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Optimal configuration of supply logistics for remote oil and gas fields

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Abstract

The objective of this thesis has been to compare alternatives to improve the supply service for remote locations offshore. First the alternative of running a conventional supply service has been assessed, where the platform supply vessels (PSVs) sailed directly from a land depot to supply the installations with commodities. The alternative to the conventional supply service was to have two converted cargo ships in use as storage units located at the oil and gas field which deliver cargo to the PSVs. For the alternative with the storage units the ships switch position, when one is in operation the other one goes to shore and stock up on supplies.

PSVs are expensive and if one can reduce the number of ships in operation it will grant great savings for the operator of the oil and gas field. Having storage units located in the proximity of the installations offshore will reduce the sailing distance of the PSVs to a fraction of the original sailing distance from a land depot. While the cost of the PSVs will be reduced one has a cost increase due to the storage units. Finding the point at which the storage units can become profitable has been the essence of this thesis.

A case study has been made to compare the two different setups for oil and gas activities outside Jan Mayen. It was expected a maximum activity level with three installations in operation. The case study has been made more general by adding up to five additional installations to get a better look at the savings of having the storage units with more installations to service. To minimize the costs of each setup it was made a mathematical formulation for each of them. For the regular setup the minimum cost of routing the supply vessels was found from a land depot, given a required supply frequency of the installations. The port in Kristiansund has been chosen as a suitable land depot for this case study. In the setup with storage units the routing from the storage units with PSVs are considered in addition to the cost of the storage units. To minimize the routing cost from the storage units the mathematical model had to consider different locations of the units. Both of the setups have the same input data as a basis to get a good comparison. The models are solved for a weekly planning period.

Some basic design characteristics of the storage units have been made. It was concluded that open hatch bulk carriers would be most suited for the operation. The vessels to be converted should have a deadweight capacity of around 57 300 tons. It is estimated here that the cost of one storage unit will be 53 000 USD per day. This price may not be very accurate and is based on many assumptions due to lack of assessable cost information, but it has been tried to make a conservative estimate.

The mathematical formulations of the models have been solved with the optimization software Xpress. For the regular supply service from land the total cost of the supply service ranged from

590 000 USD per week for three installations and up to 1 550 000 USD for eight installations. The results showed that there was a linear increase in cost when increasing the number of installations to supply. Compared to the setup with the converted cargo ships the total costs ranged from 916 000 USD per week for three installations to 1 137 000 USD per week for eight installations. In this case the cost per installation gets lower with the number of installations to supply. When solving the model for the supply service from land one gets larger ships in operation which can visit as many installations as possible on a route as they can only make one trip per week. Compared to the case with the storage units one gets a few smaller PSVs in operation which can sail many routes per week.

It has been found that the concept with the storage units would be profitable with 6 installations or more to service in this case. With less than 6 installations to service it would be more expensive to have storage units than running a regular supply service from land. Generally it can be concluded that having the storage units could be profitable if there is enough installations to service. The other factor with the biggest effect on the problem is the distance to shore, however, finding at what distance from shore the storage unit becomes profitable was not included in this study. The final conclusion of the work here is that the use of storage units could reduce the cost of the supply service, and is an interesting concept that should be studied further.

Sammendrag

Målet med denne oppgaven har vært å sammenligne alternativer for å forbedre forsyningslogistikken for olje- og gass felt i fjerntliggende strøk. Først har det konvensjonelle forsyningsproblemet blitt vurdert, hvor forsyningsskipene seiler direkte fra land til installasjonene med forsyninger. Alternativet som har blitt sammenlignet med det konvensjonelle problemet er å ha to konverterte lasteskip som opererer som fremskutte baser og leverer varer til forsyningsskipene. For dette alternativet bytter skipene posisjon, når det ene er i operasjon seiler det andre tilbake til land for å hente nye forsyninger.

Prisen av innleide forsyningsskip blir fort høy. Hvis man kan redusere antallet skip i operasjon kan dette gi store kostnadskutt for operatøren av feltet. Plassering av fremskutte baser i nærheten av installasjonene kan redusere den nødvendige seilingsdistansen for forsyningsskipene betraktelig sammenlignet med om de seiler fra land. Selv om man reduserer kostnaden av forsyningsskip får man en kostnadsøkning av de fremskutte basene. Å finne ved hvilket punkt de fremskutte basene blir lønnsomt har vært hovedmålet i denne oppgaven.

For å sammenligne disse to alternativene har det her blitt gjort et case-studie med olje og gass aktiviteter i nærheten av Jan Mayen. I denne casen er det forventet maksimum tre installasjoner ved feltet i produksjon. For å gjøre studien mer generell har det blitt undersøkt følgene av å legge til opp til fem ekstra plattformer i operasjon for å bedre se effekten og fordelene med å ha de fremskutte basene. For å beregne kostnaden av disse to alternativene har det blitt laget en matematisk modell som minimerer kostnadene i hvert av tilfellene. For det vanlige forsyningsproblemet må man finne den minste kostnaden for å rute forsyningsskipene fra land til installasjonene, med en gitt nødvendig forsyningsfrekvens. Havnen i Kristiansund er blitt valgt som land depot for denne casen. I tilfellet med de fremskutte basene må man ta hensyn til rutene fra plasseringen av den fremskutte basen til installasjonene samt kostnaden av den fremskutte basen. For å minimere rutekostnadene må den matematiske modellen finne optimal plassering av de fremskutte basene. Begge alternativene har samme grunnlagsdata for forsyningsbehov for å få en best mulig sammenligning. Modellene er optimalisert for en ukentlig planleggingsperiode.

Det har blitt laget forenklede design parametere for de fremskutte basene. Konklusjonen er at bulk skip med store lasteroms åpninger er det beste alternativet for konvertering og til denne operasjonen. Skipene som skal konverteres bør han en dødvekt på rundt 57 300 tonn. Kostnaden for en fremskutt base er estimert til å være 53 000 USD per dag. Den er knyttet usikkerhet rundt denne prisen grunnet manglende informasjon rundt kostnader, men det har blitt forsøkt å lage et konservativt kostnadsestimat.

De matematiske modellene har blitt løst med optimeringssoftwaren Xpress. For det normale forsyningsproblemet varierte totalkostnadene mellom 590 000 USD per uke for tre installasjoner og 1 550 00 USD per uke for 8 installasjoner. Ut fra resultatene kan en se at det var en lineær økning i kostnadene når man økte antall installasjoner å forsyne. Sammenlignet hadde alternativet med fremskutte baser kostnader mellom 916 000 USD per uke for tre installasjoner og opptil 1 137 000 USD per uke for 8 installasjoner. For dette alternativet gikk kostnadene per installasjon drastisk ned med antallet installasjoner å forsyne. Når man løser forsyningsproblemet fra land får man større skip i operasjon som kan besøke så mange installasjoner som mulig på en rute, men de kan bare seile en rute per uke. Sammenlignet med tilfellet med fremskutte baser får en færre og mindre skip i operasjon som seiler flere ruter per uke.

I beregningene som er gjort her er det kommet frem til at for denne casen at man trenger minst 6 installasjoner å forsyne for at det skal lønne seg å ha de fremskutte basene. På en generell basis kan man konkludere med at de fremskutte basene blir lønnsomme hvis man har nok installasjoner å forsyne. Den andre faktoren som bestemmer om det er lønnsomt er avstanden til land, det har ikke blitt gjort detaljerte undersøkelser her for å finne ved hvilken avstand fra land det blir lønnsomt. Den endelige konklusjonen ut av arbeidet er at bruken av fremskutte baser har potensiale til å redusere kostnadene av forsyningslogistikken og er interessant konsept som bør studeres videre.

Scope of work

NTNU Trondheim
Norwegian University of Science and Technology
Department of Marine Technology

MASTER THESIS IN MARINE TECHNOLOGY

SPRING 2013

For stud.techn.

Henrik Nordbø

Optimal configuration of supply logistics for remote oil and gas fields

Background
From DNV, info sent from Bjørn Egil Asbjørnslett:
There are great challenges linked to supply logistics for remote oil and gas fields, for example Artic areas and Brazil. Cairn Energy used Aberdeen as a supply base while doing test drilling close to Greenland last summer. The route between Aberdeen and Greenland is 8 days in both directions. To supply this drilling rig, 15 supply ships were in operations! There is a need for new models to make this operation more effective. The model shall be able to analyze different varieties of supply systems and seek to optimize the configuration of type and number of ships, type and location terminals (including floating terminals).

Objective
My project thesis started discussing optimal supply configurations for remote locations issues during the fall semester 2012. It was concluded that the regular supply service should be compared to having two converted cargo ships operating as floating storage units in operation.

The objectives in this master thesis to construct models which are able to analyze different varieties of supply systems and seek to optimize the configurations of type and number of ships, type and location of terminals (included floating terminals) for remote oil and gas fields.

Tasks
The candidate is recommended to cover the following parts in the master thesis:

a. Make a case study to compare the general supply setup with the use of forward storage units
b. Construct mathematical formulations of the two different setups
c. Analyze and find data that should be used as a basis for the models
d. Implement the models into Xpress and find optimal solutions for all cases
e. Look into the technical specifications of the storage units

General
In the thesis the candidate shall present his personal contribution to the resolution of a problem within the scope of the thesis work.

Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction.

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The candidate should utilize the existing possibilities for obtaining relevant literature.

The thesis should be organized in a rational manner to give a clear statement of assumptions, data, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, discussion of results and conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work.

The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

Deliverable

- The thesis shall be submitted in two (2) copies:
- Signed by the candidate
- The text defining the scope included
- In bound volume(s)
- Drawings and/or computer prints that cannot be bound should be organized in a separate folder.
- The bound volume shall be accompanied by a CD or DVD containing the written thesis in Word or PDF format. In case computer programs have been made as part of the thesis work, the source code shall be included. In case of experimental work, the experimental results shall be included in a suitable electronic format.

Supervision:
Main supervisor:
Bjørn Egil Asbjørnslett

Bjørn Egil Asbjørnslett

Sub-supervisor:
Jørgen Glomvik Rakke

Company contact:

Deadline: 10.06.2013

Preface

This Thesis completes the work of my Master of Science degree in Marine Technology at the Norwegian University of Science and Technology. The work has been carried out during the spring semester of 2013. The course code of the Marine Systems, Master Thesis is TMR4905 and it counts for 30 credits. This report is 100 % of the grade, there will also be attached a cd with the mathematical models implemented into Mosel/Xpress.

During the fall semester of 2012 I wrote a project thesis for 7.5 credits on the same topic. The project thesis was a build up for this thesis and helped me to get ideas for this master thesis.

The workload has been distributed evenly throughout the time period. Early in the process most of the work went towards planning the layout of the thesis and finding background information. The months February and March went mostly to implementing the mathematical models into Mosel/Xpress. The later months have been used to get the results and finishing work on the report.

Meetings with The Logistics Department of DNV in Trondheim were helpful in the beginning of the thesis to discuss ideas and possibilities for the thesis.

The main advisor, Professor Bjørn Egil Asbjørnslett, has been of great help discussing the topic of the thesis with some meeting during the work process. The co-advisor, Postdoctoral Fellow Jørgen Glomvik Rakke, has been of great help implementing the mathematical models into Mosel/Xpress and has helped me with issues I have had along the way concerning the programming. I would like to thank both of my advisors for the guidance throughout the work of this thesis.

Trondheim, June, 2013

Henrik Nordbø

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Abbreviations

B – Breadth

CVRP – Capacitated Vehicle Routing Problem

D –Depth

DGPS - Differential Global Positioning System

DNV – Det Norske Veritas

DP – Dynamic Positioning

DWT – Deadweight tons

ECA – Emission Control Area

FLNG – Floating Liquefied Natural Gas

FPSO – Floating, Production, Storage and Offloading

FSCIR – Finish-Swedish Ice Class Rules

LNG – Liquefied Natural Gas

LOA – Length overall

LPP – Length between perpendiculars

MCR - Maximum Continues Rating

MDO – Marine Diesel Oil

MGO – Marine Gas Oil

NWEA – North Western European Area

OED – Olje og Energidepartementet

OIM – Offshore Installation Manager

PSV – Platform Supply Vessel

Tcwl – Construction water line Draft

Tmax – Maximum Draft

TSP – Travelling Salesman Problem

VCG – Vertical Center of Gravity

VRPPD – Vehicle Routing Problem with Pick-up and Delivery

1 Introduction

The global energy demand is rising with a growing population. Not only is the population growing, but the world's middle class and the energy consumption per person is getting higher and higher. Among the challenges the earth is facing is to supply this rising energy demand. Renewable energy is requested from the society, but it is not possible to supply the global energy demand purely based on renewable energy today or in the relative near future. Oil and gas will still play a major role besides coal and nuclear fuels in many years to come. By the year 2040 ExxonMobil (2013) predicts that "*oil will remain the No. 1 global fuel, while natural gas will overtake for coal for the No.2 spot".* The era for oil and gas is far from over and fossil fuels are a necessity if the world's population continues to increase their energy consumption.

The challenges for the oil companies are towards extracting the remaining oil and gas resources in an efficient way, many of these opportunities can be found offshore. Development of new projects in the offshore oil and gas industry happen in deeper waters and more remote areas, for example Arctic and Brazil. According to DNV (2012) 20 % of the world's undiscovered hydrocarbon resources are believed to be located in Arctic regions. To exploit the opportunities in these areas the oil companies may have to be innovative and new-thinking. There are still some challenges on the way that has to be dealt with. The technical solutions that are implemented at the installations in the operated areas today may not be as efficient if they are re-deployed in an Arctic environment or far from shore. Risk towards crew, environment and equipment still has to be kept low and at the same time at a reasonable cost. In remote areas logistics is one the main challenges for the oil companies, the operation is far from shore and all equipment and resources need to be available at the spot. One cannot afford to shut down production or drilling for a couple of days to wait for supplies, then projects soon become unprofitable an might be abandoned.

Installations at the oil fields offshore require a regular supply flow of commodities to be able to keep continuous operation. This is done by purpose designed vessels, normally called Platform Supply Vessels (PSVs). Determining the optimal fleet of PSVs and their corresponding routes and schedules is by Halvorsen-Weare, Fagerholt, Nonås, and Asbjornslett (2012) named as the *supply vessel planning problem*. A stop in production due to lack of supplies is costly and not an option for the operator. Keeping a reliable service is therefore a necessity. The issue in this thesis will be to design a system/solution that can be used to handle the difficulties of supporting oil and gas installations in remote areas. PSVs are expensive tools and if one can reduce the number of vessels in operation it will grant great savings for the oil companies.

Supply logistics between a land depot and the offshore installations can be a complex logistics problem to solve for optimality. The oil company running the offshore installation wants to keep the cost of the supply logistics as low as possible. There are many parameters that need to be considered and a lot of them can change quickly. Installations may be located in areas with rough weather; this can cause delays and is a type of uncertainty that can be difficult to model. It is necessary to have some time slack in the schedules for the PSVs in case of delays so that the supplies are delivered on time. To get a cost efficient and reliable supply service, good planning is necessary.

With some simplifications the supply vessel planning problem can be looked at as a capacitated vehicle routing problem (CVRP) with several trips per vehicle. The vessels have to deliver enough cargo in the time period and have a certain frequency of visits to the platforms. Installations have limited storage capacities and need several visits from PSVs per week. Fagerholt and Lindstad (2000) and Halvorsen-Weare et al. (2012) are providing the offshore industry with mathematical models for the supply vessel planning problem, which optimize the routes and schedules in the North- and Norwegian Sea. As a result one is experiencing significant cost reduction for the supply vessel's operations. However, in cases with long distances to shore these model has not been fully tested and they might give many ships in operation and thus become very expensive.

Efficient supply logistics can be a major challenge if the oil field is far from shore and a supply depot, the solution method of supplying the installations directly from land can be used here as well. Drilling and production units have limited storage capacity and will require a high frequency of commodities to be delivered. The result of the long distances from shore when running a regular supply service is that many ships in operation are needed and the operator gets a high cost to keep up the service. If the overall cost of a project is too high for the operator, drilling or production at that location will be postponed until it is found solutions that make it profitable to do so. It will therefore be interesting to look at new methods that could reduce the number of expensive supply vessels in operations.

In my project thesis it was discussed three setups of how to deal with long distances in the supply logistic operations and give a rough cost estimate for each of them. The first option is to run a regular supply service like in the North- and Norwegian Sea. This means that the installations will be supplied directly from land by PSVs. A second setup is to have a permanent floating storage unit located somewhere close to the field. In that case the storage unit would be supplied from land by larger supply vessels, while the installations would be supplied by smaller vessels which load the cargo from the storage unit. The third setup is to have two converted bulk ships or similar that will stock up on supplies when at shore and then stay at the field for a period of time and act as a floating storage unit and then switch with the other vessel when running out of supplies. Based on the cost of the solutions the project thesis concluded that setup 1 (the regular supply operation) and setup 3 (2 converted cargo ships switching) should be studied further. The reason for this was that a permanent floating storage unit like a rig would be very expensive and it would still need a lot of supply vessels in operation. With the shipping market today it looks more reasonable from a cost perspective to look at the option of converting tankers or bulk carriers to be used as storage units. Setup 3 is therefore preferred over setup 2 and should be compared to the regular supply vessel planning problem. It should not only be considered if the storage units should be used or not, but also the location of them. The aim of having forward storage units is to reduce the number of expensive supply vessels in operation. For this aim to be met the cost reduction in supply vessels will have to be greater than the cost of the storage units. The cost of the storage units is not known and one has to base this on the cost of converting existing bulk carriers or tankers to make them suitable for this operation.

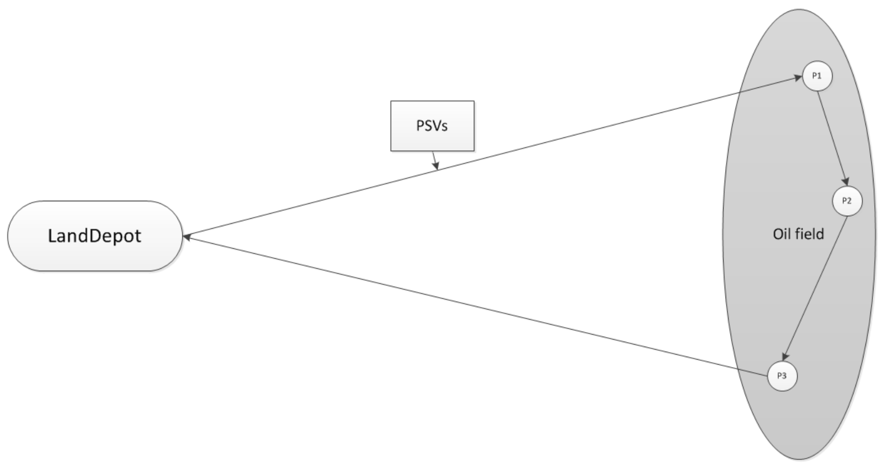

Figure 1 - Flowchart of setup 1

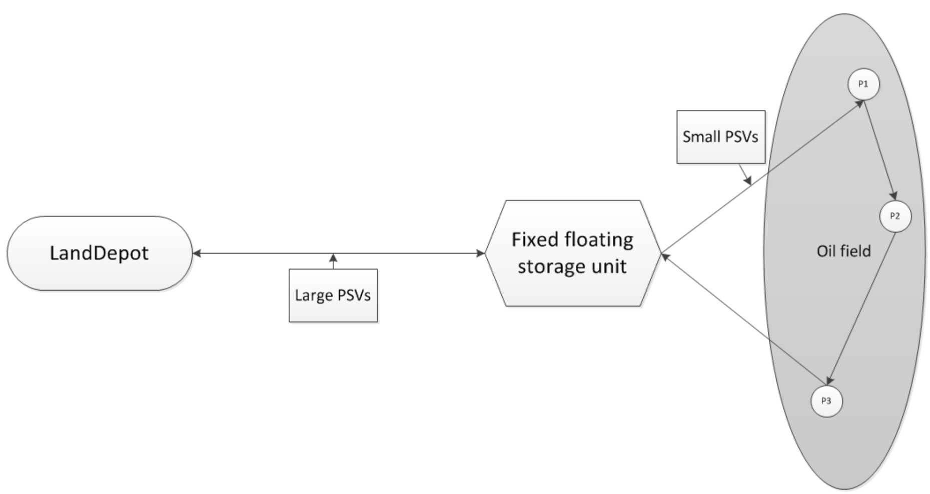

Figure 2 - Flowchart of setup 2

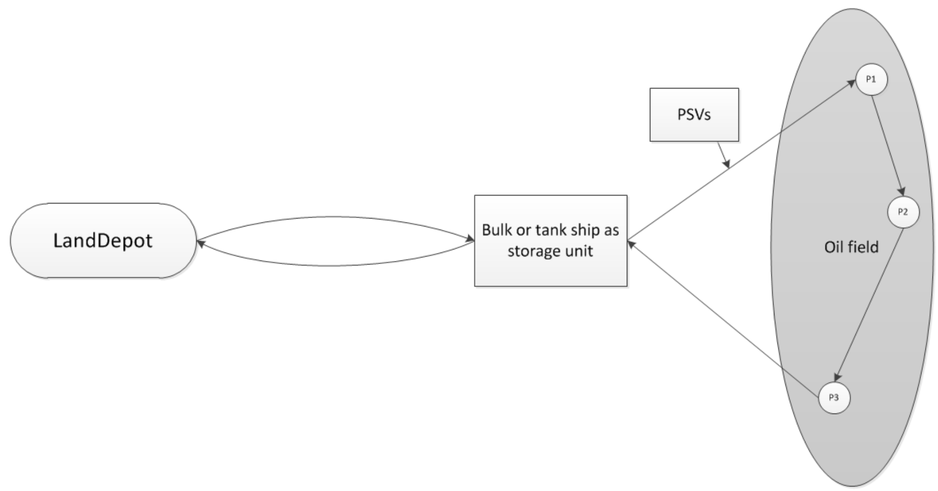

Figure 3 - Flowchart of setup 3

This thesis will evaluate two types of setups for the supply vessel planning problem. The first will be the regular supply operation with routing of PSVs from a land depot known here as setup 1 and secondly the same problem will be studied with the use of converted cargo ships as forward storage units known here as setup 3. Setup 2 is abandoned as an option as it is likely to have very high costs.

