	1		(1,8,1) :	1
				(1,7,1) :	1			
9	(1,1,1) :	1	21	(1,2,1) :	1	33	(1,3,1) :	1
	(1,2,1) :	1		(1,3,1) :	1		(1,3,2) :	1
	(1,6,1) :	1		(1,3,2) :	1		(1,4,1) :	1
	(1,7,1) :	1		(1,7,1) :	1		(1,5,1) :	1
	(2,3,1) :	1						
10	(1,2,1) :	1	22	(1,1,1) :	1	34	(1,1,1) :	1
	(1,3,1) :	1		(1,2,1) :	1		(1,2,1) :	1
	(1,3,2) :	1		(1,3,1) :	1		(1,3,1) :	1
	(1,6,1) :	1		(1,6,1) :	1		(1,3,2) :	1
				(1,7,1) :	1		(1,7,1) :	1
11	(1,2,1) :	1	23	(1,1,1) :	1	35	(1,2,1) :	1
	(1,2,2) :	1		(1,1,2) :	1		(1,3,1) :	1
	(1,3,1) :	1		(1,2,1) :	1		(1,3,2) :	1
	(1,7,1) :	1		(1,6,1) :	1		(1,7,1) :	1
	(1,7,2) :	1		(1,6,2) :	1			
				(1,7,1) :	1			
12	(1,2,1) :	1	24	(1,2,1) :	1			
	(1,3,1) :	1		(1,3,1) :	1			
	(1,3,2) :	1		(1,3,2) :	1			
	(1,7,1) :	1		(1,7,1) :	1			

O Results Phase 2 Case 2 Optimal β_{prk}* all runs

Table 38 Optimal β_{prk} Phase 2 Case 2 for all runs*

Run	(p,r,k)	**p(p,r,k)***	Run	(p,r,k)	**p(p,r,k)***	Run	(p,r,k)	**p(p,r,k)***
1	(1,3,1) :	1	13	(1,3,1) :	1	25	(1,2,1) :	1
	(1,4,1) :	1		(1,4,1) :	1		(1,3,1) :	1
	(1,6,1) :	1		(1,7,1) :	1		(1,4,1) :	1
	(3,2,1) :	1		(2,2,1) :	1		(6,3,1) :	1
	(3,3,1) :	1		(2,3,1) :	1		(6,4,1) :	1
	(3,5,1) :	1		(2,6,1) :	1		(6,6,1) :	1
2	(1,3,1) :	1	14	(1,3,1) :	1	26	(1,2,1) :	1
	(1,3,2) :	1		(1,3,2) :	1		(1,3,1) :	1
	(1,4,1) :	1		(1,5,1) :	1		(1,3,2) :	1
	(1,5,1) :	1		(6,2,1) :	1		(6,1,1) :	1
				(6,3,1) :	1		(6,3,1) :	1
							(6,4,1) :	1
3	(1,1,1) :	1	15	(1,3,1) :	1	27	(1,3,1) :	1
	(1,3,1) :	1		(1,3,2) :	1		(1,3,2) :	1
	(1,3,2) :	1		(1,7,1) :	1		(1,6,1) :	1
	(1,6,1) :	1		(2,1,1) :	1		(3,1,1) :	1
				(2,2,1) :	1		(3,2,1) :	1
				(2,5,1) :	1		(3,6,1) :	1
				(2,7,1) :	1		(3,7,1) :	1
4	(1,2,1) :	1	16	(1,3,1) :	1	28	(1,3,1) :	1
	(1,3,1) :	1		(1,4,1) :	1		(1,3,2) :	1
	(1,3,2) :	1		(5,3,1) :	1		(1,6,1) :	1
	(1,7,1) :	1		(5,5,1) :	1		(10,2,1) :	1
							(10,3,1) :	1
							(10,5,1) :	1
5	(1,1,1) :	1	17	(1,3,1) :	1	29	(1,3,1) :	1
	(1,2,1) :	1		(1,3,2) :	1		(1,4,1) :	1
	(1,4,1) :	1		(1,6,1) :	1		(1,5,1) :	1
	(1,6,1) :	1		(6,2,1) :	1		(1,7,1) :	1
	(1,6,2) :	1		(6,3,1) :	1		(2,2,1) :	1
				(6,7,1) :	1		(2,3,1) :	1
							(2,5,1) :	1
							(2,7,1) :	1
6	(1,2,1) :	1	18	(1,3,1) :	1	30	(1,3,1) :	1
	(1,3,1) :	1		(1,4,1) :	1		(1,4,1) :	1