Setup 3 with the converted cargo ships as forward storage units has not been studied before; its mathematical model should minimize the total cost of the supply service. Then both routing cost of the supply vessels including charter cost and the cost of the storage unit has to be considered. It is necessary to look to other industries to see if any similar problems have been solved. These problems have to consider both routing of vehicles and the location of a depot. There are problems known as location routing and facility location problems that could prove useful to investigate here. Problems regarding emergency response planning could be valuable to look into as these models consider some of the same issues.

There should be made a basic design of the storage unit to find out what capabilities and storage capacities it should have. Besides the supply service operations the ships operating as a forward floating storage units could have additional technical capabilities. These could include a helicopter depot, storage of equipment for emergency oil spill operations and as a tanker in an emergency oil spill event. Including these capabilities could solve other logistical problems that the oil companies might have in remote areas.

The main purpose of this thesis is to investigate the effect of using floating storage units for supply operations. A secondary goal is to briefly look into if it could be used for other services at remote locations in the offshore oil and gas industry. As introduced earlier the general supply vessel planning problem (setup 1) will be used for comparison with setup 3 of having two converted cargo ships as storage units. To do this a case study will be done, based on a scenario with drilling and production of oil close to Jan Mayen. The problem is to find out which of the two setups 1 and 3 is preferred based on the case study and to see if setup 3 is a realistic setup with regards to cost and technical solutions. To be able to perform the case study regarding the supply logistics one has to specify location of land depot for the operation, distances to the field, location and number of installations to be supplied, required supply frequency and demand and fleet of available PSVs and their technical specifications. To compare the two setups it is necessary to construct mathematical models for both of them where the routing of the PSVs in each of the cases is considered. Optimizing the models will be done by implementing them into Mosel/Xpress. This will answer which one is preferred when comparing the cost of each of them. Setup 3 is an untried solution and the technical aspects of it should be discussed to see if it actually is a possibility to do this and get a rough estimate of what the cost of these vessels would be.

The remainder of this thesis is organized as follows: Chapter 2 discusses relevant literature for creating mathematical models and making some specifications for the storage units. Chapter 3 looks into some of the aspects with the case study around Jan Mayen. Chapter 4 discusses how the problem can be formulated mathematically into optimization models. Chapter 5 is used to describe the data that is put into the models created in chapter 4. In chapter 6 the results from solving the models are presented. Chapter 7 discusses the technical specifications of the storage units and makes an estimate of the cost of them.

2 Relevant literature

Within maritime transportation Christiansen, Fagerholt, Nygreen, and Ronen (2007) discuss three different terms of planning level. The planning horizon can be classified into strategic, tactical and operational problems. The strategic problems handles more an overview of the situation and is usually planning for a longer time period (1 year or more), such as market and trade selection, ship design, network and transportation system design, fleet size and mix decisions and port location, size and design. Tactical planning usually involves planning for more than one voyage in the maritime industry and handles problems such as adjustment to fleet size and mix, fleet deployment, ship routing and scheduling inventory ship routing and more. The operational planning normally concerns the next voyage and determines specifications such as speed selection, ship loading and environmental routing concerns.

The classic supply vessel planning problem is a combined fleet composition and periodic routing problem. Combining the vessels into an optimal fleet is a tactical decision, we want to deploy a fleet of available supply vessels and minimize the cost of routing them with the given demand at the offshore installations. The problem is related to the classical vehicle routing problem (VRP), but it also includes additional constraints to get the necessary detail level of the formulation. Fagerholt and Lindstad (2000) and Halvorsen-Weare et al. (2012) has already studied this problem and made mathematical formulations of it. The models created in these publications provide a good ground work for this thesis. Aas, Gribkovskaia, Halskau Sr, and Shlopak (2007) is looking into the routing of supply vessels. This article does only consider the routing of a single vessel and finding an optimal route for it, in other words it is only looking at the operational planning level and is not considering the optimal fleet of PSVs. The model discussed in this paper might not be that relevant here, but it provides a good description of the operations of a PSV and is useful to get a better understanding of the problem at hand.

It has to be made a strategic design decision regarding system design whether to use the storage units or run a regular supply service, solid models are needed. Two important aspects of the setup with the forward storage units are to find an optimal location of them and find the optimal routes for the PSVs from the units to the installations. It is not possible to use the models from the papers mentioned above regarding the classic supply vessel planning problem alone. Firstly one has to update them to be able to take the storage unit and the location of it into consideration. What could be done is to use the known models regarding the supply vessel planning problem and assume that the forward storage unit is a land depot. Then calculate the routing cost of supply vessels for each of the possible location of the storage unit and add the cost of having the storage unit at that location. For large problems this might require a lot of computation, and other methods should be discussed as well. Relevant problems in the optimization world are the location routing problem and the facility location problem that has been looked into in the papers discussed next.

Naji-Azimi, Renaud, Ruiz, and Salari (2012) and Tzeng, Cheng, and Huang (2007) have both models regarding relief distribution system in disaster areas, one important aspect of these is to find the optimal location of a satellite distribution center. The article by Perl and Daskin (1985) is looking into location optimization and is describing a Warehouse Location-Routing problem (WLRP). This problem consist of distributing goods from one or more factories to a number of distribution centers and then from the distribution center to the customers. The three papers mentioned here involve transportation of goods to a distribution center in addition to the routing from the distribution center to the demand. These models are more suitable for setup 2, but less relevant for setup 3.

Lundgren, Rönnqvist, and Värbrand (2010) discuss a facility location model. This model can be used to find optimal locations of distribution centers or other types of storage facilities. However, the model does not consider routing in the way that is necessary here, but the principle for the location issues could be more relevant.

A multi depot vehicle routing problem or location routing problems are problems where one are considering routing a set of vehicles from a set of pre-defined locations to a set of customers. A capacitated location version of this problem is discussed by Baldacci, Mingozzi, and Calvo (2011) and Mingozzi, Prins, and Calvo (2007).

Verma, Gendreau, and Laporte (2013) looks at optimal locations of oil-spill response facilities with a stochastic model where the first stage handles the location of the facilities and the second stage handles the resource allocations. In this type of problem one does not have specific routes to "known customers" but one has to cover a specific area. Brotcorne, Laporte, and Semet (2003) has studied similar problems regarding location optimization for Ambulances stations.

Oran, Tan, Ooi, Sim, and Jaillet (2012) formulates a mathematical model for the maximal covering location problem (MCLP) within emergency response planning. These problems consider some of the same location and routing issues as desired in this thesis.

For finding the specifications of the vessels operating as storage unit the System Based Ship Design theory discussed by Levander (2009) can be used. This theory is used by naval architectures to find a good design of a vessel based on the mission and function of it. This method is considered more efficient than design processes where one start by defining the main dimensions of the vessel before the mission and functions are defined. System based ship design gives fewer iterations compared to other design methods.

3 Case description

Jan Mayen represents a potential case located in a remote area where oil and gas fields are in the proximity. This case will be studied in this thesis with regards to the supply vessel planning problem and the use of forward floating storage units. Before a field can be opened up for the petroleum industry an opening process has to be conducted. Firstly it consists of an evaluation of the potential resources in the area and secondly an evaluation of the industrial, environmental and other social impacts from starting the petroleum activities. An impact assessment has been sent into the Norwegian government for this area and potential exploration drilling could start as early as 2017 according to OED (2012c). Jan Mayen has little or no infrastructure and has long distances to the closest onshore supply depots. This makes it an excellent case study to see if there could be any potential cost savings of using setup 3 with forward floating storage units.

OED (2012c) has worked out two scenarios for Jan Mayen, one high- and one low activity scenario. The preferred scenario to look at in this case will be the high activity scenario. It is easy to understand that using forward storage units will require some economic of scale (many installations to service) and it will be most relevant to look at the case with higher activity. In the high activity scenario the three most likely locations for discovery of hydrocarbons have been picked out. In the low activity scenario only 1 unit will be in production and in that case a PSV could be used as a forward storage unit and do the deliveries of goods itself. The calculations for a low scenario could have been done manually due to the small problem size.

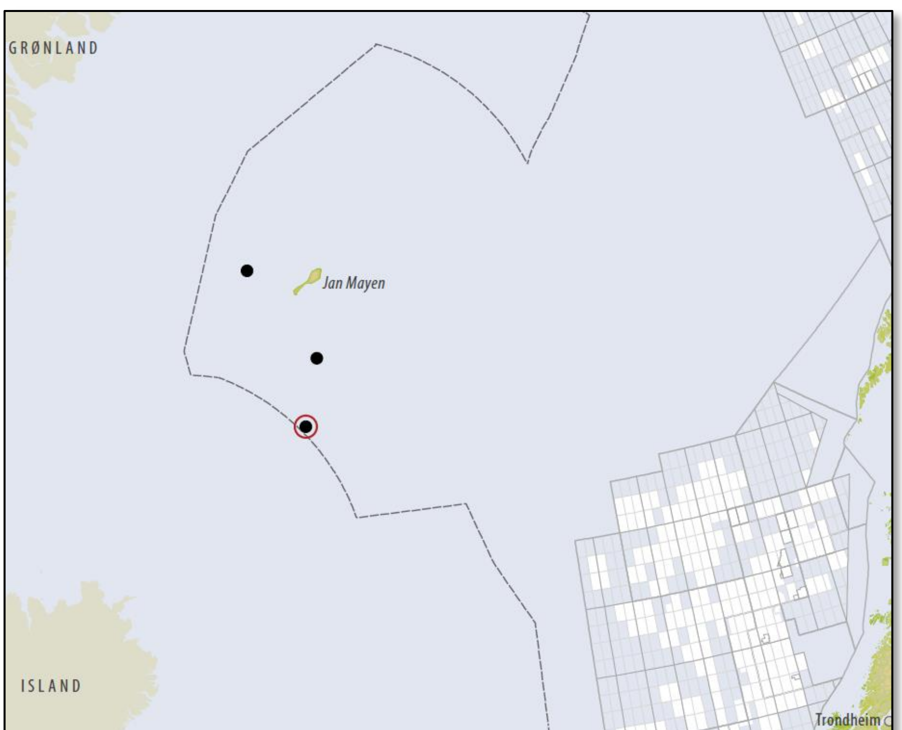

Figure 4 - Most probable locations of activities. High scenario (black dots) and low scenario (red ring). Figure taken from: (OED, 2012c)

3.1 Physical conditions at Jan Mayen

In the years 2001-2011(see Figure 5) the maximum ice cover has reached the location of the most northern point of the three fields. However, the statistics from 2009-2011(see Figure 6) show that the maximum ice covers has been far from the fields. It is assumed in this case that this development will continue, and it is therefore assumed ice free conditions all year round. It is preferred to look at a case with no ice cover as the effect of ice will complicate the operations during periods with ice. The largest ice cover is in January, February and March.

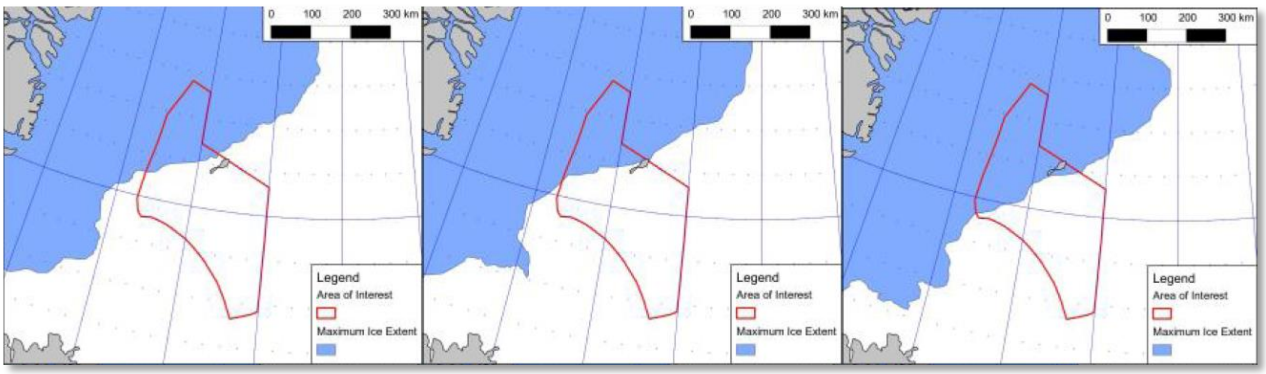

Figure 5 - Maximum ice cover in the period 2001-2011, from January to March. Figure taken from (OED, 2012b)

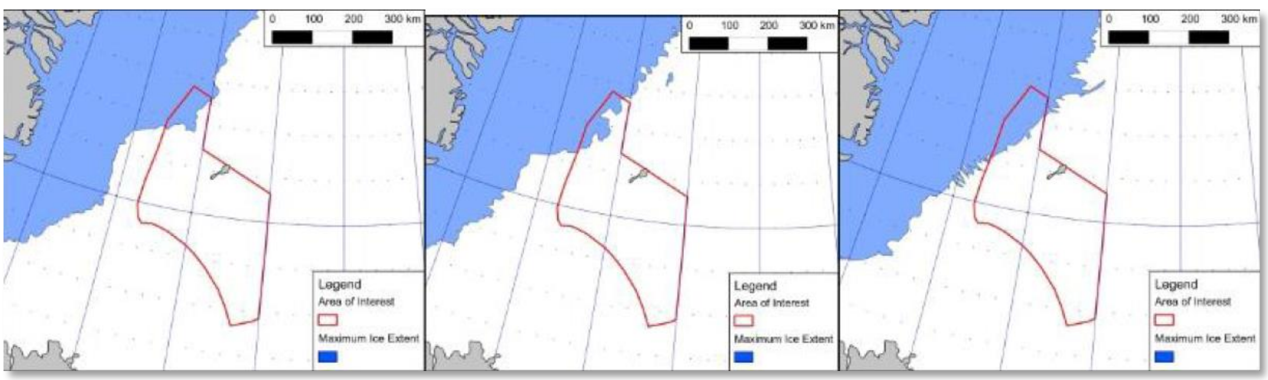

Figure 6 - Maximum ice cover in the period 2009-2011, from January to March. Figure taken from (OED, 2012b)

Even if the sea is not covered by ice in the area, icing on equipment due to low temperatures in the winter months could be an issue. It is estimated that in 13 % of the time light icing conditions will occur, 2-5 % of the time moderate icing can occur and major or extreme icing can occur respectively between 0.3-1.4 % and 0.1-0.7 % according to OED (2012c). Compared to Goliat where no major or extreme icing is expected to occur, extra considerations have to be taken into account for installations, equipment and ships. Icing on ships can be a major problem, making the ships top heavy. This will cause the ship's center of gravity to rise, thus decrease the metacentric height and stability of the vessel. A measure to reduce the icing on the vessel and its equipment is to reduce the speed of the vessels (Statoil, 2013). A speed reduction will of course have an impact on the supply service, but it is not easy to consider this in the model without taking changing weather by means of stochastic into consideration and thus complicating the problem even more. This is something that has to be considered on an operational planning level. The effect of speed reduction due to icing is therefore not taken into consideration here, as it is also only a small amount of time this may occur. During the worst conditions it might be difficult to perform operations anyway.

Expected wind conditions is presented by OED (2012c). The maximum wind conditions are estimated to be in the area between 29 and 31 meters per second. This is similar to fields like, Statfjord (30 m/s) in the North Sea, Heidrun(28 m/s) in the Norwegian Sea and Goliat (28 m/s) in the Barents Sea. It is estimated that the fields will experience winds with strength of fresh breeze or stronger 11-12 percent of the time. Wind speed of fresh gale or stronger is estimated to be present 0.3 percent of the time. These conditions have to be considered for operating in the area, and could play a role when performing ship to ship or ship to platform operations at the oil fields. However, there is not much difference in the wind speed between these fields and the fields already operated today in the North- and Norwegian Sea.

OED (2012c) discuss the expected wave conditions in the area, which are directly linked to the wind conditions. At the three locations looked at in this case a maximum significant wave height, H_s, is estimated to be 13.8 m (71°N 11°W), 14.2 m (70°N 08°W) and 16.0 m (68°N 08°W). Compared with the North-, Norwegian- and Barents Sea (Statfjord, Heidrun and Goliat) this is actually a little lower. It is expected that the fields close to Jan Mayen will have a significant wave height above 3 meters 50-65 percent of the time. This means that there are no special wave conditions compared to other areas for Norwegian offshore oil and gas activities.

The air temperature can be found to be lower at the oil fields close to Jan Mayen compared to other oil fields at the Norwegian continental shelf. For the position furthest north the temperature is estimated to drop to a minimum of -27.6 C°, while the field in the middle has a minimum temperature of -18.4 C° (OED, 2012c). Comparing these to the Barents Sea where subzero temperatures are normal, the Goliat field has a minimum temperature of -12.8 C°. Freezing temperatures in the winter months are therefore something to keep in mind when performing operations in the area. Together with wind conditions subzero temperatures can be a challenge for both crew and equipment. Crew operating on deck under such conditions is not safe and one might have to implement automatic/robotic solutions for some of the cargo handling on deck for the PSVs.

The visibility in the area is affected by the light conditions (darkness most of the day in the winter months), snow and fog. Compared to other areas with offshore activities on the Norwegian continental shelf, fog is occurring in a higher degree and all year round. It is estimated that fog will occur from 7 % to 20 % of the time according to OED (2012c). According to the NWEA guidelines (see Appendix 3 and Appendix 4) it should not be performed ship to platform or ship to ship transfers if the visibility is less than 250 meters.

Summarizing the physical conditions one can see that there could be challenges towards ice and low temperatures. To make this case study more general this will not be looked into in much detail here. Wave and wind conditions are similar to the North- and Norwegian Sea and the effects of these should not be necessary to study in detail in this thesis.

3.2 Activity level

As mentioned the high scenario will be the most relevant to look at here and will be used as a basis case for the number of installations to service. In the high scenario the first exploration drilling is assumed to start in 2017 and a gas field containing 100 billion Sm^3 is discovered. After that discovery, one exploration well is drilled each year, and it is assumed that one will make discoveries every third year. It is expected by OED (2012c) that there will be found two oil fields both containing 40 million Sm^3, respectively in 2020 and 2023. For a well to be developed the findings of hydrocarbons has to be of a significant scale. The numbers presented here is based on limited geological data and the actual findings may in reality be higher or lower, but in this case these data are good to use as a first estimate. The last exploration well will be drilled in the year 2027. From discovery to production it is estimated a time period of 10 years, which is average for the Norwegian continental shelf according to OED (2012c).

Year	Activity Jan Mayen	Location
2017	First exploration well is drilled, + gas discovery, 100 bn. Sm^3	70°N 08°W
2018	New exploration well is drilled	
2019	New exploration well is drilled	
2020	New exploration well is drilled + oil discovery, 40 m. Sm^3	68°N 08°W
2021	New exploration well is drilled	
2022	New exploration well is drilled	
2023	New exploration well is drilled + oil discovery, 40 m. Sm^3	71°N 11°W
2024	New exploration well is drilled	
2025	New exploration well is drilled	
2026	New exploration well is drilled	
2027	Production starts in gas field	70°N 08°W
2028		
2029		
2030	Production starts in oil field	68°N 08°W
2031		
2032		
2033	Production starts in oil field	71°N 11°W

Table 1 -Expected activity development Jan Mayen. Data collected from: (OED, 2012c)

From the expected high activity level by OED (2012c) all three location will be in production in 2033. There will be two Floating, Production, Storage and Offloading (FPSO) units and one Floating Liquefied Natural Gas (FLNG) unit which will require a regular supply service to keep up production. If the forward floating storage unit proves to give a cost reduction in the supply operations for this case with three units to supply, it will also be relevant to look at scenarios with less activity. If it is not proven to be cost efficient it might be necessary to make a case with a higher activity level and more units to be supplied. The demand of commodities at each installation will be discussed further in chapter 5.2.

To get a better look at the effect of having the floating storage unit it is in this thesis defined a few more scenarios with more installations to service in the same area. The problem is extended from the basis case with three installations to service and up to a total of eight installations. All of the installations are put in the same oil field, and not that far from each other. If we look at all the cases from three and up to eight platforms and compare them with the case where they are supplied directly from land, it should be possible to get a good picture of the effect on the overall costs on the supply service of having the storage units. In the high activity scenario by OED (2012c) there were only three installations in operation, but what is being done here is to make some scenarios with some randomly placed installations close to the real installations. This is done for the purpose of the objective of the thesis to get a look at the effect of having the forward floating storage units. In Figure 7 one can see a map showing the assumed positions, number one to three are the ones from the high activity scenario by OED (2012c) while the rest are randomly created.

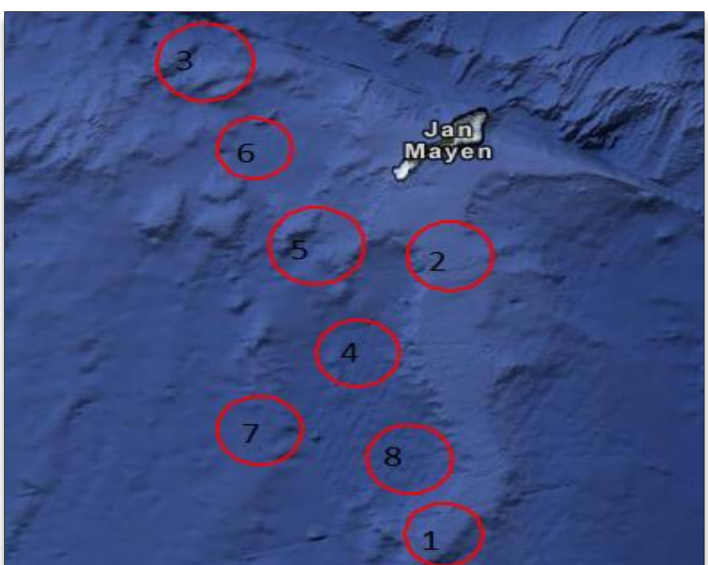

Figure 7 - Map with all the installations

3.3 Land depot

As mentioned Jan Mayen is located in a remote area, and there is no land depot nearby for supply operations. According to OED (2012a) the closest ports are located on Iceland, but they are however small and not operable for a supply service at the present. For this thesis it is assumed that a Norwegian land depot will be used. Some Icelandic ports might be closer located than ports in Norway, but to avoid any political concerns and for the purpose of this thesis it is assumed that a Norwegian port will be used. Here 5 Norwegian ports are compared against each other based on the average distance to each of the locations in the scenario from OED (2012c).

Land Depot	Location	Average distance [nm]
Kristiansund	63°N 07°E	586
Brønnøysund	65°N 12°E	557
Bodø	67°N 14°E	541
Harstad	68°N 16°E	545
Hammerfest	70°N 23°E	651

Table 2 - Average distance to location from possible land depots.
Gathered from: http://www.sea-seek.com/tools/tools.php

The complete set of distances for each land depot to each location can be found in Appendix 1. Based on the distances to the locations for the possible oil activities Bodø and Harstad are giving the shortest distances to travel. On the other hand the port in Kristansund is already in use as a land depot for the offshore supply logistics in the Norwegian Sea. If the port in Kristansund is used as a land depot it will not require significant investments to make this port operable as a land depot for Jan Mayen as well compared to the other alternatives. The additional sailing times will increase with only 8 % compared to Bodø, and result in 3-4 hours of additional sailing time in each direction, based on a sailing speed of 12 knots. If the regular supply service in setup 1 is proved to be more cost efficient than setup 3, then Bodø might be the better option as land depot since the PSVs will have to sail the complete distances to the field. If oil activities are started up in Lofoten and Vesterålen, an investment in a land depot in Bodø might be more valuable. In the cases for setup 1 the port in Kristansund will be used as the land depot.

To calculate the distances between two points based on longitude and latitude it is necessary to use a spherical coordinate system. Because the earth has a spherical form it is not possible to simply draw a straight line on a map to get the distance between two points. The calculation for the distances of the land depots to the different locations is based on an online calculator; see the source mentioned in Table 2. This will also be done when collecting all the distances in chapter 5.3 and preprocessing the distance matrices for the models in Xpress.

4 Mathematical model

A good mathematical formulation of the supply logistic setups is necessary to be able to model the wanted situation. As setup 1 and 3 is the preferred options to investigate further both of them will be given a mathematical model to work with that can optimize their routing of vessels. Luckily setup 1 is already well-known, it is possible to get formulations from Fagerholt and Lindstad (2000) and Halvorsen-Weare et al. (2012). Setup 3 has to be constructed from scratch, but the models from setup 1 together with known models regarding location routing could prove to be helpful.

4.1 Setup 1

This model describes a situation where one has a given number of installations to supply from a land depot. Each of the installations requires a regular supply service of various commodities, the amount of deck cargo is the binding constraint of the cargo. Platform supply vessels can be looked at as the workhorse of the operation and can have variation in size. The day rates for the PSVs can amount to tens of thousands USD per day in addition to fuel consumption, depending on size and capabilities. What will be modeled is a fleet of PSVs routed from a land depot to the installations on schedules making it possible to fulfill the required demand of deck cargo. The models that will be described are known models used for oil and gas fields in the North- and Norwegian Sea. Optimal routes and schedules has proven to save oil companies Millions of USD per year, but this was in fields much closer to shore and in the current case it could prove to be very expensive due to many ships in operation.

4.1.1 Model 1 - (Fagerholt & Lindstad, 2000)

The model below described by Fagerholt and Lindstad (2000) is a two-step model. In the first step all the possible routes will be generated, these routes are the variables in the model. This is called a path flow formulation of the problem, where the model is solved based on the routes generated in step 1.

Sets:

K – Vessels in the pool, indexed by k.

N – Offshore installation, indexed by i.

R_k – Schedules for ship k (generated in step 1), indexed by r.

Parameters:

D_r^k - The duration in hours of schedule r for ship k (calculated in step 1).

T_r^k - The total time in hours of schedule r for ship k (calculated in step 1).

A_{ir}^{k} - Constant that is equal to 1 if vessel k services installation i on schedule r and 0 otherwise (derived in step 1).

S_i - Minimum number of weekly services for installation i.

C^k - Cost of supply vessel k.

M - Large number.

m - Small number.

Variables:

δ^k - Binary variable that is equal to 1 if vessel k is used in the optimal solution and 0 otherwise.

x_r^k - Integer variable indicating the number of times per week ship k sails its schedule r.

$$\min z = M\sum_{k\in K} C^k \delta^k + m\sum_{k\in K}\sum_{r\in R_k} D_r^k x_r^k \tag{1}$$

$$\sum_{k\in K}\sum_{r\in R_k} A_{ir}^k x_r^k \geq S_i, \ \forall i \in N, \tag{2}$$

$$\sum_{r\in R_k} T_r^k x_r^k \leq 168, \ \forall k \in K, \tag{3}$$

$$\sum_{r\in R_k} x_r^k - M\delta^k \leq 0, \ \forall k \in K, \tag{4}$$

$$x_r^k \ \text{integer}, \ \forall k \in K, r \in R_k, \tag{5}$$

$$\delta^k \in \{0,1\}, \ \forall k \in K. \tag{6}$$

The objective function (1) is to be minimized. This is written so that the first term in the main objective should be minimized, i.e. minimizing the total cost of using the vessels; this is the main cost. The second term seeks to minimize the total sailing time for the fleet. Fuel costs and service cost are neglected in the objective function. However, the fuel price might not be negligible today with higher prices today compared with 2000 and should be considered to be included. The objective function can alternatively be formulated as

$$\left[\min z = \sum_{k\in K} C^k \delta^k + \sum_{k\in K}\sum_{r\in R_k} C_r^{Sk} x_r^k\right] \tag{7}$$

where C_r^{Sk} is the service (fuel and miscellaneous) cost per route r for ship k. Constraints (2) ensure that each facility is serviced the necessary amount of times. Constraints (3) ensure that a vessel cannot be used more than the time available for each week. Constraints (4) ensure that if a vessel is used for a route in the schedule then the vessel has to be used, this connects the two variables. Constraints (5) and (6) ensure integer and binary requirements.

4.1.2 Model 2- (Halvorsen-Weare et al., 2012)

The model described by Halvorsen-Weare et al. (2012) is similar to the model described by Fagerholt and Lindstad (2000), but has a higher detail level with regards to time. This is also a two-step model, and will require a similar route generation process as Fagerholt and Lindstad (2000). The model is described below.

Sets:

V – Vessels in the pool, indexed by v.

N – Offshore installations, indexed by i.

R_v – Pre-generated voyages for vessel v, indexed by r.

T – Set of days in the planning horizon indexed t.

L – Set containing all possible voyage durations in days.

$R_{vl} \subseteq R_v$ - Subset that contains all candidate voyages of duration l that vessel v may sail.

Parameters:

D_{vr} - The duration in days of voyage r sailed by vessel v.

F_v - The number of days vessel v may be used during the week.

A_{vir} - Constant that is equal to 1 if vessel v services installation i on voyage r and 0 otherwise.

S_i - Minimum number of weekly services for installation i.

B_t - The maximum number of supply vessels that may be serviced at the supply depot on day t.

C_v^{TC} - Weekly time charter cost of vessel v.

C_{vr}^{S} - All sailing and service costs for voyage r sailed by vessel v.

Variables:

δ_v - Binary variable that is equal to 1 if vessel k is used in the optimal solution and 0 otherwise.

x_{vrt} - Binary variable that is equal to 1 if vessel v sails route r on day t and 0 otherwise.

$$\min \sum_{v \in V} C_v^{TC} \cdot \delta_v + \sum_{v \in V} \sum_{r \in R_v} \sum_{t \in T} C_{vr}^{S} \cdot x_{vrt} \tag{8}$$

S.t.

$$\sum_{v \in V} \sum_{r \in R_v} \sum_{t \in T} A_{vir} \cdot x_{vrt} \geq S_i, \; i \in N \tag{9}$$

$$\sum_{r \in R_v} \sum_{t \in T} D_{vr} \cdot x_{vrt} - F_v \cdot \delta_v \leq 0, \; v \in V \tag{10}$$

$$\sum_{v \in V} \sum_{r \in R_v} x_{vrt} \leq B_t \tag{11}$$

$$\sum_{r \in R_{vl}} x_{vrt} + \sum_{r \in R_v} \sum_{v=1}^{l-1} x_{vr,((t+v) \bmod |T|)} \leq 1, \; v \in V, \; t \in T, \; \mathrm{l} \in \mathrm{L} \tag{12}$$

$$\delta_v \in \{0,1\}, \; v \in V \tag{13}$$

$$x_{vrt} \in \{0,1\}, \; v \in V, \; r \in R_v, \; \mathrm{t} \in \mathrm{T} \tag{14}$$

The objective function (8) seeks to minimize the sum of the charter costs and the sailing costs. Constraints (9) ensure that all installations get their required number of visits during the planning horizon. Constraints (10) ensure that the total duration of all voyages sailed by a vessel does not exceed the maximum number of days the vessel may be in service during the planning period. These constraints also ensure that if a vessel v is used, the binary variable δ_v must equal 1. Constraints (11) ensure that there are no more supply vessels at the supply depot on day t than there is capacity to service. Constraints (12) ensure that a vessel does not start on a new route before it has returned to the supply depot after the last route. Constraints (13) and (14) ensure binary requirement. In addition there are constraints that are added to get spread of departures if needed.

4.1.3 The route generation process

In step 1 the feasible routes are created. This is done by first considering the set of routes that only include one installation, then two and up to the total number of installations. There are two constraints that have to be to satisfied in the supply vessel planning problem, first the capacity of the vessel cannot be exceeded and secondly a time constraint that ensures that the installation is not serviced when it is closed. The time constraint is only necessary to include if the installations are closed some hours of the day. To simplify the model and calculations it is assumed that the installations will be open all hours; this is also assumed for the land depot.

Fagerholt and Lindstad (2000) investigates the effect of including opening hours and the cost savings are relatively small and the conclusion of the case looked at in that article was that the installations should be open all hours. A reduction in the opening hours for the installations would affect the schedules of the vessels, and some might be forced to wait or take another route. This has a negative effect on the cost of the supply vessel operations and it gives a bigger chance of delays if a vessel misses its opening window. The only time constraint that will be considered here is that the time of a route is no longer than the planning period we are looking at.

When a set of installations to be serviced and a route has been created for a vessel it will first be checked if it is possible to complete this route based on the capacity- and time constraints; if not feasible, a route containing this set of installations for this vessel will be disregarded. The result of the route generation process should give the total time, sailing cost and service constants for each route. It is beneficial that the routes have an optimal visiting sequence, i.e. shortest possible sailing distance. To ensure that each route is optimal one has to solve a TSP (Travelling Salesman Problem), i.e. finding the shortest distance, for each set of possible routes. When the TSP is solved the outcome is the sailing time and distance, from this the sailing cost is calculated. One gets the service constant based on which installation is included in the route.

Route generation procedure

```
Create all sets of possible routes for all vessels from only containing one installation up to all inst.
    For all sets of routes for each vessel
        Add the supply demand for the installation in the set
            If cargo demand of route exceeds vessel capacity
            Remove route from set
            End-if
        Find travel time by solving a TSP containing the land depot and all the installations in the set
            If time of the route exceeds the time span of the planning horizon
            Remove route from set
            End-if
    End for all
Return Number of routes for each vessel and total time, service matrix and cost of each route
```

Table 3 – Simple pseudo code for the route generation procedure

It would in this case be possible to solve the TSP by full enumeration, i.e. finding all possible routes. This is possible to do since a vessel in any case at most will visit 5-6 installations on a single trip because of the capacity constraint. According to Fagerholt (2012) the number of possible solutions that has to be added is (n-1)!/2 for a symmetric TSP, where n is the number of nodes in the problem. If there are 6 installations to visit, there are 7 nodes in the problem (the depot node has to be included); this result in maximum 360 computations. For respectively 1, 2, 3, 4, and 5 installations it will be 1, 1, 3, 12 and 60 computations. In this case we have a symmetric TSP, which means that the distance/cost is independent if we sail from node 1 to 2 or 2 to 1. An asymmetric TSP would result in twice as many computations. The solver in Xpress can easily solve the TSP problem very quickly, but one needs to add the sub tour eliminating constraints manually or write a script in in Mosel that automatically adds these constraints. To take advantage of the solver in Xpress a sub tour eliminating procedure will be added when solving the TSP here. It would also have been possible to solve it by full enumeration, but the sub tour elimination procedure is preferred to implement into Xpress.

Advantages	Disadvantages
• One variable per route instead of per leg • The set partitioning problem has a structure that is much easier to solve than the direct formulation • Flexibility in how the routes are generated • Often easy to include practical constraints, such as time windows, maximum route duration, capacity etc. in the route generation process	• This will require a 2 step approach, one has to create all the candidate schedules up front • To ensure optimal solution all feasible routes has to be generated • The number of variables grows exponentially with problem size

Table 4 - Advantages and disadvantages with the route generation method. (Fagerholt, 2012)

Table 4 shows the advantages and disadvantages of using the route generation method. Alternatively to the two-step models looked at so far, a one-step arc flow model could be used. An arc flow model would not require all the routes to be pre-generated before solving the model. However, the number of variables would be increased as one will have one variable per node instead of one variable per route in the model. Arc flow models will even for small problems quickly give a very high number of variables. In this case the number of nodes will probably not get too high, but since there in addition are created separate variables for each vessel the number of variables in the arc-flow model could get high and when one looks at setup 3 this requires many variables. The path-flow model is therefore the preferred option to use.

4.1.4 Comparison of model 1 and 2

It is preferred in this thesis to avoid the use of heuristics, dynamic column generation and advanced solution methods to simplify the calculation and not to use too much time on programming. The focus of this thesis is to get a generic decision support model that can be used for realistic problem sizes where a forward floating storage unit might be used. It should be answered if it is economical beneficial to use it and find the optimal location of it.

The main difference between the two models is that model 2 has taken the time aspect (at which day) the vessels sail their routes into consideration. This requires more variables and is more advanced to solve. The purpose of this is to be able to ensure that you get spread departures of the routes, i.e. not on the same or consecutive days. In model 1 it is assumed that once the optimal routes and schedule is found it can be arranged without excessive effort to get the wanted time spread between each route. Model 2 is therefore more detailed than model 1. For the problem instances solved by model 1 by Fagerholt and Lindstad (2000) it was able to provide a definite optimal solution. This was because of the relative small problem size; in that case it was between 500 and 1000 generated schedules with full enumeration. It is assumed that the input data for the current case will be of the same size or smaller, the only difference will be longer sailing distances. This will probably result in an optimal solution for the cases here within a reasonable amount of time. The problem instances solved by model 2 by Halvorsen-Weare et al. (2012) was in most cases able to be solved for optimality. This model creates a larger number of variables in the route generation process, making it more time consuming to solve the model. In a few cases it was not able solve the problem for optimality within the given CPU time and one got an optimality gap. Additional solution methods (heuristics) could have been used to find good solutions faster. For the setup 1 case in the current problem this model should probably give optimal solutions, on the other hand if it should be used as a basis for the setup 3 case it might require heuristics in the solution method if one are looking at many possible locations for the storage unit.

For the purpose of the objective here model 1 is easier to use to and it also provide a good estimate of the routes and detailed routes with spread of departures and time windows are not necessary to use. The conclusion of this is to use the model by Fagerholt and Lindstad (2000) for solving the supply vessel planning problem and use it as a basis for setup 3. To take the fuel costs into consideration the adjusted objective function (7) discussed in 4.1.1 will be used in this case.

4.2 Setup 3

4.2.1 Model 1 as a basis

As concluded under the chapter for setup 1, the model by Fagerholt and Lindstad (2000) was the preferred model to use as a basis for setup 3. One possibility here is to extend the model with the location index of the forward floating storage unit. From each possible location of the storage unit the model will be solved. For example if there is 10 possible locations that could be suitable for the storage unit one has to solve the model by Fagerholt and Lindstad (2000) for each of the locations. This will of course require more computation time for the model, and the size of the problem will be proportional with number of possible locations. The argument for using the model for setup 1 as basis for this model as well is that the forward floating storage unit can be considered as a land depot when solving the model and just add the cost of having the storage unit.

Sets:

K – Vessels in the pool, indexed by k.

N – Offshore installation, indexed by i.

L – Set of possible locations, indexed by l.

R_{kl} – Schedules for ship k from location l (generated in step 1), indexed by r.

Parameters:

D_r^{kl} - The duration in hours of schedule r for ship k from location l (calculated in step 1).

T_r^{kl} - The total time in hours of schedule r for ship k from location l (calculated in step 1).

A_{ir}^{kl} - Constant that is equal to 1 if vessel k from location l services installation i on schedule r and 0 otherwise (derived in step 1).

S_i - Minimum number of weekly services for installation i.

C^k - Cost of supply vessel k.

C_r^{Skl} - Cost of using vessel k from location l on route r.

C_l^{SC} - Cost of using storage units at location l (might not be dependent of location or negligible differences).

M - Large number.

m - Small number.

Variables:

δ^k - Binary variable that is equal to 1 if vessel k is used in the optimal solution and 0 otherwise.

x_r^{kl} - Integer variable indicating the number of times per week ship k from location l sails its schedule r.

z_l - Binary variable that is equal to 1 the forward storage unit is placed at location l

$$\min \mathrm{z} = \sum_{k\in K} C^k \delta^k + \sum_{k\in K}\sum_{r\in R_k} C_r^{Skl} x_r^{kl} + \sum_{l\in L} C_l^{SC} z_l \tag{15}$$

$$\sum_{k\in K}\sum_{r\in R_{kl}} A_{ir}^{kl} x_r^{kl} \geq S_i - (1 - z_l)\cdot m, \ \forall i \in N, \ l \in L \tag{16}$$

$$\sum_{r\in R_{kl}} T_r^{kl} x_r^{kl} \leq 168 \cdot z_l, \ \forall k \in K, \ l \in L \tag{17}$$

$$\sum_{r\in R_{kl}} x_r^{kl} - M\delta^k \leq 0, \ \forall k \in K, \ l \in L \tag{18}$$

$$\sum_{l\in L} z_l \geq 1 \tag{19}$$

$$x_r^{kl} \text{ integer}, \ \forall k \in K, r \in R_{kl}, \ l \in L \tag{20}$$

$$\delta^k \in \{0,1\}, \ \forall k \in K. \tag{21}$$

$$z_l \in \{0,1\}, \ \forall l \in L. \tag{22}$$

The objective function (15) is to be minimized. The first and second part of the objective function is as before the charter cost and service cost for the supply vessels. The last and new part of the objective function is the cost of adding the floating storage units (this cost should include both units). Constraints (16) ensure that each facility is serviced the necessary amount of times. The new part of this constraint is that the forward floating storage unit has to be in use for this location for the constraint to be valid. This connects the z variable for the storage units and the x variables for the routes. The small m should be equal to S_i. Constraints (17) ensure that a vessel cannot be used more than the time available for each week. Constraints (18) ensure that if a vessel is used for a route in the schedule than the vessel has to be used, this connects the two variables. Constraint (19) ensures that minimum one location will be used for the storage units, without this the output of the model would give no value to all the variables. It is assumed that there will be sufficient capacity at the storage unit in the planning period. The technical aspects of the storage capacity of the unit will be studied further in chapter 7, and is left out of this model assuming there is enough storage capacity for the planning period. The remaining constraints, (20), (21) and (22) ensures integer and binary requirements for the variables.

4.2.2 Facility location and other alternatives

The model (15)-(22) created under 4.2.1 with the known model by Fagerholt and Lindstad (2000) as a basis has some similarities to the facility location problem and uses some of the same principles when connecting the variables. This problem is described by Lundgren et al. (2010). The simplest form of this problem is to choose from a set of m facilities, for example terminals, depots or distribution center, and support a set n of customers. Each facility has a supply capacity and each customer has a demand. The objective is to minimize the fixed cost of the facility and the transportation cost from the facilities to the customers.

Sets:

m – Number of facilities.

n – Number of customers.

Parameters:

c_{ij} - Transport cost between facility i and customer j.

f_i - Fixed cost of using the facility at location i.

s_i - Supply from location i for one transport.

d_j - Demand at customer j.

Variables:

$$y_i = \begin{cases} 1, & \text{if facility i is open} \\ 0, & \text{otherwise} \end{cases}$$

$$x_{ij} = \text{ flow from facility i to customer j}$$

$$\min\ z = \sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}x_{ij} + \sum_{i=1}^{m} f_i y_y \tag{23}$$

$s.t.$

$$\sum_{j=1}^{n} x_{ij} \le s_i y_i,\ i = 1,\dots,m \tag{24}$$

$$\sum_{i=1}^{m} x_{ij} = d_j,\ j = 1,\dots,n \tag{25}$$

$$x_{ij} \ge 0,\ i = 1,\dots,m,\ \ j = 1,\dots,n \tag{26}$$

$$y_i \in \{0,1\},\ i = 1,\dots,m \tag{27}$$

The objective function (23) is to minimize the cost. (24) is to ensure that one does not transport more than available from facility i. These constraints also connects the two variables x and y. These constraints could be useful if the storage unit has a limited storage capacity. Constraints (25) ensure that the demand of each customer is met. In the current problem the demand is given as frequency of visits necessary. (26) is ensuring non-negativity to the x variables, while (27) ensure binary requirements for the y variables.

It is noted that this model is a simplification of what is presented in 4.2.1. It does not consider the routing to several customers on one trip from a facility and the amount of cargo transported is given by its own variable x. However, the principle is the same as if we want to decide which location of facilities is most profitable.