	(1,4,1) :	1		(1,6,1) :	1		(1,6,1) :	1
	(1,6,1) :	1		(6,2,1) :	1		(5,2,1) :	1
				(6,4,1) :	1		(5,3,1) :	1
				(6,7,1) :	1		(5,5,1) :	1
7	(1,3,1) :	1	19	(1,3,1) :	1	31	(1,2,1) :	1
	(1,4,1) :	1		(1,4,1) :	1		(1,3,1) :	1
	(1,6,1) :	1		(1,6,1) :	1		(1,3,2) :	1
	(5,3,1) :	1		(7,2,1) :	1		(1,7,1) :	1
	(5,5,1) :	1		(7,6,1) :	1			
	(5,7,1) :	1		(7,7,1) :	1			
8	(1,3,1) :	1	20	(1,1,1) :	1	32	(1,3,1) :	1
	(1,4,1) :	1		(1,3,1) :	1		(1,6,1) :	1
	(1,7,1) :	1		(1,3,2) :	1		(1,7,1) :	1
	(3,2,1) :	1		(1,3,3) :	1		(1,7,2) :	1
	(3,5,1) :	1					(4,2,1) :	1
	(3,6,1) :	1					(4,3,1) :	1
							(4,7,1) :	1
9	(1,3,1) :	1	21	(1,2,1) :	1	33	(1,3,1) :	1
	(1,4,1) :	1		(1,3,1) :	1		(1,3,2) :	1
	(1,5,1) :	1		(1,7,1) :	1		(1,6,1) :	1
	(10,3,1) :	1		(2,3,1) :	1		(9,2,1) :	1
	(10,5,1) :	1		(2,3,2) :	1		(9,3,1) :	1
	(10,6,1) :	1					(9,7,1) :	1
10	(1,2,1) :	1	22	(1,3,1) :	1	34	(1,1,1) :	1
	(1,3,1) :	1		(1,3,2) :	1		(1,3,1) :	1
	(1,3,2) :	1		(1,6,1) :	1		(1,3,2) :	1
	(1,7,1) :	1		(2,1,1) :	1		(1,6,1) :	1
				(2,2,1) :	1			
				(2,8,1) :	1			
11	(1,3,1) :	1	23	(1,1,1) :	1	35	(1,1,1) :	1
	(1,3,2) :	1		(1,3,1) :	1		(1,3,1) :	1
	(1,6,1) :	1		(1,3,2) :	1		(1,3,2) :	1
	(2,2,1) :	1		(1,3,3) :	1		(1,6,1) :	1
	(2,5,1) :	1						
	(2,5,2) :	1						
	(2,5,3) :	1						
12	(1,3,1) :	1	24	(1,1,1) :	1			
	(1,3,2) :	1		(1,2,1) :	1			
	(1,7,1) :	1		(1,2,2) :	1			

	(9,2,1) :	1		(1,7,1) :	1			
	(9,6,1) :	1		(3,3,1) :	1			
	(9,7,1) :	1		(3,3,2) :	1			

P Iceberg Drift Characteristics in the Barents Sea 1987 – 2005

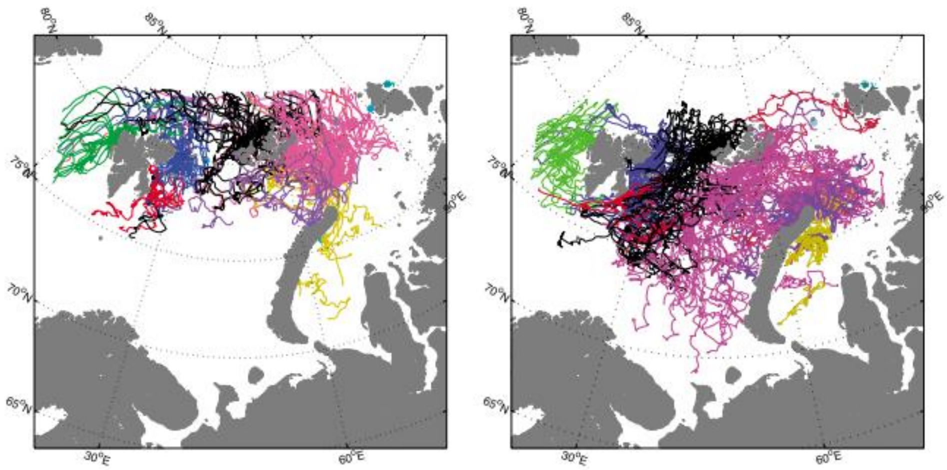

Figure 12 Iceberg drift charateristics in the Barents Sea 1987-2005

Study of iceberg drift characteristics in the Barents 1987 – 2005.The figure illustrate iceberg trajectories from the year 2000 (left) and 2005 (right). The figures are based on different sources, thereby the different colors.