Another similar problem that might be relevant is the capacitated location-routing problem described by Baldacci et al. (2011). This problem consists of considering one or more pre-defined depot locations and route vehicles from the open depots to the demand of the customer nodes. In this problem each depot has a limited capacity, as a result only a limited number of vehicles can support the customers from each depot. What is considered here is the supply of customers from only one location. However, the rest of the problem is very relevant. Another difference is that each customer is maximum visited by one route in the solution and the time period is not considered in the same manor. The main difference between this model and the one presented by Lundgren et al. (2010) is the formulation of the x variables. The model by Baldacci et al. (2011) is discussed below.

Sets:

L – Set of possible locations, indexed by k.

R_k – Set of possible routes from location k, indexed by l.

V – Set of customers, indexed by i.

Parameters:

c_l^k - The cost of route l from location k, here also the fixed cost of the vehicle is included.

U_k - The cost of using the depot at location k.

w_l^k - The cargo load on route l from location k.

W_k - The storage capacity of the depot at location k.

Variables:

y_k - Binary variable that is equal to one if the depot at location k is used and 0 otherwise.

x_l^k - Binary variable that is equal to one if route l is used from location k and 0 otherwise.

$$\min\ z = \sum_{k \in L} \sum_{l \in R_k} c_l^k x_l^k + \sum_{k \in L} U_k y_k \tag{28}$$

$$s.t.$$

$$\sum_{k \in L} \sum_{l \in R_k} x_l^k = 1,\ \forall i \in V \tag{29}$$

$$\sum_{l \in R_k} w_l^k x_l^k \leq W_k y_k,\ \ \forall k \in L \tag{30}$$

$$x_l^k \in \{0,1\},\ \forall k \in L, \forall l \in R_k \tag{31}$$

$$y_k \in \{0,1\},\ \forall k \in L \tag{32}$$

The objective function (28) minimizes the total cost, the first part considers the routing costs and the second part considers the depot costs. This is similar to the case that is wanted to model here. Constraints (29) ensure that each customer i must be visited. Constraints (30) connect the two variables x and y and ensure that one is not delivering more than there is capacity to from that depot. (31) and (32) are setting the binary requirements for the variables x and y.

The mathematical formulation (28)-(32) has some similarities to what is suggested under 4.2.1 when it comes to the storage depots and connecting the variables for the routes and the depots. This model would however be more relevant if one have larger number of customers/installations and there where capacity issues of the storage units within the time aspect of the planning period in the model.

Oran et al. (2012) present a model formulation of the maximal covering location problem with priority for emergency planning. The model considers a set of possible sites for placing different emergency response facilities. Response vehicles have to cover a set of emergency points by having a travelling time or distance that is shorter than a coverage standard. The model considers multiple types of emergencies with different priority levels. One main difference from our problem is that it does not pre-generate routes, but considers this directly in the formulation. In addition there is only one emergency location that is visited on each route. The model will be assessed in further detail below.

Sets:

J – Set of locations for the facilities, indexed j.

I – Set of locations for the emergencies, indexed i.

K –Set of vehicle types, indexed k.

N_i^k - Types of vehicles k that can cover emergency i within the time limitation from facility j. This set of vehicles has to be decided before solving the model.

Parameters:

Q – Number of available facilities for operation

P^k - Number of available vehicles of type k.

p_i^k - Priority of emergency point $i \in I$ for vehicle of type k.

d_i^k - Number of distinct facilities required to cover $i \in I$ with vehicle of type k.

α_i^k - Weight for vehicle type k at emergency $i \in I$.

Variables:

y_j - Binary variable that is equal to 1 if facility is sited at location j, 0 otherwise.

x_j^k - Binary variable that is equal to 1 if vehicle type k I allocated to facility j, 0 otherwise.

w_i^k - Binary variable that is equal to 1 if emergency point I is covered by vehicle k, 0 otherwise.

$$\max \sum_{k\in K}\sum_{i\in I}\alpha_i^k w_i^k \qquad (33)$$

$$s.t.$$

$$\sum_{j\in J} y_j \le Q\ , \qquad (34)$$

$$\sum_{j\in J} x_j^k \le P^k,\ \forall k \in K \qquad (35)$$

$$x_j^k \le y_j\ ,\ \forall k \in K,\ \forall j \in J \qquad (36)$$

$$\sum_{j\in N_i^k} x_j^k \ge w_i^k\ ,\ \forall k \in K,\ \forall i \in I \qquad (37)$$

The objective function (33) maximizes the coverage of the vehicles. In our case we want to minimize the total cost of the model, but here the priority is to have as good coverage of emergencies as possible. Constraint (34) makes sure that there is not used more facilities than possible. This constraint also shows the same difference to our problem as the objective function, we only want to use one facility and have a minimization problem. Constraints of type (35) exclude the possibility to use more vehicles than available. This is considered in a different matter at our problem as we consider the routes that are pre-generated. Constraints (36) ensure that one does not route vehicles from a facility that is not in use. This could be similar at the problem here. (37) ensures that a point i is covered by a vehicle of type k , only if there is at least one vehicle of type k already sited at a facility that can cover i within the required time. This connectivity constraint can be similar in our model with some modification. In addition there is general binary constraint for the variables, x, y and w in the model.

4.2.3 Final model for setup 3

Model (15)-(22) under chapter 4.2.1 will be used for the case with the forward storage unit to get the most precise formulation of the problem. The three models discussed under chapter 4.2.2 are not giving a complete formulation of what is wanted to model here. Their modeling of the routes does not meet the level of detail desired, but with some modifications these models could be similar to the model created under 4.2.1. It should be possible to solve the model under 4.2.1 within a reasonable amount of time and the problem size will be proportional to the number of locations considered. The model formulation is exactly the same as the normal supply vessel planning problem except for the locations of the storage unit that are considered. Problem sizes usually looked at for the supply vessel planning problem is considered small compared to other industries and solving this problem within a reasonable amount of time without the use of adding heuristics or dynamically pre-generate routes should be possible. However, if one is considering handling larger problem instances where for example the storage unit should be used for more than one field and there are many installations to service, many locations possible locations for the storage units or having more than one set of storage units in use the problem might be too big to solve for optimality within a time limit. Then it could be investigated the possibility of finding smarter solutions methods that can reduce the time to solve it and with an optimality gap that is within a reasonable size.

Here the same solution method with the same route generation procedure as the standard supply vessel planning problem extended with a new index for the possible locations of the storage unit will be used.

4.3 Additional constraints

For the models in both for setups it is defined a number K of vessel types indexed by k. In an optimal solution we might want to have more than one vessel of a type. Therefore it is wanted to do small modifications to the models to ensure the possibility to use more than one vessel of each type. The number of vessels will be extended, and it will be a total of K multiplied with number of each vessel type we want in the model. As a result the size of the problem will increase significantly. For large problem sizes where many vessel types are considered, many installations to visit and also consider the location of the forward storage unit the time to solve the model might increase beyond reasonable limits.

All vessels of the same type are equal; meaning that vessels 1, 2, 3 and 4 of type 1 have the same specifications. When the solver in Xpress are solving this it has to go through all of these vessel types that are in reality equal, which causes the model to have longer running times. However, it is possible to exploit this symmetry of equal vessels when solving the model by adding new constraints to the problem. What can be done is to add a constraint that regulates number of routes in use for ship 2 of type k has to be less or equal the number of routes in use for ship 1 of type k. The same constraint has to be added up to where the number of routes in use for ship n of ship type k has to be less than the number of routes in use for ship n-1 of ship type k. The result of these constraint is that ship n of type k cannot be used before ship n-1 of type k has been used and we get a more constrained problem. All the vessels of same type have the same specifications, but the symmetry is now removed. This should give a great reduction in the solution time in Xpress.

$$\sum_{r \in R_{t_k l}} x_r^{t_k l} \leq \sum_{r \in R_{(t-1)_k l}} x_r^{(t-1)_k l}, \ \forall t_k \in T_k, \ 2 \leq |t_k| \leq T_k, \ r \in R_{kl}, \ l \in L \qquad (38)$$

In the constraint the new index t is the vessel number of type k.

For example these constraints have been benchmarked on a test case with 4 vessel types and 4 vessels of each type, 8 installations and 8 possible locations of the storage units. The model was not solved within 2 hours without the constraint, with the constraints the model was solved within 18.5 seconds. Hence there is a great benefit of adding the constraints and restricting the problem.

5 Collection of data

Most of data used for the models here are based on assumptions as the case with oil and gas activities close to Jan Mayen are some years into the future. However, for example the fleet of supply vessels and supply demand at the installations will be based on the current situation in the North- and Norwegian Sea. Both the case with the normal supply vessel planning problem and the case with the forward storage units will have the same data inputs, regarding supply vessels and supply demand at the installations. The accuracy of the data should be good enough to make a general case to see if it, from an economical perspective, is profitable to use forward storage units as described here.

5.1 Fleet of supply vessels

Platform supply vessels are ships designed to carry supplies to offshore installations from a supply depot. PSVs have a large open deck area aft on which containers, pipes and other cargo can be stored. The capacity of the deck area is limited to the number of square meters and the maximum load per square meter the deck can handle. Below the deck miscellaneous internal tanks are located to transport among others dry bulk, mud, brine, fuel, drill water and drinking water to the offshore installations. A standard PSV has a very familiar design and is easy to recognize, however the sizes of the ships are within a wider range. The largest PSVs built today have a length overall of around 100 meters, and have a maximum deadweight of around 6500 dwt. It is normal that the ships are designed for a speed around 12 knots and have a diesel electric propulsion system. Typical operations for a platform supply vessel are loading cargo at an onshore depot, steaming to an offshore installation, offloading and steaming back to the depot. Offloading cargo at the installations require a dynamic positioning (DP) system to avoid collision with the rig. Some vessels are also used in stand-by oil spill emergency response operations at the oil fields.

The input data for the mathematical formulation of the models in Mosel/Xpress requires a set of PSVs to choose from. Optimizing the models based on cost might prove to give better results with a diversified fleet of vessels. A diversified fleet of vessels means that the available ships vary in size and cost. The fleet of PSVs can stay the same for the calculations of the different setups or scenarios, but the ones that are picked for the optimal solution are likely to change based on the case that is looked at.

The main cost driver for a PSV is the day rates, these can as mentioned account to tens of thousands USD per day depending mainly on size. When the term size is used here it has the meaning of available storage capacities for deck cargo and miscellaneous tank capacities. Both Fagerholt and Lindstad (2000) and Halvorsen-Weare et al. (2012) has found that for the supply vessel planning problem the capacity for delivering deck cargo is the limiting factor for the storage capacity. There is in almost all cases enough bulk tank capacity to supply the demand at the installation, making the deck capacity the binding constraint.

The other cost driver that will be taken into account is the fuel consumption of the vessel. This will vary pending on the operation the vessel is in, for example the consumption in steaming, DP-mode or at quay will be different from each other. The route cost should be calculated based on the fuel consumption on the route. To simplify the calculations the fuel cost could be regarded as the time spent on the route (included loading/offloading times) multiplied with the fuel consumption during steaming as this will be the main contributor to the fuel consumption. This will probably provide a little higher cost estimate on the fuel consumption. It is preferred to have a safe estimate on the cost compared to a more detailed calculation that probably will provide a little lower fuel cost estimate. To not complicate the model it is assumed that all vessels will have a design speed of 12 knots, and the fuel consumption at this speed is used. PSVs usually use MDO or MGO as fuel, in a few cases there are PSVs running on LNG. In the future it is likely that there will be more LNG driven PSVs due to environmental requirements from both operators and governments. The MARPOL conventions are setting the requirements for pollution from ships(IMO, 2011). For the purpose of this study it is assumed that all ships will be using MDO or MGO as it is easier to find information regarding fuel consumption and prices. But one should keep in mind that the trend is more supply vessels running on LNG. Especially in arctic regions and emission control areas (ECAs) the environmental requirements are likely to be strict and LNG fueled vessels might be necessary. On www.bunkerworld.com(10.04.2013) the fuel prices for MDO and MGO are found to be in the area around 900 USD per metric ton. This fuel price will be used in the calculations.

Regarding the deck cargo it is important that it is properly secured on the deck so that it is sea safe. Another aspect is that the cargo should not be stacked too high and the center of gravity of the cargo has to be kept below a certain limit depending on the vessel. This is with respect to the stability of the vessel. However, it is unlikely that this will be a problem due to the design of the vessel and the shape of the cargo and it will be assumed here that the cargo is stored in a proper way both in regards to stability of the vessel and keeping it at place. Some cargo is not possible to stack on top of each other and the cargo is usually not stacked higher than the railings of the ship. The weight limitation of deck cargo per square meter is assumed to not be relevant for the calculations here.

PSVs are not only designed to perform deliveries to the installations, they should in addition be able pick up the back flow of cargo from the platforms according to Aas et al. (2007). This means that the available capacity after a delivery is performed should be large enough to take up back flow of cargo. In most situations this is not a concern. Adding additional information to the model regarding pick up of goods is complicating the problem when looking at a whole fleet of vessels and is not the objective here. If this was considered in the model it would have been a variant of the vehicle routing problem with pick-up and delivery (VRPPD). The problem discussed by Aas et al. (2007) are more regarding visiting sequence based on the back flow of cargo in addition to the delivery to the installations. This is a problem on an operational planning level while we here are looking at a tactical and strategic planning level. It is therefore not taken into account in this study.

Here a relative modern fleet will be used as a basis as one is likely to have requirements from the operator of the field regarding the age of the vessels and their technical aspects. Another argument for looking at modern fleet of vessels is that the location of the installations will be in an area with rough weather and safe and efficient operation is a requirement. Many of the Norwegian ship owners whom have platform supply vessels have published technical aspects of their ships at their website that can be used as a basis for the fleet here. The fleet used as a basis here is ranging in deck size from 620 to 1176 square meters. The charter rates are based on the spot rates published on www.seabrokers.co.uk. Spot rates tend to vary through the year normally with a peak in the summer and the lowest rates during the winter months. The rates that have been used as basis for making an estimate of the charter rates here are to be seen in Appendix 5. PSVs are here expected to be on long term charter rates and their rates are not fluctuating like the spot rates. The spot rates that are used as basis for the long term charter rates are from 2011 and 2012 and are average numbers for the vessels above and below 800 square meters. A rate for the cheapest ship are set to 17 000 USD per day and the highest at 35 000 USD per day. To make an estimate of the charter rates for the rest of the vessels it is assumed that there is a linear function between the lowest and highest rates depending only on the size (deck area size in m^2) of the vessels, this graph is presented in Appendix 5. In reality the rates would depend on several factors, like age, fuel consumption, bulk capacities and most importantly what specifications the oil companies are looking for, but it is made a simplification here to get an estimate of each of them. The rates used here are relatively high in the spot market and long term charter rates could be lower than these. It is preferred to have a conservative estimate on the rates and not too low.

PSV data	1	2	3	4	5	6	7	8	9	10
Main Dimensions										
LOA [m]	69.5	73.4	78.6	81.7	85.65	86.2	91.6	93.6	92.8	96.9
Breath Moulded [m]	16.4	16.6	17.6	18	19.7	19	22	19.7	19.6	21
Draught (max) [m]	6.3	6.425	6.5	6.5	6.2	6.66	7.2	6.3	6.5	7
Cargo related specifications										
Deck cargo [t] (VCG 1 m above main deck)	1600	1600	2500	2500	3164	2700	3200			3400
Deck area [m2]	620	703	800	810	941	978	1022	1046	1082	1176
Deck strength [t/m2]	5	5	5	10	5	10	10	10	10	10
Deadweight [t]	2946	3628	3787	4000	4150	4929	5800	4785	4976	4600
Other data										
Fuel oil capacity [m3]	1055		910		1230			1140	711	1167
Fuel consumption 12kn [m3/24h]	11	10	9.1	11	15	13.2	14	10.2	11.5	12
Built	2006	2006	2009	2013	2005	2003	2012	2008	2012	2008
Day rate [USD]	17000	19687	22827	23151	27392	28590	30014	30791	31597	35000

Table 5 - Overview of PSV data. Underlined parameters are relevant to use in the model. The data is collected from the website of various Norwegian ship owners.

Only the parameters for deck area size, fuel consumption and day rates for the PSVs are relevant as input data for the model. These data should give a good variation of available supply vessels for the model. Having many different vessels to choose from might give better solutions than a small set of vessels to choose from as it might be possible to exploit benefits of having smaller or larger vessels in the solution. Having only large expensive vessels that are not utilizing all their capacity are not efficient when smaller vessels could have done the same job at a lower cost.

5.2 Supply demand at the installations

The supply demand at an offshore installation is connected to the operating state of the platform. Here the operating states can be separated into exploration-drilling and production. The supply demand will also depend of the activity level at the installation, measured in square meters of deck cargo for each installation. Within a given operating state at the platform the cargo demand will vary from day to day and week to week. In other words the cargo demand is not fixed and the demand pattern is not easy to predict in detail for a longer time period. We are looking at the problem from a tactical and strategic planning level, meaning that we will deploy a fleet of vessels to supply the installations for a given time period. The individual cargo demand specified shortly before a supply service is performed is within the operational planning level scope. A tactical planning level should however provide routes/results that could be used as a basis for the supply service; of course minor changes can occur depending on the day to day changes in demand. To handle the demand peaks at a tactical planning level the demand quantities are set to 150 % of the average demand, which is the same practice as by Fagerholt and Lindstad (2000) to get a more robust routing policy and to handle the demand peaks.

As mentioned in chapter 3 it is expected that full production in all three location will start in year 2033 with two FPSO units and one FLNG unit. This will be the first case to study and here the operating state is production. A set of basic supply demand have been given by Professor Bjørn Egil Asbjørnslett for analytical purposes and is not time related. These sets of demands will be used as a basis here, and are given in average tones of deck cargo per visit for the installations. The size of the cargo deck area in square meters of a PSV is the limiting factor for the supply service. In the data set the number of tones was converted into square meters by using a conversion factor of 0.56 tones per square meter, then this was multiplied with the average number of visits per week to get the supply demand of deck cargo per week for each installation. The average number of visits varied between 2.7 and 4.6 visits per week in the production state. Based on these numbers and the numbers presented by Fagerholt and Lindstad (2000) and Halvorsen-Weare et al. (2012) an installation should have between 2 and 5 visits per week. Only visiting twice per week will result in more cargo per visit and opposite for 5 visits per week. The average supply demand in square meters varied between 118 and 571 for the platforms in production state depending on the current activity level. To handle the demand peaks we say that the weekly demand should be 750 m^2. The supply demand data that has been used as a basis are listed in Appendix 6.

The aim is to find the cheapest solution of the normal supply vessel planning problem supplied from land and compare this to the scenarios with the forward floating storage unit. For the case where the installations are serviced directly from the land depot, it is anticipated that a visiting frequency as low as possible gives the best solution. This will result in fewer, but larger vessels in operation and will probably give a lower overall cost if one can reduce the number of ships in operation. In the other case with the use of a forward floating storage unit, higher visiting frequencies might be give good solutions. For the purpose of this thesis we set that all installation will require 3 weekly visits. This means that in each visit it must be delivered 250 m^2 of deck cargo.

In a real case it is likely that the required number of weekly visits and supply demand are varying between the installations. These numbers can vary from week to week and there can be some changes in the optimal solution from time to time. The model here is suitable for different input data, but the ones described above will be used as a basis here for the supply demand.

5.3 Possible locations for the forward storage unit

The ships operating as forward storage units have to sail to the location it is operating at by its own engine power. This means that there could be some difference in the cost of the unit on the different locations. However, it is deemed fair to assume that these differences in fuel cost should be small when looking at the total cost of the units. The cost of the storage units is therefore assumed to be the same independent on the location. In the total cost of the storage units the fuel cost should be considered, but in the calculations all will have the same fuel cost. In chapter 7.6 the cost of having each storage unit is found to be 53 000 USD per day.

The main objective of the problem at hand is to find the cheapest overall cost for the supply service for the installations at the oil field. Since the cost of the storage units is independent of the location, the objective will be to find the location that gives that lowest cost of the supply vessels in operation. This means that the optimal location will probably be close to the installations and within the area between the installations. Figure 8 shows the set of possible locations for the basis case with three units in production. The distances between the locations and the installations can be found in Appendix 2, all distance data is gathered from http://www.sea-seek.com/tools/tools.php.

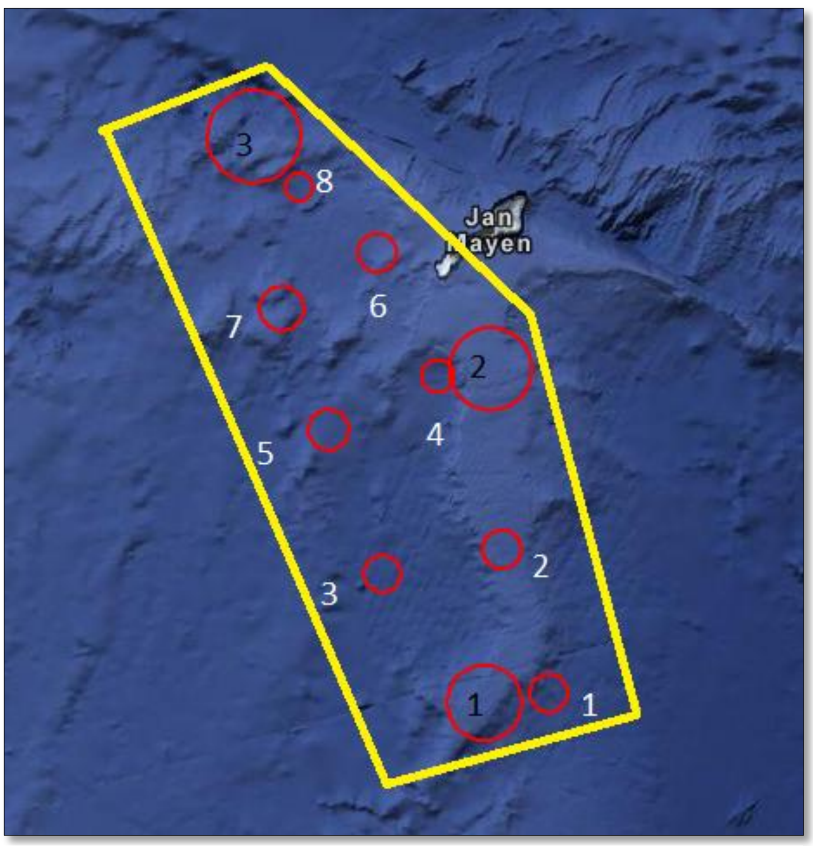

Figure 8 - Set of possible locations for the storage units for the basis case, marked with small red rings

All the possible location can be seen in Figure 8. The same locations will be used for the cases with more installations. It could have been added many more possible locations to the problem, this would increase the solution time but would not have a big effect of the overall cost of the system we are looking at. The scope of the current thesis does not include the exact position of the forward storage units. Adding many more possible locations to get a more detailed solution are only time consuming and do probably only give small cost savings in the objective function.

In chapter 7.5.5 the risks of having the storage unit located in the oil field with regards to collision risk with platforms is assessed. As a result there might be locations that are unsuitable to have the storage units and one might be required to keep a minimum distance to installations and consider weather directions. This is not considered in the model, but is noted.

5.4 Time aspects

The supply vessel planning problem is usually solved for one week. However, in the case for remote areas as here the sailing time in each direction might be over 2 days. For example the closest installation at Jan Mayen will have a sailing time of 44 hours from the land depot in Kristiansund with a sailing speed of twelve knots. The result of this is that each vessel can at most make one trip per week, and the model might engage more vessels than what is necessary. It could therefore be more realistic to look at a two week planning horizon, and then each vessel might be better utilized in the model.

The aim of increasing the time period is to exploit the slack of the routes and to provide an extra trip. When running the model for the normal supply vessel planning problem one gets the same solutions for both a weekly and two week planning horizons. The reason for this is that the routes that visit the most installations takes around 130 hours and has a slack of around 38 hours per week. To get an extra trip out of the slack one has to use at least a 4 week planning period. It is preferred to have a robust solution and have some slack on the routes to be able to handle delays due to weather limitations. The routes that only visit one or two installations might be able to get an extra trip out of having a 2 week time period in the model. However these routes are not likely to be picked in an optimal solution as they are not exploiting the full capacity of the vessel and it is preferred to visits as many installations as possible on one trip due to the long sailing distances. The conclusion will be to have a 1 week planning period in the model for the normal supply vessel planning problem. If a longer planning period is desired it should include restrictions in the model to ensure spread of departures as the distribution of the routes will be harder to find manually. Hence the model by Halvorsen-Weare et al. (2012) could be used in that case as one will get the required spread of departures. The model by Fagerholt and Lindstad (2000) is good enough to provide a solution to the current scope.

In the case with the forward storage units it is also deemed sufficient to look at a one week planning period. Here the routes will have shorter sailing distances and it should be possible to do several trips for one vessel during a planning horizon of one week.

6 Results

Both of the mathematical models created for the two setups (1)-(7) and (15)-(22) have been solved by implementing them into the optimization software Xpress IVE. The programming language used is Mosel. A general data file has been used as an input for the model files; there are a total of three model files. The model file for solving the TSP is connected to the route generation file and is loaded and run for each route when running the route generation model. When the route generation model is executed all the route data is included in a new file. When this is carried out, the main model file can be solved and the results are found. Figure 9 shows a schematic overview of how the different model files are connected to each other.

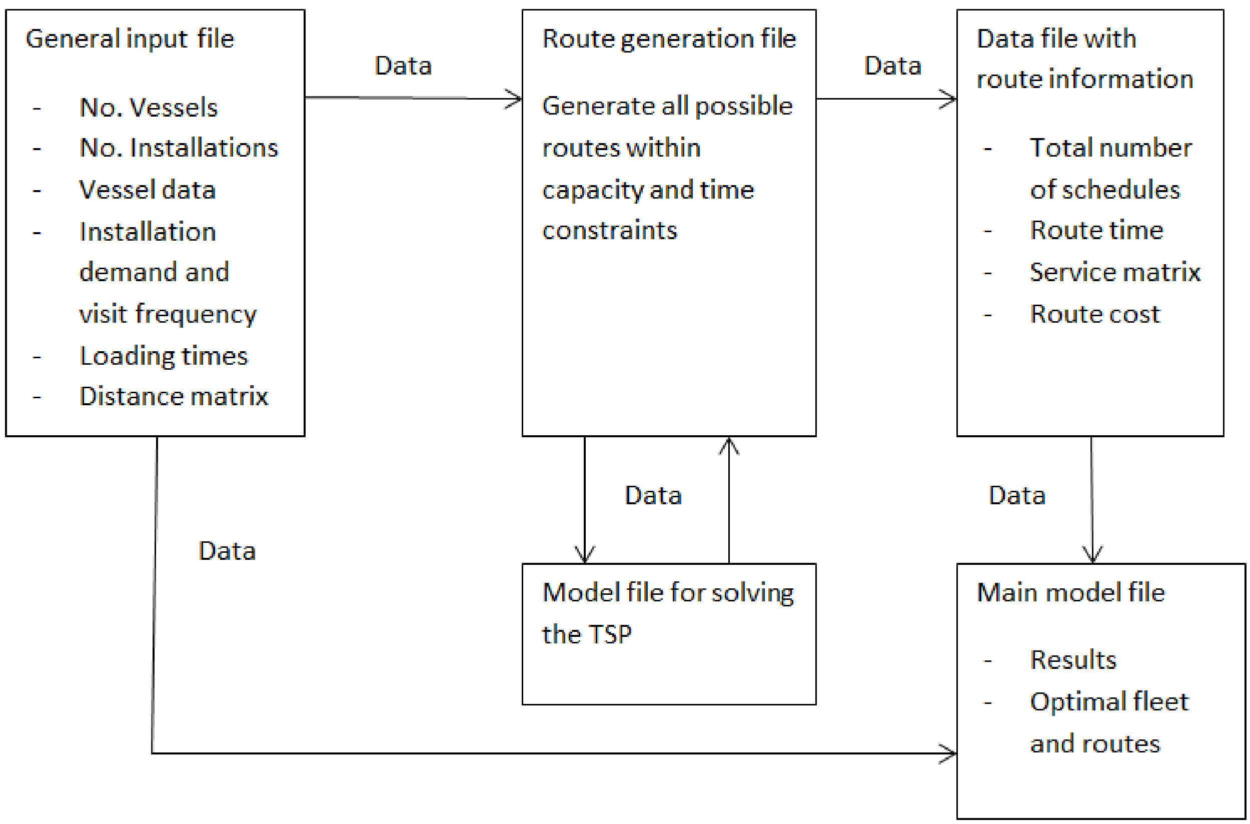

Figure 9 - Schematic overview of file structure and solution method

The model codes for solving setup 1 and 3 can be found in respectively Appendix 11 and Appendix 12.

6.1 Setup 1

The results from running the models for the normal supply vessel planning problem can be seen in the table below. Ship type numbers in all tables are corresponding to the ones presented in Table 5.

No. Inst.	No. vessels	Ship Types	Fuel cost	Charter cost	Total cost	Cost per installation	PSV sailing distance[nm]
3	3	(3x3)	111384	479374	590758	196919	4071
4	3	(3x8)	129142	646619	775761	193940	4080
5	4	(1x3)(3x8)	162065	806410	968475	193695	5236
6	5	(2x3)(3x8)	195828	966201	1162029	193672	6480
7	6	(3x3)(3x8)	228864	1125993	1354857	193551	7632
8	7	(4x3)(3x8)	260604	1285784	1546388	193299	8773

Table 6 - Main results from solving the model for setup 1. Costs are in USD.

The basis case with 3 installations get an overall cost of around 590 000 USD and the biggest case with 8 installations has an overall cost of around 1 550 000 USD. We can also see that the cost per installation of maintaining the supply service is fairly equal in all the cases. Due to the long distances one does not get an economic of scale with more installations to service. The results show that ship type 3 and 8 are the ones that will be most frequently used with the data input here. In Table 6 the ship types can be read out from the third column, for example (4x3) and (3x8) tell that there will be used four ships of type 3 and three ships of type 8. The increase in sailing distance is fairly equal when increasing the problem with one installation as one is likely to only put in one extra vessel to be able to supply the demand.

No. Installations	Route 1	Route 2	Route 3	Route 4	Route 5	Route 6	Route 7
3	34.917	34.917	34.917				
4	31.333	31.333	31.333				
5	47.167	31.417	32.417	32.667			
6	47.167	38.417	32.333	31.083	40.667		
7	47.25	47.25	47.25	32.75	32.75	32.75	
8	45.917	50.083	50.083	38.417	32.333	43.333	32.75

Table 7 - Time slack for each vessel/route in hours per week

Table 7 shows that all the vessels have between 31 and 50 hours of time not used in the solution. Some slack is wanted for a robust solution and to avoid big delays. The results show there should be enough slack in all cases. It is likely that the time slack would be smaller if the model was solved with time windows. Every vessel can only make 1 trip per week, without delays the vessels could start on a new trip after 6 days with no delays. In reality the cases with a higher number of installations might be possible to reduce with one ship as the total slack of the problem is high. However, this will not be further assessed.

No. Installations	Route generation [s]	Main model [s]	Variables	Constraints
3	1.13	0.06	312	113
4	4.15	0.07	584	114
5	6.17	0.25	1040	115
6	10.69	0.32	1760	116
7	18.78	0.41	2840	117
8	31.84	1.17	4392	118

Table 8 - Solution times and other solution data

Table 8 shows that the time to solve the models and generating the routes are short and not an issue for the problem sizes looked at here. The number of constraints does not get much larger with the number of installations; on the other hand we see that the number of variables increases drastically. The number of variables is connected to the number of routes generated. The number of routes generated is multiplied with the number of available vessels of a type, here set to 4, to get the number of routing variables. In addition there are the variables that decide if a vessel is in use or not.

No. Inst.	1	2	3	4	5	6	7	8	9	10	Total
3	6	6	7	7	7	7	7	7	7	7	68
4	10	10	14	14	14	14	15	15	15	15	136
5	15	15	25	25	25	25	30	30	30	30	250
6	21	21	41	41	41	41	56	56	56	56	430
7	28	28	63	63	63	63	98	98	98	98	700
8	36	36	92	92	92	92	162	162	162	162	1088

Table 9 - Number of routes generated for vessel 1 to 10 in each case

Table 9 shows the number of routes that has been generated for each vessel type in each case. All possible routes are generated, that is within the capacity and time constraints. The largest case will have a total of 1088 routes generated before solving the main model. The number of routes is growing almost exponentially with the number of installations. This is because with more installations to service there is an increasing number of possible ways to configure the routes. It is seen that with the supply demand data that is used and the capacities of the PSVs, vessel 1-2 can only visit two installations per route, vessel 3-6 can visit three installations and vessel 7-10 can visit 4 installations on one route. This is also the case for setup 3.

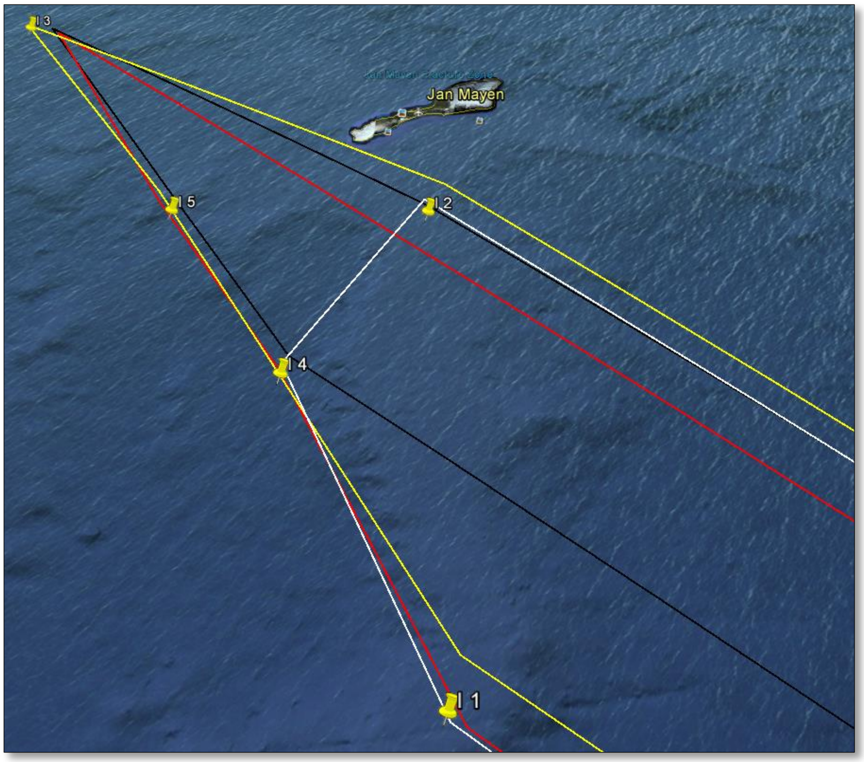

Figure 10 - Routing with 5 installations, made in Google Earth

Figure 10 shows how the optimal solution for a case with 5 installations will be routed on a map. The yellow route is for a ship of type 8 visiting 1, 2, 3 and 5. The black route is for a ship of type 8 visiting 2, 3, 4 and 5. The red route is for a ship of type 8 visiting 1, 3, 4 and 5. The white route is for a ship of type 3 visiting 1, 2 and 4. All the routes are sailing to and from the land depot in Kristiansund.

6.2 Setup 3

The main results from having the storage unit can be seen in the table below.

No. Inst.	Loc.	No. Vessels	Ship Types	Fuel cost	Charter cost	Storage cost	Total cost	Cost per inst.	No. Routes	Dist.
3	2	1	(1x1)	55262	119000	742000	916262	305421	5	1027
4	2	1	(1x3)	46288	159791	742000	948079	237020	4	1031
5	4	2	(2x1)	74556	238000	742000	1054556	210911	8	1128
6	4	2	(2x1)	83875	238000	742000	1063875	177313	9	1215
7	5	2	(2x1)	99237	238000	742000	1079237	154177	11	1418
8	5	2	(2x1)	109953	238000	742000	1089953	136244	12	1554

Table 10 - Main results from solving the model for setup 3. Costs are in USD.

The results in Table 10 show that the concept with storage units located at the field provide cheaper service per installation with an increasing number of installations to service. In all cases the cost of the storage unit is the main contributor to the overall cost. It is possible to supply the demand in all cases with only one or two vessels. Because only smaller vessels are preferred in the solution, it is necessary to have many routes per week for each vessel. The optimal location indicated in the second column is corresponding to the numbers presented in Figure 8.

No. Installations	1	2
3	6.46	
4	2.1	
5	75.25	42.75
6	44.67	46.08
7	4.42	41.42
8	12.67	1.83

Table 11 - Time slack for each vessel in hours per week

Table 11 shows that the time slack for some of the vessels in the cases with 3, 4, 7 and 8 installations are small. The model does not consider that the time slack should be of a certain size. These solutions should in a real case be adjusted so that the time slack should be increased, as a result one might need to use a vessel that could take more cargo on one route. The result of increasing the time slack is increased costs. In this case with 7 installations one of the vessels has a lot of slack while the other has almost none; this could be mended by giving some of the routes for the first ship to the other. In the cases with 3, 4 and 8 installations the ship size could be increased to increase the time slack of the vessels in use. This could be arranged in the model by either a tighter time constraint or reducing the large number M which is the maximum number of routes a vessel can sail.

No. Installations	Route generation	Main model	Variables	Constraints
3	9.17	5.57	2224	905
4	17.67	10.62	4400	913
5	49.87	25.63	8048	921
6	76.61	31.9	13808	929
7	145.76	33.4	22448	937
8	226.83	47.67	34864	945

Table 12 - Solution times and other solution data

The solution times of the models are relatively short and not an issue. However, the number of possible location for the storage units are relatively small and a high number would probably give much longer solution times. Number of variables and constraints compared to setup 1 is proportional to the number of locations for the storage units that are considered.

No. Installations	1	2	3	4	5	6	7	8	9	10	Total
3	48	48	56	56	56	56	56	56	56	56	544
4	80	80	112	112	112	112	120	120	120	120	1088
5	120	120	200	200	200	200	240	240	240	240	2000
6	168	168	328	328	328	328	448	448	448	448	3440
7	224	224	504	504	504	504	784	784	784	784	5600
8	288	288	736	736	736	736	1296	1296	1296	1296	8704

Table 13 - Number of routes generated for vessel 1 to 10 in each case

The number of generated schedules for each vessel compared to setup 1 is proportional to the number of possible locations of the storage units. The increase in the number of routes generated is also the cause for longer time for running the route generation model.

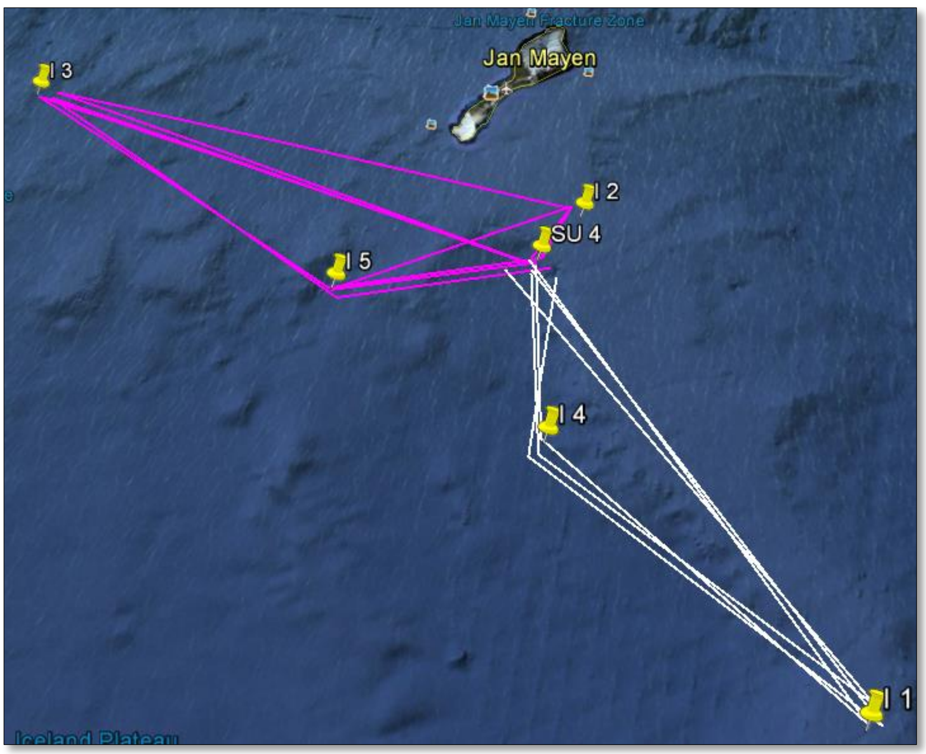

Figure 11 - Routing with 5 installations from the storage units, made in Google Earth

Figure 11 shows how the routes in the case with 5 installations can be serviced from the storage unit. The pink routing shows the routing of the first vessel and the white routing shows the routing of the other vessel. Both vessels are of the same type. Compared to setup 1 more routes are necessary, but the total sailing distances are shorter as one does not have to sail all the way from the land depot in Kristiansund; here they sail from the storage units that are located a location 4.

6.3 Adding robustness to setup 3

The cases for setup 3 with 3, 4 and 8 installations to service had little time slack in the optimal solution, i.e. they would have to run a very tight schedule and could be difficult due to external factors like weather conditions. It is desired to have robust routing that can handle reasonable delays. What has been done is to decrease the maximum number of routes per week a vessel can sail in order to force the model to choose larger or more than one vessel. This will lead to some increase in the overall cost of the supply service, but hopefully the increase might not be significant.

No. Inst.	Loc.	No. Vessels	Ship Types	Fuel cost	Charter cost	Storage cost	Total cost	Cost per Inst.	No. Routes
3	2	1	(1x3)	38430	159791	742000	940221	313407	3
4	2	1	(1x8)	46774	215540	742000	1004314	251079	3
5	4	2	(2x1)	74556	238000	742000	1054556	210911	8
6	4	2	(2x1)	83875	238000	742000	1063875	177313	9
7	5	2	(2x1)	99237	238000	742000	1079237	154177	8
8	5	2	(2x3)	75673	319583	742000	1137256	142157	8

Table 14 - New optimal solution for setup 3, costs are in USD

It can be seen from the results of Table 14 that the overall costs is increased for the three cases (3, 4 and 8 installations). The reason for this cost increase is that there have been used larger vessels in the optimal routing. The case with 3 installations uses ship type 3 instead of 1, with 4 installations ship type 8 is used instead of 3 and for 8 installations ship type 3 is used instead of type 1.

No. Installations	1	2
3	30.25	
4	19.5	
5	75.25	42.75
6	44.67	46.08
7	4.42	41.42
8	34.6	30.2

Table 15 - Time slack for each vessel in hours per week

Table 15 shows the new time slack for the vessels in the solutions. We can see that the total time slack is increased to get more robustness in the routing. For the case with 7 installations to service one of the vessels still has a low slack, but there could be a possibility to transfer some of the responsibilities of this vessel over to the other ship with more time slack.

6.4 Comparison setup 1 and 3

Table 16 shows the main results of setup 3 compared to the main results of setup 1 in percent. It shows how the storage unit affects the fuel costs and charter costs of the platform supply vessels. The effect on the total cost of the supply service is presented in next column, while the effect on the total sailing distance is presented in the last column. Based on these results the case with the storage unit is profitable with 6 installations or more.

No. Installations	Fuel cost PSVs	Chart cost PSVs	Total cost	Sailing dist.
3	34.5 %	33.3 %	159.2 %	25.2 %
4	36.2 %	33.3 %	129.5 %	25.3 %
5	46.0 %	29.5 %	108.9 %	21.5 %
6	42.8 %	24.6 %	91.6 %	18.8 %
7	43.4 %	21.1 %	79.7 %	18.6 %
8	29.0 %	24.9 %	73.5 %	17.7 %

Table 16 - Comparing main results for setup 3 against setup 1

Figure 12 compares the overall cost of the two setups from 3 and up to 8 installations to service. Setup 1 show a linearly growth while setup 3 only have a small increase in total cost when increasing the number of installations to supply.