(Keghouche, et al., 2010)

Q Iceberg occurrence in the Barents Sea

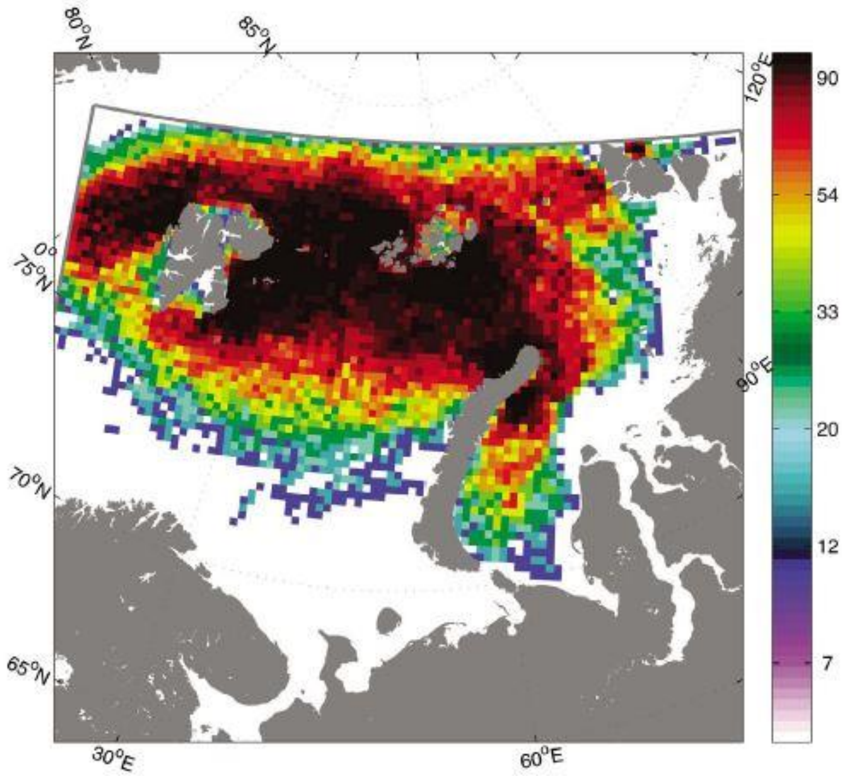

Figure 13 Iceberg occurence in the Barents Sea 1987-2005

Study of iceberg occurrence in the Barents Sea "Probability (%) of encountering an iceberg within a year in the domain from 1987 to 2005 within a 25 × 25 km grid cell. The scale is logarithmic. The northern boundary of the model is shown by the thick gray line."

(Keghouche, et al., 2010)

R Additional analysis

Table 39 Additional analysis for faraway installations

Location H	Location I	Location J	Z* Hub	b*	h*	Z* No Hub	b*	h*	Decision
80,30	74,36	71,15	9919	1	7	5304	1	1	No hub
80,30	72, 15	71,50	9919	1	6	5304	1	1	No hub
71,50	72,29	80,30	9919	1	1	5304	1	1	No hub

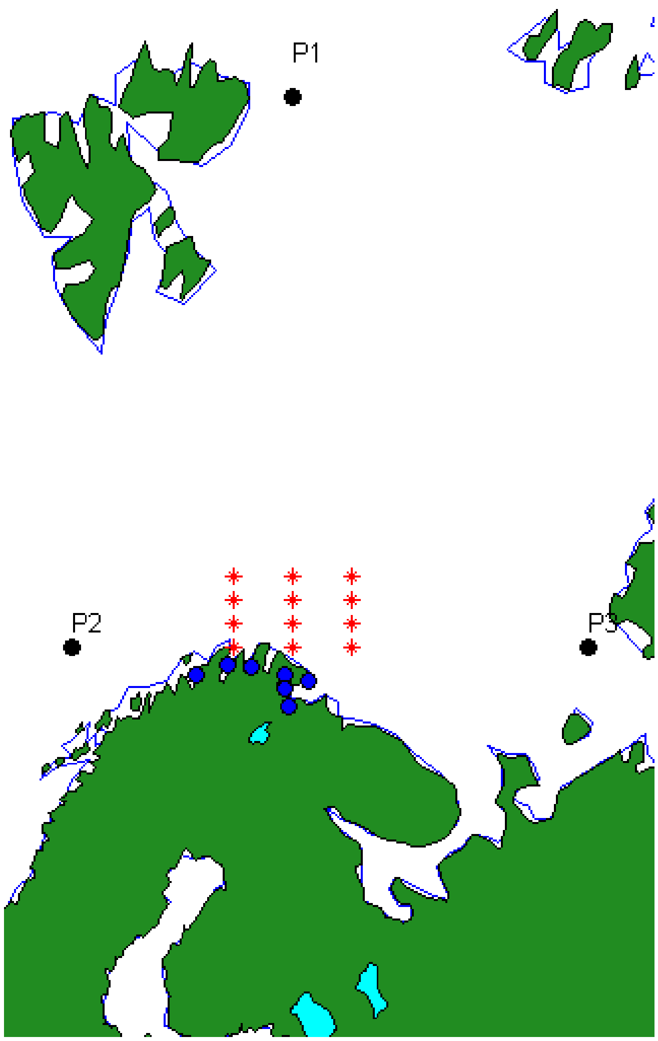

Figure 14 Map over faraway installations for one of the additional analysis