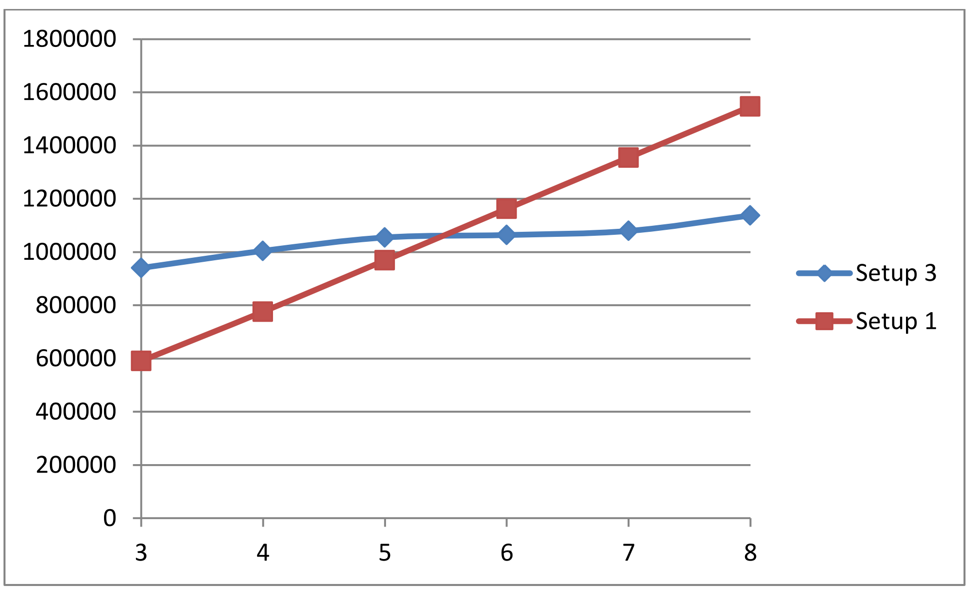

Figure 12 – Total cost of supply service (USD) versus number of installations to supply

6.5 Accuracy of results

The results are based on a general case based on assumptions when it comes to the supply demand of the installations. Actual supply demand at the installations may vary over time. Even if the data is not accurate and based on assumptions, the results should be able to identify if the storage units potentially could bring the cost of the supply service down.

The rates of the platform supply vessels used are based on spot rates and there are set a linear relation between cargo deck area and charter costs. In real life several other factors may apply. The rates that are used here may not be accurate, but as a basis for the general case they are deemed sufficient for cost estimates.

A case with storage units in use is highly dependent of the cost of having the storage units. The calculated cost for the storage units in chapter 7.6 are based on many assumptions and could be too high or too low. There has been attempted to make a conservative estimate to obtain a safety margin on the costs. The cost estimate is not based on very accurate data and is only a first and early estimate of what the cost of a storage unit would be. The technical specifications of the storage units are only studied briefly and there is therefore only possible to make a rough estimate of the price.

While the results might be improved with more accurate input data, they are deemed sufficient to make an estimate if it is beneficial to have to the storage units or not.

7 Ship technical issues

7.1 Vessel design

System based ship design is used to make basic design characteristics of the storage units. This means that the main dimensions should be designed around the technical specifications of the vessel. As a result the capabilities of the ship are to be determined first.

Mission →Function →Form → Performance → Economics

Table 17 - Main principles of system thinking(Levander, 2009)

Levander (2009) address mission and function of the vessel first. After the mission and function has been determined the design spiral can start including form, performance and economics. Compared to a general design process the design spiral is smaller and a smaller number of iteration is needed when performing system based ship design.

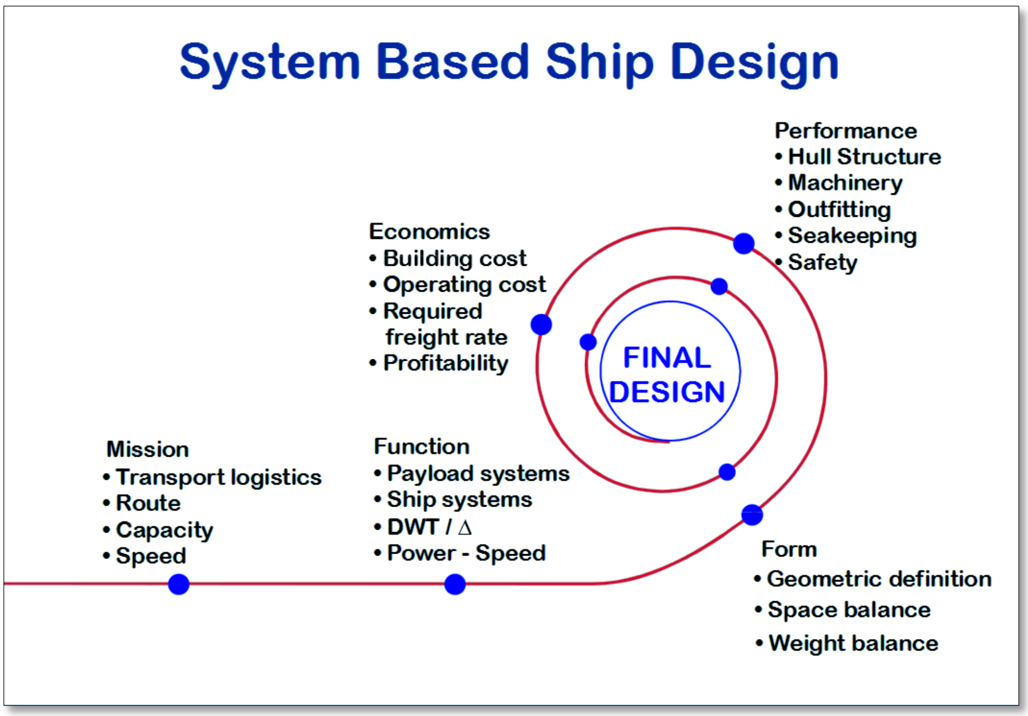

Figure 13 - Design process for system based ship design. Figure taken from (Levander, 2009)

The preferred option when building a forward storage unit with regards to cost is assumed to be the conversion of an existing tanker or bulk ship to get the wanted capabilities of the vessel. A new building project is usually significantly more expensive and with the current shipping market it should not be an issue to find cheap vessels that might be suitable for this. To find out what is the best solution and find out what work is necessary to do one has to study the required capabilities to have on the storage units.

7.2 Mission of storage unit

The mission of the vessel is quite simple. First the vessel will go to port and stock up on supplies, then sail to its wanted location stay there and deliver cargo to the supply vessels, after a given time period it sails back to port and stock up on new supplies. In this case the vessel will sail between Kristiansund and the oil field close to Jan Mayen, where it will stay in operation for 2 weeks. The vessel is not required to have a high maximum speed when sailing and a transit speed of 12 knots should be sufficient, and is the same as for PSVs. The sailing speed of the storage units is not assessed to be an important factor.

It could be expected that the storage unit is used for additional purposes. For example the vessel could be used as a base for emergency response, hospital, helicopter and oil recovery operations in addition to the supply operations. All these examples mentioned bring logistical challenges for the oil companies in remote areas. And having one combined solution for all of them could make the option with forward storage units more versatile.

As mentioned it is necessary to have two storage units switching position when one is running out of supplies. If we had a case where the storage unit was to stay in operation for a longer time period, say 4 weeks, then the vessel could operate as a regular cargo vessel in between the operation windows. This would of course depend of the length of the route it should sail. In this case it is assumed that the storage units are only used for the services around the oil field only.

7.2.1 Storage capacities

It might be a good starting point to assume that the storage capabilities of the forward storage units have to be similar of a PSV. This means that the storage unit should have designated tank volumes for bunkers for the PSVs, bunkers for own use, fuel for installations, fresh water, liquid mud, cement, base oil, methanol, dry bulk, oil recovery operations and internal ballast tanks. In addition the vessel needs to have designated areas for containerized cargo, miscellaneous equipment and pipes. It might be difficult to find ships for conversion that already have enough deck area for cargo and internal tanks to handle all these cargo types without doing extensive rebuilding work. If a conversion is too complicated and expensive the best option might be to build a new vessel that is purposed designed for this operation. For the purpose of this thesis it is only looked into the option of converting an existing cargo ship.

It is obvious that the vessels operating as forward storage units are required to have storage capabilities that are also matching the demand of the installations that will be serviced from them. It is preferred to have as few rush orders as possible from land to the installations offshore with cargo or equipment that cannot be found at the storage unit. Some rush order trips might occur as it can be difficult to plan ahead in 100 % detail what equipment and cargo that will be necessary to have in the upcoming weeks. For the bulk and general commodity cargoes it should however be relative easy to have a safety margin that ensures that one will not run out of these supplies. When it comes to special equipment and work tools that the offshore installations needs it might be harder to predict what is needed. One has to assume that some rush orders from land with equipment might be necessary, but this will not be considered in detail here. If the vessel should operate for more than two weeks at the time the number of rush orders are likely to rise as it is more difficult to plan for longer time periods.

To determine the cargo capacity of the storage unit one has to look at the supply demand to cover. It makes most sense to base the numbers for the storage capacity on the case study. It is assumed that the storage unit is to stay in operation for two weeks before heading back to shore and loading up on new supplies. The number of installations to service is maximum 8. To handle peak demands from installations in either drilling or production state we look at the average demand and add 50 % to handle peak demands and to also have a general safety margin. The supply demand data that has been used as a basis is presented in Appendix 6 and Appendix 8. These data show that it is during exploration drilling that the supply demand is highest and the supply demand during exploration drilling will therefore be used as the basis for deciding the storage capacity of the vessel. The aim of the forward floating storage units are to reduce the number of supply vessels in operations, it is therefore assumed that maximum 5 PSVs will operate from the unit.

Demand from installations	Average [tons]	Peak [tons]	Space requirements [m3]
Fuel	2618	3927	4980
Fresh water	4864	7296	7680
Liquid mud	4617	6925	6075
Cement	6400	9600	6737
Base oil	4800	7200	8916
Methanol	3200	4800	6316
Dry Bulk	1984	2976	1566
Deck cargo	6012	9018	32208
Total	34494	51742	74478

Table 18 - Cargo capacity for supply demand (drilling) at installations

The table above shows that vessels should have at least a cargo capacity of around 52 000 tons to handle the peak demand from the installations. The vessels need to have around 75 000 m^3 available cargo space. In addition the vessels need to have storage capacities to supply the PSVs with fuel, fresh water and general supplies and have storage capacities for internal use. This is estimated to be around 1 500 tons, see Appendix 8. When searching for a reference ship one should keep in mind that this ship should have sufficient deadweight to also support weight of adding new systems onboard, machinery upgrade and new steelwork to cargo holds and hull structure. To get an estimate of the additional steel weight the space requirements could be used as a basis. Levander (2009) indicates a coefficient of 0.075 ton/m^3 for hull structure for tankers. Assuming that there is structure in the old cargo holds on the ship that is going to be used; the coefficient is set to half of its original value to 0.0375 ton/m^3. This gives an additional steel weight of 2800 tons. If we choose a tanker for conversion this number might be a little high since tankers already have a lot of internal steel structure in the cargo holds. On the other hand if a bulk carrier with large open cargo holds is chosen for conversion this number should be more reasonable to use because a bulk ship will need more new steel structure.

7.2.2 Schedule

The normal schedule of the vessel can be divided into time in port, sailing time, time in DP and standby time at the oil field. It is assumed that the needed time in port to load the ship with cargo is 48 hours. The sailing distance will be around 600 nautical miles in each direction, some variations may occur due to changes in the optimal location. As a result there will be 50 hours of sailing in each direction; the total sailing time is 100 hours. The storage units should stay in operation for two weeks (336 hours) at the oil field supplying cargo to the PSVs. It is assumed that a cargo transfer between a PSV and the storage unit will take 8 hours and that only 1 PSV can be supplied at the time. If looking at the case with the maximum number of PSVs in operation, which is set to 5, and say that each of them will make about three trips per week we get a total of 30 cargo transfers in the two week period. This accounts to 240 hours that the storage unit will have to stay in DP mode, i.e. transferring cargo to the PSVs. The total time left in the two week operation window is 96 hours in which the storage unit is in standby mode, but the vessel may still have to do some maneuvering to stay within a specified area. The total time in DP calculated here represent a maximum case and the real case and with a lower number of installations to serve it will probably be fewer hours in DP mode. The schedule is presented by time in port, sailing time, DP mode and time in standby mode so that it is easy to make an estimate of the fuel consumption of the storage unit.

Schedule		
Time in port	48	[h]
Sailing time	100	[h]
DP mode	240	[h]
Standby mode	96	[h]
Total time	484	[h]
	20.2	[days]

Table 19 - Schedule for storage units

It is easy to see that with this time schedule (see also Figure 14) there will be a possibility for the two storage units to overlap each other. When one storage unit has finished its two week operation period at the oil field the other takes over. The time chart diagram below shows the schedule of the two storage units in operation. With the current schedule each vessel will have approximately 8 days (188 hours) with no activities. With this schedule it is unlikely to get any alternative tasks in periods not in operation. It could be investigated further how this free time could be exploited as to get the maximum utilization of the vessel, but this will not be studied here.

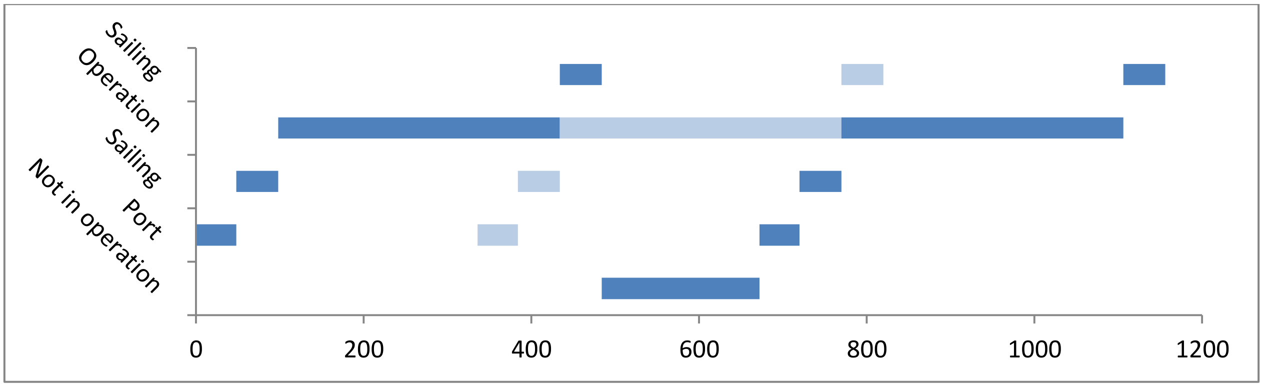

Figure 14 - Time chart diagram for the schedules of the storage units. Dark blue is the first vessel and light blue is the second vessel. The numbers on the x-axis are hours.

If it is considered to be collision risks with platforms it might be a requirement that the vessel should stay in DP mode at all times. But the results from Table 19 will be used to calculate the fuel consumption on one schedule.

7.3 Function of storage unit

7.3.1 Offshore loading/offloading

A critical part of the supply logistics offshore is to offload the cargo from the supply vessel to the installations. In addition to the procedure of offloading cargo in the normal supply vessel planning problem, one has to consider the operations of loading the supply vessels from the forward storage unit. It should be sufficient to assume that the requirements for a ship to ship transfer between a PSV and the forward storage unit should be the same as for the procedure between an installation and a PSV.

Figure 15 - Offloading operations from a PSV to Troll C. Figure taken (08.04.2013) from http://www.logistikkportalen.no

NORSOK r-003 chapter 6.1.5 is handling requirements for "loading and unloading of supply boat". It is important that the safety of the crew, equipment and cargo is maintained at all times.

"The NORSOK standards are developed by the Norwegian petroleum industry to ensure adequate safety, value adding and cost effectiveness for petroleum industry developments and operations. Furthermore, NORSOK standards are as far as possible intended to replace oil company specifications and serve as references in the authorities regulations".(StandardNorge, 2013)

Before the loading and unloading can start the following topics from NORSOK r-003 chapter 6.1.5 should be communicated between the vessel and the installation:

- *a review of the extent of the operation, positioning of load, backload etc.,*
- *bulk delivery, number of hoses that shall be used and need for manned crane,*
- *operational conditions that can create difficulties for the execution of the operation,*
- *any heavy lift or other loads that require special precautions, e.g. acid, isotopes etc.,*
- *any seafastenings,*
- *information exchange about personnel under training or other factors that shall be taken into consideration,*
- *transfer of material safety data sheets for loads requiring this.*

An important factor that must not be underestimated during loading and offloading operations is the weather conditions. Waves cause movements in the vessels and this can put people and equipment at risk. It is important that the cargo cranes are installed with a heave compensating system to cancel out the movements and to perform safe and efficient operations when lifting deck cargo. The PSVs have a dynamic positioning system installed which allows them to remain at a location and avoid collision. In the case with the forward floating storage unit, the converted cargo ships need a dynamic positioning system to avoid collision and keep the wanted position during operations. Hoses are used to perform the transfer of all bulk materials between the units, it is important that these are installed correctly and are designed to handle the cargo loads in the given weather conditions.

It is necessary to know the limitations of the weather conditions for when one can perform operations. NWEA Guidelines for the Safe Management of Offshore Supply and Rig Move Operations describe adverse weather conditions for leeside and weather side working.

Trigger	Precaution
Unfavorable Wind Direction	*No installation overboard venting or discharges whilst working supply vessels, unless previously agreed with vessel Master.*
20 knots mean wind speed at 10m level	*Secure loose items and advise greater caution to prevent injury to personnel and damage to equipment.*
20 - 25 knots Mean Wind Speed at 10m level	*OIM, Crane Operator and Master should evaluate the weather conditions and forecast. If necessary, a risk assessment should be carried out before commencing / continuing the operation. Consider vessel motion and potential cargo damage when reviewing prevailing weather conditions and immediate forecast.*
25-40 knots mean wind speed at 10m level	*Any operations in this range must only be carried out with full agreement of OIM, Crane Operator and Master. Weather conditions should be continuously monitored. NO7.*

Table 20 - Example of adverse wind conditions for leeside working with triggering conditions and precautions. Gathered from NWEA Guidelines.

Table 20 shows an example of adverse wind conditions for leeside working. Appendix 3 and 4 shows the overview for all the adverse weather working guidelines from the NWEA guidelines.

The storage unit vessels are not moored like a platform, and have to be able to remain at its position with a DP system during ship to ship transfer. One important requirement is that if thruster or propeller use is exceeding 45 % of propeller and/or thruster utilization during weather side working the master of the PSV will stop the operation. This means that the ships operating as forward storage units will be required to exceed the PSVs abilities to stay in DP.

A difference between doing offloading and loading from a rig (not FPSOs) and doing the same operations with a vessel (the forward storage unit) is that they behave differently in waves. A ship versus a rig has a high water plane area while for an example a semi-submersible platform has a low water plane area; as a result the ship has larger heave movements. This is important to remember when installing cranes on these ships; they will probably need a better heave compensating system compared to cranes on rigs. A ship also has a long ship's side that makes it very vulnerable to wind, currents and waves if not facing the bow in the direction of the weather. When performing loading and offloading between the PSVs and the storage unit the storage unit should direct the bow against the weather. In addition there are hydrodynamic ship to ship interactions that have to be considered.

PAFA (2001) address the opinions of the masters of PSVs of performing operations under tough weather conditions. The masters have to cope with commercial pressure from the oil companies to deliver their service, and at the same time they have to maintain the safety of the crew and vessel. In the end it is on the shoulders of the masters of the vessel to judge if it is safe to perform operations or not. An operation might be unsafe even if the weather at present is not as severe as in the guidelines due to several imposing weather conditions. The master of the vessel has the right to abort an operation at any time if he feels that the operation is not safe. A qualified and experienced crew both on the PSVs and the vessel operating as storage unit are therefore as important as any technical specifications of the vessels.

PAFA (2001) discuss the use of an on duty meteorologist to interpret and discuss the weather with the personnel onboard the vessels. *"The meteorologist are aware of the limitations of on-board weather sensors and the weather forecasts that apply to the area and use their own observations and experience to make appropriate corrections and allowances".(PAFA, 2001).* In arctic regions and in the case with Jan Mayen to have a meteorologist onboard the storage unit could be beneficial during winter months with rough and cold weather. This could be beneficial for the PSVs and the forward storage units.

7.3.2 Type of vessel to convert and storage systems

The storage capacities of the vessel show that it needs many different capabilities and will need designated spaces for the different cargo types. Each cargo hold will require different capabilities regarding strengthening of the structure around and for the system needed for efficiently loading and offloading. It is preferred to find a vessel that can be converted to a storage unit where the end product fulfills the design requirements and the overall costs are as low as possible. It is then necessary to find a balance between the original cost of the vessel and the cost of the conversion work.

There are two types of ships that might be suitable for the mission of the storage units, which are tankers and open hatch bulk carriers. These are relatively simple vessels with a lot of storage space and they are usually designed for relatively low speeds. Both of the vessel types have a similar hull design and have therefore relatively equal behaviors in waves.

The cargo holds on an open hatch bulk carrier has a large opening, is easy to access and has a simple cubic form. If to convert an open hatch bulk carrier there has to be done extensive work to the cargo holds to build internal tanks for the different liquid cargo. In addition there have to be installed pumps and hoses that can be used to load and discharge cargo. It might be necessary to have designated pumps of each type of cargo. It is preferred to build the internal tanks in the bottom of the cargo holds and as low as possible in the ship to exploit as much of the cargo holds as possible and to keep the center of gravity low. If not all of the “deck cargo” can be stored in the open deck area on the ship some, or all, of the “deck cargo” is to be stored in the cargo holds and new decks have to be built above the tanks. One has to make some modifications to the holds so the cargo can be loaded and unloaded easily. It might be an option to build several decks in the cargo holds where “deck cargo” is stored. The cargo holds will have to be available for the cranes on the vessel to load and offload the cargo. If there are several cargo decks it might be an idea to have a hoist able lift, or other system, for the cargo. Open hatch bulk carriers usually have cranes on the deck for loading and unloading of its own cargo efficiently. It would be preferable to use a ship that has already cranes onboard because then there are already made sufficient strengthening to the hull side and deck for crane operations. However, it might be necessary to sell these cranes as these are not likely to have a sufficient heave compensating system. When the storage unit discharge cargo offshore movements may arise in the ship, due to waves and shift in gravity center. Heave compensating cranes are therefore necessary and should be bought for safe and efficient loading and unloading for the cargo. Old existing cranes on the ship are likely to have a much larger lifting capacity than needed for lifting containers, pipes and other cargo for the supply service. The new heave compensating cranes might not have to be of the same size and it should be possible to get a good second hand price for the old cranes. It is assumed that there is no additional cost for cranes if using an open hatch bulk carrier with existing cranes.

Conversion of tankers may have some different concerns. If to convert a tanker and there is not enough space at the open deck area to store all the “deck cargo” it has to be done modifications to the cargo hold structure to make it possible to store the “deck cargo” under deck. This will require extensive rebuilding work to the existing cargo holds and one might need to build new tanks for bulk cargo after this is done. Tankers are rarely built with own cargo cranes as this is not necessary for liquid cargo. New cranes are needed and in addition strengthening work around the deck and hull side for the cranes is required. On PSVs the bulk cargo is loaded into special tanks depending on the cargo type, it might be necessary to do some minor changes to the existing tanks to make them suited for the different cargoes. It should be sufficient pump capacities already onboard a tank ship for loading and unloading of bulk cargo.

In both cases the open deck area might need strengthening to support the weight of the "deck cargo". Neither of the ship types is designed to have cargo on the open deck area. When comparing bulkers and tankers for conversion to storage units it is desired to get the lowest overall cost of the project and at the same time to fulfill the design requirements. Based on the numbers from UNCTAD (2012) they have a fairly equal price in the second hand market. This may however change due to market fluctuations and the conversion cost should be evaluated for both of the vessel types instead. The great advantage with the open hatch bulk carriers are that they have large open cargo holds and it should be easy to make the rebuilding work as wanted. A tanker on the other hand already has a more advanced cargo hold structure with different tanks and it might be difficult to make the new design as pleased. The bulk carriers already have crane systems onboard, while tankers have pumps. When it comes to installing new systems on the ships like DP system, hospital and emergency response equipment they should have a fairly equal amount of work that has to be done. The conclusion is to base which ship type to convert on the amount of steelwork that has to be done. It is easier to fit new work on open hatch bulk carrier compared to tankers. Open hatch bulk carriers are the preferred choice for conversion.

7.3.3 Cargo considerations

The containerized cargo can be stored on top of each other. In holds with containerized cargo there should be made slots where they could be stored, see example in Figure 16. Back load of cargo also need considerations. Having a system for the cargo that makes this possible without having to shuffle the cargo around is needed. Standardizing all containers that are going in and out of the cargo holds could make the work more efficient. It might be possible to store other deck cargoes like pipes directly in the cargo holds, but it is important that they can easily and safely be unloaded by onboard cranes.

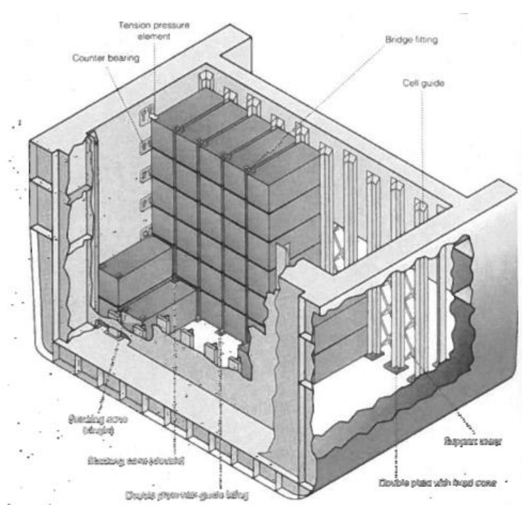

Figure 16 - Cargo hold for containerized cargo(Levander, 2009)

It might be preferred to avoid green water on the cargo deck if some of the cargo is stored on an open deck area, this may of course be dependent of the cargo type. The characteristic design of the PSV with the high bridge and wheelhouse in the bow is ensuring that the deck cargo is not hit by water when in heavy waves. Typical cargo vessels are normally designed with the wheelhouse and bridge aft and are therefore more vulnerable to green water. It should not be a problem for containerized cargo or pipes to be hit by some green water and it should be without problems to store this type of cargo on an open deck area. On the other hand equipment and other sensitive cargo might be necessary to store below the open deck area if not stored in containers. Another possibility is to have some superstructure above some of the deck area to avoid it. If new build is considered and not a conversion of existing cargo vessel it might be a point to have the superstructure and bridge in the front part of the vessel to minimize green water.

Figure 17 - Storage of containers and pipes on PSV deck, Skandi Waveney and Skandi Rona. Figures taken from www.dof.no (11.04.2013)

If the forward floating storage unit is operating in an Arctic area like in the case with Jan Mayen, green water is not the only concern regarding cargo at an open deck area. The other issue is icing on the ship and how this affects the cargo that is stored at the open deck area. If this is a problem for the pipes or some containerized cargo, a superstructure might be needed for protection from the surroundings. In addition to icing on cargo, Statoil (2013) identifies several other hazards related to icing. Icing can make operational equipment unavailable, disable communication antennas, make ladders or gangways slippery, it can put emergency equipment out of operation and it can cause stability concerns. Statoil (2013) identifies several risk mitigation actions with regards to icing. The ones that can be relevant here are adjusting speed or heading, physical or chemical removal, shielding equipment or cargo, preventive coatings and heating.

To simplify the design issues and avoid any concerns of having cargo on the open deck area it is assumed that all cargo is stored within the cargo holds of the vessel.

7.3.4 Other functions

As mentioned before the vessel should have functions regarding emergency oil spill equipment, hospital capabilities and helicopter deck. These functions and the technical solutions will not be studied in detail here, but could be important to have onboard. Equipment for oil spill response should be easy to access and might be stored on deck with a superstructure over it. A hospital area should be considered in the accommodation area and it might be necessary to do some modifications. The helicopter deck could either be placed in the bow of the vessel or behind and above the accommodations. It is important to have sufficient fuel capacity to supply the demand from helicopters. Possibly the storage units could supply other vessels in the area with general supplies and fuel, like construction and anchor handling vessels. These ideas could be worked on further in other works or in a more detailed design process.

Compared to a normal bulk carrier the forward storage units might require a larger crew to support the new capabilities of the vessel. It might be necessary to do some adjustment to the accommodation area to support a larger crew. It could also be a possibility that the storage unit could operate as a hotel for rig workers while waiting for helicopter transport to and from shore, but this will not be studied here.

Even though it is assumed ice free conditions in the case with Jan Mayen, the PSVs and the forward storage unit will be operating in an arctic climate and having an ice class on the vessels might be necessary. This means that if the ship that is to be converted to a storage unit and does not already have an ice class it is necessary to strengthen the hull of the vessel. If the vessels is to have an ice class one has to use the Finish-Swedish ice class rules(FSICR, 2008) to assess what strengthening that has to be done. This will not be looked into in detail here, but it is noted that a storage unit operating in an arctic environment is likely to need ice strengthening and other equipment to fulfill an ice class.

7.4 Main dimensions

In chapter 7.2.1 it was estimated that the reference ship needed deadweight for 52 000 tons to supply the installations, 1 500 tons for supplies to PSVs and own use and 2 800 tons for additional steel structure. In addition there has to be taken into consideration that the vessel is likely to require more machinery and some additional systems onboard. It is assumed that these unknown systems (helicopter deck and miscellaneous equipment) require around 1 000 tons. Added up the vessel used as a reference ship should have a deadweight of approximately 57 300 tons. The new deadweight for the converted ship will be 53 500 tons and 3 800 tons will have to be added on the lightweight of the ship.

Levander (2009) has published statistics for bulk ships based on data for many different vessels. From these statistics one can, based on the deadweight of the vessel, estimate gross tonnage volume distribution, displacement, deadweight/displacement, length, breadth, depth, draught, power, speed, lightweight and lightweight/volume. The graphs for this can be found in Appendix 7. These data are only estimates, but provides a good basis for making the design of the vessel and finding a ship that could be suited for conversion.

Basic design parameters		
loa	215	[m]
lpp	205	[m]
B	33	[m]
D	17	[m]
Tmax	13.5	[m]
Tcwl	12.5	[m]
DWT	57300	[ton]
Gross tonnage	40000	[100 cft]
Displacement	70000	[ton]
DWT/Displacement	0.84	[-]
Lightweight	12700	[ton]
Lightweight/Volume	0.095	[-]
Volume Distribution		
Cargo	85000	[m^3]
Ballast	20000	[m^3]
Other	25000	[m^3]

Table 21 - Basic design parameters for reference ship

The deadweight and lightweight of the converted ship will be respectively 53 500 and 16 500 tons. Sufficient space to allocate all the cargo is necessary, we saw in chapter 7.2.1 that the space requirement was 75 000 m3 while the ship to be converted are likely to have 85 000 m3 of cargo space. It is practicable to have a safety margin on the cargo volume as new tanks and cargo systems will require some space for the structure of the tanks and the strengthening of the hull.

A vessel that has some similar specifications as the ones estimated based on the statistical data by Levander (2009) and could be suitable for conversion is the vessel HK Challenger. This is an open hatch bulk carrier which has three existing cranes onboard and is used to carry wood. It has a deadweight of 58656 tons, a length overall of 210 meters, breadth of 36 meters and propulsion power of 9370 kW.

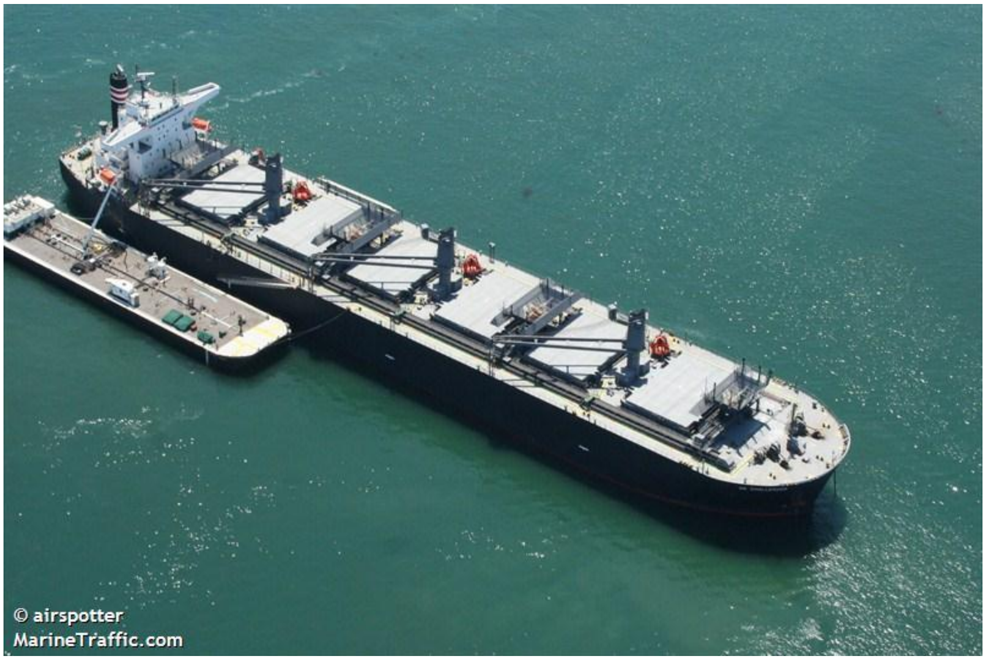

Figure 18 - Picture of HK challenger. Taken from http://www.marinetraffic.com/ais/jp/showallphotos.aspx?imo=9553127 (02.05.2013)

7.5 Performance

7.5.1 Conversion work

Conversion work is complicated and to make the conversion work efficient it is according to DNV (2013) important that Classification Society, yard and designer are working closely together. DNV (2013) also identifies the following challenges regarding the conversion work:

- *new structures and systems are blended with those already existing*
- *readability and availability of original documentation may be limited*
- *constantly developing Rules and Regulations requirements must be met*

For the discussed case the first and last point might bring the hardest challenges. It is necessary to make a lot of new steel structure for tanks and cargo decks and the changes made must at all times be up to date with rules and regulations.

To get a good start according to DNV (2013) a kick-off meeting should be held with the aim of:

- *exchange information: drawings, general arrangement and conversion specifications*
- *identify and discuss possible areas of concern focusing on the "way forward"*
- *develop the drawing approval schedule to match commercial requirements, and any concerns identified*

- *establish the extent of Class involvement, the required documentation for submittal and when this should be submitted*

It is important to get a classification society involved as early as possible in the conversion process. A yard that has experience in doing this type of work should be chosen and the quality of the work should be the highest priority.

In this case it will be done extensive rebuilding work in the cargo holds and engine rooms. This requires solid collaboration between the involved actors to make everything work out as well as according to rules and guidelines.

7.5.2 Propulsion and Auxiliary machinery estimates

Statistical data by Levander (2009) can be used to get an estimate of the necessary propulsion power and auxiliary power for the vessel. Based on the graphs attached in Appendix 7 the ship will need 10 MW of propulsion power and 2 MW of auxiliary power. The estimate of the propulsion power should be sufficiently accurate as there are no changes to the hull shape of the vessel. With this propulsion power the ship will have a top speed of 14.5 knots based on the statistical data by Levander (2009). In operation the vessel should operate on 80 % MCR (Maximum Continues Rating) to lower fuel consumption and maintenance costs. This gives a service speed of 12.8 knots, based on the formula below(Levander, 2009). The formula is multiplied with 1.15 to take a sea margin of 15 % into consideration.

$$P_{Service} = 1.15 \cdot P_{Max} \cdot (V_{Service} / V_{Max})^3 \quad (38)$$

The speed of the vessel was said to be of little of importance and the new service speed is therefore set to 12.8 knots. This will only have minor changes to the schedules already created.

The estimated auxiliary power of 2 MW might be too low due to new systems onboard. The vessel will require increased power consumption during DP operations; this will be discussed in chapter 7.5.3. There must be installed new generators and engines to support the power consumption and the switchboards might need upgrades. In addition it is assumed that the general energy needs onboard will get higher so a safety margin of 50 % will be added on the 2 MW, so there will be 3 MW for auxiliary systems plus the needed power for DP operations. For emergency power generation it is assumed that the existing unit on the ship to be converted has sufficient capacity.

7.5.3 Dynamic positioning system

For the specifications of the DP system onboard the storage units they are comparable with shuttle tankers that have a DP system installed. As mentioned bulk carriers have a similar design as tankers and have similar sea keeping abilities.

There are three equipment classes for dynamically positioning systems. IMO (1994) have made these equipment classes based on redundancy requirements.

Equipment class	Description
Equipment class 1	*Loss of position may occur in the event of a single fault.*
Equipment class 2	*Loss of position should not occur from a single fault of an active component or system such as generators, thruster, switchboards, remote controlled valves etc. But may occur after failure of a static component such as cables, pipes, manual valves etc.*
Equipment class 3	*Loss of position should not occur from any single failure including a completely burnt fire sub division or flooded watertight compartment.*

Table 22 - Requirements for DP system of class 1, 2 and 3(IMO, 1994)

According to IMCA (2007) most DP shuttle tanker are of DP class 1 or 2. The storage units are in this case to work in an area with weather conditions considered similar to the North Sea. Based on the known existing shuttle tanker operating in the North Sea today and due to harsh weather conditions, it is assumed that the storage units will require DP systems of equipment class 2. There has also since 2002 been a regulatory requirement that DP 2 shuttle tankers shall be used on all Norwegian oil fields(Vinnem, 2010b).

A DP-2 vessel needs to have three Positioning Reference systems. There should be two DGPS (Differential Global Positioning System) and a third system. According to Søberg (2013) there are challenges regarding DP systems in areas far north due to satellite coverage. The case with Jan Mayen is on the limit of what can be done regarding regular DP systems. When talking about remote areas it does not necessarily mean areas far north, it could also be other areas of interest, for example oil fields in Brazil far from shore, where there is no issues regarding DP systems.

Lauritzen tankers has two shuttle tankers, Dan Cisne and Dan Sabià, of size 59 000 DWT both installed with a DP-2 system(LauritzenTankers, 2013). These ships are installed with a bow thruster of 1720 kW, two retractable thrusters, one fore and one aft of 2150 kW. This adds up to a total of 6020 kW of propulsion power for the DP system, in addition the main propulsion system can be used. The main dimensions of the vessel are loa 207m, Breadth 32.20 m and scantling draft of 13.5 m. These are comparable to the dimensions of our forward storage unit, so it will be assumed that they will require the same propulsion powers as Dan Cisne and Dan Sabià.

7.5.4 Machinery summary

The machinery layout should be similar to shuttle tankers with DP capabilities, and the arrangement on Dan Sabià will be used as a basis to decide which components to include in the machinery layout. Dan Sabià has three main generator diesel engines of size 2970 kW, it is assumed that our ships that will be converted has the same engines for producing power in addition to the 10 MW size engine for propulsion power. Total auxiliary power equals 8910 kW, which is an increase for the bulk ship to be converted of almost 7000 kW. The size of the emergency generator diesel engine on Don Sabià is 1020 kW; it is assumed that our ships will have the same already installed onboard.

Component name	Estimated size [kW]
Auxiliary boiler, vertical shell type ASL (Aux Boiler/ Mission OL)	
Auxiliary boiler, composite ACU (Composite boiler/ Mission OC)	
Emergency generator diesel engine (Harbor)	1020
Intermediate shaft A	
Intermediate shaft F	
Main generator diesel engine C	2970
Main generator diesel engine P	2970
Main generator diesel engine S	2970
Maneuvering retractable azimuth thruster arrangement A	2150
Maneuvering retractable azimuth thruster arrangement F	2150
Maneuvering thruster electric power unit	
Maneuvering thruster electric power unit A	
Maneuvering thruster electric power unit F	
Maneuvering thruster, tunnel	1720
Propeller shaft arrangement	
Propeller, controllable pitch	
Propulsion diesel engine	10000
Steering gear	

Table 23 - Machinery summary, similar components as Dan Sabià. Source: http://exchange.dnv.com

7.5.5 Operational risks

Vinnem (2010a) looks at Norwegian platform collision statistics. Supply vessels were in the period 1975-2001 responsible for 63.4 % of the collision incidents, while standby vessel and other attending vessel accounted for respectively 15.6 % and 13.3 % of the incidents. The rest of the incidents were from passing and unspecified vessels.

When having large vessels (here storage units) located close to platforms at the oil field the collision risks with the platforms must be considered. There is also a risk of collision incidents to the storage unit, like there is for supply vessels to platforms. Here the latter will not be studied further as collision risk between supply vessels and the storage units could be considered in the same way as collision risk between a supply vessel and a platform or FPSO and should therefore be known. Here we will look at the new risks caused by having the storage units located at the oil field.

Storage units could be considered in the same manner as shuttle tankers at the field with regards to impact energy, as they are of similar sizes and shapes. In (Vinnem, 2010a) these type of vessels are considered as field related attendant vessel traffic. The storage unit will have two operational modes that should be considered. While in standby or at DP the vessel may lose engine power and start drifting and there is a collision risk when the vessel is sailing to and from the field.

The closest location to a platform that is considered for the calculations for the models in the case made in chapter 5.3 was 15 nautical miles. Most collision incidents for shuttle tankers and supply vessels occur while the ships operate in the vicinity of the platforms. The storage units should have no reason to operate in such a close vicinity to the platforms as shuttle tankers and supply vessels, and this type of collision incidents is assumed never to occur for the storage units.

Because shuttle tankers will be located on the leeward side while waiting for operations, Vinnem (2010a) finds the contribution from shuttle tankers to collision incidents as low during this mode. A part of the objective of this thesis was to find optimal locations for the storage units; this might not be in the leeward side of the weather. In the set of possible locations for the storage unit one might have to consider weather restrictions and statistics for most common wind directions.

Due to large displacement of the storage unit a collision during transit could be critical due to a high energy impact. According to Vinnem (2010a) semi-submersible platforms could have an energy absorption capacity in the area of 60 MJ. The following formula can be used to estimate the amount of kinetic energy of the storage unit that can be dissipated as strain energy:

$$E = \frac{1}{2}(m + a_m)v^2 \frac{\left(1 - \frac{v_i}{v_v}\right)}{1 + \frac{m + a_m}{M + A_m}} \qquad (39)$$

E = Kinetic energy

m = Vessel displacement

M = Installation displacement

A_m = Installation added mass

v_v = Vessel impact velocity

v_i = installation velocity after impact

Vinnem (2010a) finds the critical velocity based on this formula and a critical impact energy of 60 MJ. For a vessel of 50 000 dwt this gives a critical velocity of 1 m/s, so it is easily seen that almost any collision with a platform would result in global failure of the platform. Global failure is by Vinnem (2010a) defined as "*The impact leads to large deformations of the structure requiring personnel to evacuated and operations to be shut down*". It is however unlikely that such an event will occur. During transit to and from the field the crew should be aware of the platforms because they operate in the area all the time and there should be sufficient watch-keeping to avoid collisions. The ships should have course lines without platforms in the direct course line.

If the vessel loses engine power and starts drifting a critical velocity would in this case also be 1 m/s, which equals 1.94 knots. According to Vinnem (2010a) the vessel will get a mean drifting speed of 2 knots with wind speeds of 7 on the beaufort scale, which will result in a global failure during collision. Lower wind speeds might give critical velocities if wind a current work in the same direction. If the storage unit is located 15 nautical miles away from the platform and start drifting in the direction of the platform it will take 7.5 hours before the impact. It is very unlikely that one is drifting in the critical heading and hits the platform and is not able to perform preventive actions to avoid collisions. There should be available supply vessel or other offshore vessel in the vicinity available for towing operations. Summed up the storage unit need to lose maneuverability abilities and drift in the "correct" heading without preventive actions for an incident to occur. For the vessel to lose all maneuverability all thrusters have to be out of function which will only occur if the vessel has a total black out. ¨

The storage units do not need to be in the direct vicinity of the platforms and should have a very low probability of having any collision incidents with a rig. However collision risk between the storage units and supply vessels are more likely to occur and could be regarded as the same as between supply vessels and FPSOs.

7.6 Economics

Both the second hand prices of ships and conversion/building cost are following a volatile market. All amounts are based on estimates of the present value with safety margins.

In the offshore industry it is normal that the operators have long term charter arrangements with ship owners when they need a vessel. The operators hire vessels for a given period of time and the ship owner has the responsibility of the daily operation and manning of the ship. It is assumed that a ship owner will see the market opportunity by owning and chartering out forward storage units to the operators. It is therefore necessary to find the daily charter rate that a ship owner would require for the use of his vessels.

Pruyn (2012) are describing three standard types of charter contracts, bareboat charter, time charter and voyage charter. In the discussed case it is most likely that the storage unit will be hired on time charters to the operator. For this type of charter the charterer pays port fees and bunker costs in addition to the day rate the ship owner require. The ship owner has to make sure that he can cover maintenance, crew, interest and depreciation costs based on the day rate he is given, as well as ensuring a profit.

The price of the ship is calculated based on the price of the ship type on the second hand market and the rebuilding cost including new systems to be installed onboard. From the main dimensions, deadweight and performance it is possible to estimate a second hand price of a 5 year old ship. UNCTAD (2012) provides estimates of prices of bulk and tank ships in the second hand market in addition to estimates of operational costs. Shipping is a volatile business and the market moves in cycles. Since the financial crisis in 2008 the shipping market has been in distress and suffered from low rates. Second hand prices of vessels follows the general rates on the shipping market, in good times they are expensive and in bad times they are cheap. In many segments of the shipping market second hand prices has dropped with over 50 % since the financial crisis according to UNCTAD (2012). It is difficult to predict how the shipping market will develop in the future. If we take today's second hand prices as a basis for the cost of buying a storage unit it might be a little too low due to the poor shipping market, it will therefore be added 50 % to the second hand price to have a conservative estimate of the price. Based on the information by UNCTAD (2012) the second hand price of a bulker carrier of the given size should be around 25-30 M USD, to have pessimistic approach a second hand price of 30 M USD is used. It would be beneficial to buy the ships that are going to be converted when the market is low to keep the cost down, however this might not always be the case. With additional safety margin due to the volatile shipping market the buying price of the vessel could be estimated to 45 M USD.

Levander (2009) provides an example for a building cost estimate of container vessels. The estimate is based on material and labor costs, some of the coefficients and assumptions are adapted in this thesis. The cost and amount of work for the steel work and machinery is assumed to be the same. In addition there are used estimates on oil recovery equipment, helicopter deck and the cost of the DP system. In addition it is assumed a 50 % safety margin on both material and labor hours to have a conservative estimate. There are costs for making the design, financing, broker fees and profit to the yard that has to be taken into account in the price estimation. The calculations can be found in Appendix 9. The conversion of the vessel will cost approximately 68 M USD, giving a total investment cost of approximately 113 M USD per ship.

To get a required day rate for the vessel it is necessary to find the yearly costs of the vessel. Pruyn (2012) shows examples of how the required day rate can be calculated based on maintenance, manning, insurance, stores and lubrication oils, interest, depreciation and other costs. The investment costs are taken into account in the depreciation of the vessel. The port fees and bunker costs are added on top of the day rate when calculating the cost of having the storage units for the operators. A new built vessel today has normally an estimated life time of around 25 years, if we buy a 5 year old vessel in the second hand market it is assumed that it will have 20 years left in operation. The value of the vessels after they have been rebuilt will therefore be depreciated linearly over 20 years. It is assumed that the vessels will be financed partly by loan and partly by own capital, respectively 80 and 20 % is used in the calculations. The ship owner will also require a profit for his investment and it will therefore be necessary to add a profit margin on the costs of the ships of 20 %. This gives a total cost per day for each vessel at 53 000 USD, including both bunker expenses and port fees in addition to a day rate to the ship owner. The calculation can be found in Appendix 10, and the total cost of having the storage units will amount to 106 000 USD per day as one are required to have two units to keep continues service.

8 Discussion

One has to analyze all the involved factors to conclude if having the storage units is profitable. The number of installations to service seems to be an important factor when deciding if converted bulk ships could be used for storage units or not. It is possible to see from the results that the number of installations to supply has a great influence to the effect of having the storage units. The more installations to service the greater saving effects the setup will have. We saw in chapter 6.4 that for the cases with three to five units to supply the effect of having the storage units would have a negative effect on the total cost of the supply service. With 6 and more installations to service the effect of having the storage unit would be profitable.

Another factor that could affect the profit of having the storage units are distance to shore and a land depot. Longer distances mean that one can reduce the sailing time of the supply vessels drastically; hence it would give better results. The results are only found for one oil field and do not provide an answer to which effect the sailing distance has on the profit of having the storage units in general. The aim of the storage units is to reduce the sailing distances and the number of vessels in use. For cases closer to shore the savings potential is less compared to cases far from shore.

The purpose of the mathematical models solved was to estimate the cost of the supply-service with and without storage units located at the oil field. The cost estimates here have uncertainties, but as this is the first time this topic has been studied the aim is to see if the concept of having converted bulk ships as storage units could be a possibility and proposed for further studies. Confidence are given to the models, they make estimates for the cost of both the regular supply service and with the use of storage units. The formulation of the model and routing for the normal supply vessel planning problem is based on known work by Fagerholt and Lindstad (2000) which has proved to give cost reductions for oil companies in the North- and Norwegian Sea. The same model is extended in the case with the storage units and should give the same level of accuracy for the routing.

The operator of the oil field wants some robustness in the routing to avoid delays. Setup 1 provided good robustness and time slack in all cases. For setup 3 it was necessary to do some modification to improve the robustness of the routing. The level of robustness for the routing should be decided by the operator in a real case; here this is based on personal judgment. Adding robustness will affect the optimal solution, for the calculations here we saw only small increases in the total cost of the supply service due to the increased vessel sizes in the solutions. It could also have been possible to increase the robustness by adding more vessels, but this would probably give a larger increase in the overall costs.

The time slack of routes in setup 1 is very large, and it could maybe be possible to better the solutions with many installations to service. In the cases where the total slack of all the routes are larger than one route or a week, more efficient planning might be possible. This is difficult to handle in the optimization models. The length of the time period could be adjusted to six days and one would still get the same solution, although this would give less time slack for the routes. If one take the solutions and try to simulate how the routing will be over a longer time period it could have been seen if it is possible to reduce the number of ships in operation. However it should still be attempted to maintain the robustness of the solutions, i.e. have enough time slack to handle delays.

Time windows for the routing are not considered in this thesis. As a result one has a less restricted problem and it is easier to find robust solutions. Time windows would need some modifications in the route generation process. Including time windows might have given some higher total cost in both setups and would be negative for the robustness of the routing in both cases. Time windows have therefore not been considered as an important factor for this study.

In the optimal solutions for setup 1 it was preferred to use larger ships that could visit more installations on a single trip. For setup 3 the model seemed to prefer smaller and cheaper vessels and more trips to service all the installations. This is logical as for the cases where it is necessary to sail all the way from land it is wanted to visit as many installations as possible on the trip to get better utilization of the route. In cases with the storage units applied it is possible to supply the demand with smaller vessels as the PSVs sail much shorter distances and can make many trips per week. If there is many trips per week and the time slack is small, the number M (maximum number routes a vessel can sail) in the model can be reduced to increase the time slack.

In the calculations done here only eight possible locations have been considered for the location of the storage units. In a real situation more locations could have been considered. It would not have a great benefit for the objective of this thesis to include many more possible locations of the storage units, this would most likely only increase the solution times and have minor effects on the overall costs. If a better location could reduce the number of ships in operation then it could have been worth to consider more locations for the storage units. It should be kept in mind that the total time slack of the solution has to be large enough, finding better locations of the storage units might give better robustness to the routing.

In the input data used it was assumed that all installations would require 3 weekly visits to make a general case. If the number was higher it would probably result in more ships in operation and higher overall costs for the regular supply vessel planning problem. For the case with the storage units the increase in the overall costs would probably be lower. If it was only required two visits a week for the installations the overall costs for the supply service would be lower as one could reduce the number of vessels in operation, this would have the greatest effect on the regular supply vessel planning problem. We saw in chapter 5.2 that the average number of weekly visits for installations for a case varied between 2.7 and 4.6 over a few months. It should therefore be sufficient to assume that each installation will require 3 weekly visits. However, one should keep in mind if it is possible to only do two visits per week this would be preferred and could probably have a great cost reduction for the regular supply vessel planning problem.

The aim of the forward storage units was to reduce the cost of hiring expensive supply vessels. To make the case with the forward storage unit profitable the storage unit cannot be unreasonable expensive. This means that the technical requirements have to be met within a price range; the results for setup 3 showed that the cost of the storage units was the main contributor to the overall costs.

Here the technical details around the storage units have only been looked into briefly. This gives quite a big uncertainty around the actual cost of using the storage units. The practical appliance of the project looks to be feasible, and the technical issues that are looked into here is nothing that is more complicated than other existing technical solutions.

Ship owners are usually considered conservative when it comes to introducing new ideas and concepts for their business. There has to be a certain payoff/saving for introducing a new concept compared to the old and known systems. In this case it is the oil company that will have a saving for introducing the new concept as presented. This means that the cost benefit of having the storage unit must be of a significant scale for them to go through with the project. In addition the technical specification and limitations to the project have to be investigated in detail.

The oil companies have to set a demand that they really need the storage units and convince the ship owners to build them. Convincing relative conservative thinking ship owners to invest in a new type of project might be difficult and the oil companies might have to offer lucrative long term charter deals to start up the project.

There has to be sufficient oil and gas activities at remote locations so that the storage units will be used for their remaining life time. No ship owner will invest in buying and converting bulk ships unless they are safe to make money out of it. If the concept does not work out in practice it might result in great losses for the owner of the vessel. The investment cost in the storage units is high and the ships are designed for a specific task. It might be possible to use the converted ships on conventional trading routes. If the converted bulk ships were to operate on a regular trading route it might be difficult to utilize the full capacity of the vessels. The ship owner might get stuck with very expensive vessels that actually would be less efficient on regular trading routes than other cheaper open hatch bulk carriers. As a consequence the owner of the storage unit might be forced to sell them at much lower prices than they invested.

It should therefore be investigated alternative uses of the storage units to lower the risk for the owner if the project does not work out in practice.

One possible alternative use of the storage units if the project is not working out in practice could be to use them for transport of cargo to land depots. For example if the oil companies have one large central depot with a large storage capacity it can be used to transport cargo from this depot to other smaller ones. As a result all the depots would not require many different cargo transports and would only need supplies to be delivered to the central depot. For example if an oil company has a large supply base in Tananger, in addition to supply depots in Mongstad, Kristiansund and Hammerfest, the converted bulk ships could be used to transport cargo from the central depot in Tananger to the smaller ones.

The contribution of this thesis to the literature is a model for the supply service which takes into consideration the use of storage units and the location of them. A similar model has not been found in the literature, but the model created here is really only an extension of the model by Fagerholt and Lindstad (2000). The model formulated is different from the other facility location and location routing models from different industries that has been looked into. The formulation of the model for setup 3 provides more detailed routing than for example the facility location models by Lundgren et al. (2010) and Baldacci et al. (2011) and the covering model by Oran et al. (2012).

9 Conclusion

Based on the study performed here it can be concluded that the use of converting bulk ships to storage units could reduce the cost for the supply service at remote locations. This will depend on several factors; based on the results provided in this thesis the number of installations to service has a great impact to the average cost per installation. The cost of the storage units is important for the overall cost. The full effect of the distance to shore has not been found here, but this is an important factor for the overall cost. Longer distances to shore should have a great saving potential for the storage units as one can reduce the sailing distance further. The cost of the storage unit is fixed and the increase in cost of supplying more installations from the storage unit is only modest. The cost of the setup for the conventional supply vessel planning problem seemed to increase linearly with the number of installations to service. For the case looked at one will need to supply at least six installations to make it profitable to have the storage units. On a general basis it looks profitable to have storage units located at the oil field instead of running a regular supply service if the supply demand is large enough (number of installations to service) and the distance to shore is long enough.

In the real case with Jan Mayen it was expected most three installations to service, based on the results presented it would not be profitable to have the converted bulk ships as storage units. Possible explanations for this are that the field is probably not far enough from a land depot and that there are too few installations to service, if the sailing distances were longer it could have been profitable.

The technical feasibility of the project should not be an issue and the project is not dependent on any new technical solutions. Technology that makes the project possible does already exist. However, the total cost for completion of the project has at this stage some uncertainties.

The setup of having converted bulk ships as storage units looks like an interesting concept. Based on the study performed here it seems possible to reduce the overall cost of the supply service by the use of storage units. The concept looks promising and is something that should be of interest for oil companies operating in remote areas.

10 Further work

For the optimization model including the bulk ships as storage units it could have been included more possible locations of the storage units. This might result in long solution times and heuristics or dynamic route generation might be required to find a good solution faster. One could look at the benefit on the total cost and robustness in a few cases for finding even better locations of the storage units. If there is only minor benefits of including more possible location of the storage units it might be wasted to develop faster solution methods for the model and increasing the number of possible locations.

Once the optimal location of the storage unit is found one could run the model by Halvorsen-Weare et al. (2012) for that case to get a better description of the routing and to consider spread of departures and possible time windows. In a practical situation more detailed planning on an operational planning level is necessary. Then the routes needs to be planned more detailed from the storage unit to the installations.

The models could have been run for more variations of data set to see how this affects the solutions. In real life the supply demand at the installations changes from time to time and it could be of interest to see how the solution changes with different data input. In a practical situation the location of the storage unit might change from week to week.

For setup 1 it could be possible to find better solutions, there is a large total time slack in the solution with many installations to service. This is depending on the case that is looked at, and the distance to shore is affecting the time slack of the routes for a weekly planning period. As mentioned this could be difficult to handle in the optimization models and running a simulation model instead for a longer time period could show if it is possible to reduce the number of ships and hence reduce the total cost in these cases. This could potentially reduce the savings from the use of the forward storage units and should be investigated.

The model for finding the optimal location of the storage unit might be suitable for other purposes. For example the same model could be used to decide the optimal location of a land depot given a set of demands at the installations it should supply.

Here the effect of having the storage units for a case with given distance to shore has been done. It might be of interest to see how the savings of having the storage unit would change for different distances to shore. A relevant problem description could be to find out at from which distance from shore this problem is worth studying.

The technical aspects of the storage unit have only been looked into briefly here without much detailed calculations due to time and resource (available data) limitations. Making the conceptual design of the storage unit is a big task and was only a sub-task in this thesis. The cost estimate of the storage unit is based on many assumptions due to lack of accessible information regarding the cost of the different systems onboard and building costs. Yards should be contacted to get more detailed cost estimates. It should be looked into in detail which additional systems the storage units should have regarding other operations than the supply logistics. The operational costs should be studied in detail, as the estimate provided here might not be accurate. There should in addition be done a cost benefit analysis not only for the supply service but for the entire operation of the oil field of having the storage units.

The storage units has an empty slot in their schedule that is presented here, it should be investigated how the utilization of the vessel could improve. For example there could be operations between the periods it is in operation for the supply service. Alternatively the vessel could be made smaller and stay in operation for a shorter time period.

A what-if analysis could be useful in the case that the concept with storage units is not working in practice. This should answer what other operations the storage unit could be suitable for and if this would be profitable, and the potential consequences for the ship owners.

The full effects of including other logistic challenges in the forward storage units have not been included in this study. Including oil recovery and emergency response facilities could reduce the cost of having emergency response vessels located at the field. Using the storage units as helicopter base could prove useful. The full effects of having the storage units should therefore be investigated. This could contribute to bring the overall cost down to a level where it gets profitable for even smaller oil fields.

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Appendix 1 Distances for land depots to field

Location Jan Mayen	Land Depot	Distance [nm]
70°N 08°E	Kristiansund	577
70°N 08°E	Brønnøysund	548
70°N 08°E	Bodø	525
70°N 08°E	Harstad	528
70°N 08°E	Hammerfest	633
69°N 08°E	Kristiansund	533
69°N 08°E	Brønnøysund	515
69°N 08°E	Bodø	519
69°N 08°E	Harstad	535
69°N 08°E	Hammerfest	659
71°N 09°E	Kristiansund	649
71°N 09°E	Brønnøysund	609
71°N 09°E	Bodø	580
71°N 09°E	Harstad	572
71°N 09°E	Hammerfest	662

All distances are found using http://www.sea-seek.com/tools/tools.php.

Appendix 2 Distance matrix

	I1	I2	I3	I4	I5	I6	I7	I8	LD	S1	S2	S3	S4	S5	S6	S7	S8
I1	0	95	163	62	97	131	58	28	533	16	43	45	87	82	120	116	142
I2		0	84	38	33	59	74	64	577	86	21	59	15	44	41	57	65
I3			0	96	60	30	111	131	649	161	122	120	78	74	41	42	16
I4				0	35	99	38	37	580	68	32	24	30	22	61	53	79
I5					0	64	61	70	610	99	61	57	20	20	27	22	46
I6						0	89	107	635	133	94	88	50	49	20	19	13
I7							0	42	581	72	54	20	62	40	85	71	100
I8								0	542	35	22	21	62	58	95	89	115
LD									0	517	544	569	583	601	618	628	641
S1										0	X	X	X	X	X	X	X
S2											0	X	X	X	X	X	X
S3												0	X	X	X	X	X
S4													0	X	X	X	X
S5														0	X	X	X
S6															0	X	X
S7																0	X
S8																	0

The distance matrix is symmetric.

All distances are given in Nautical Miles.

I1-I8 = Installation 1-8

LD = Land Depot

S1-S8 = Location of storage unit 1-8

X = Not relevant

All distances are found using http://www.sea-seek.com/tools/tools.php.

Appendix 3 Adverse Weather for Leeside Working Guidelines

The guidelines are gathered from NWEA guidelines for the Safe Management of Offshore Supply and Rig Move Operations.

Trigger	Precaution
Wind	
Unfavorable Wind Direction	No installation overboard venting or discharges whilst working supply vessels, unless previously agreed with vessel Master.
20 kts mean wind speed at 10m level	Secure loose items and advise greater caution to prevent injury to personnel and damage to equipment.
20 - 25 knots Mean Wind Speed at 10m level	OIM, Crane Operator and Master should evaluate the weather conditions and forecast. If necessary, a risk assessment should be carried out before commencing / continuing the operation. Consider vessel motion and potential cargo damage when reviewing prevailing weather conditions and immediate forecast.
25-40 knots mean wind speed at 10m level	Any operations in this range must only be carried out with full agreement of OIM, Crane Operator and Master. Weather conditions should be continuously monitored. NO7.
Sea State	
3m - 4m Significant Wave Height	OIM, Crane Operator and Master should assess the situation on positioning and cargo handling before arrival within safety zone. Account for vessel motion, any awkward lifts, potential cargo damage due to heave and potential effects of sea on hose work.
Tidal Streams	
Strong Currents or Tides	Consider delaying discharging until slack tides if vessel cannot hold station satisfactorily (propeller and/or thruster utilization below 50%) against tide
Visibility	
Poor visibility	Cease cargo operations if crane operator is unable to see vessel deck crew clearly.
Visibility <250m	Remain outside safety zone of installation to avoid collision with installation or other vessels. Maintain radar watch.
Vessel and Equipment	
Vessel rolling heavily	Master may cease operations at lower wave heights than those above if rolling starts to affect station keeping or crew safety.
Vessel moving violently	If vessel motion adversely affects vessel's station-keeping equipment Master will cease operations and clear installation.
Forecast for vessel's specific criteria to be exceeded	Consider making for sheltered waters or port to avoid risk to personnel or equipment or cargo.
Hose operations	Continue hose operations at Master's discretion. If station keeping requires in excess of 45% of propeller and/or thruster utilization consider ceasing hose operations.

Appendix 4 Adverse Weather for Weather Side Working Guidelines

The guidelines are gathered from NWEA guidelines for the Safe Management of Offshore Supply and Rig Move Operations.

Trigger	Precaution
Wind	
20 - 25 knots Mean Wind Speed at 10m level	Secure loose items and advise greater caution to prevent injury to personnel and damage to equipment.
Above 25 knots at 10m level	Operations cease. When on Norwegian Continental Shelf see NO8.
Sea State	
3m - 4m Significant Wave Height	OIM, Crane Operator and Master should assess the situation on positioning and cargo handling before arrival within safety zone. Account for vessel motion, any awkward lifts, potential cargo damage due to heave and potential effects of sea on hose work.
Above 4m	Operations cease. When on Norwegian Continental Shelf see NO8.
Tidal Streams	
Strong Currents or Tides	Consider delaying discharging until slack tides if vessel cannot hold station satisfactorily (propeller and/or thruster utilization below 50%) against tide
Visibility	
Poor visibility	Cease cargo operations if crane operator is unable to see vessel deck crew clearly.
Visibility <250m	Remain outside safety zone of installation to avoid collision with installation or other vessels. Maintain radar watch.
Vessel and Equipment	
Vessel rolling heavily	Master may cease operations at lower wave heights than those above if rolling starts to affect station keeping or crew safety.
Vessel moving violently	If vessel motion adversely affects vessel's station-keeping equipment Master will cease operations and clear installation.
Forecast for vessel's specific criteria to be exceeded	Consider making for sheltered waters or port to avoid risk to personnel or equipment or cargo.
Thruster and propeller Utilization	If vessel thruster or propeller use exceeds 45% of propeller and/or thruster utilization Master will cease operations.

Appendix 5 PSV spot rates

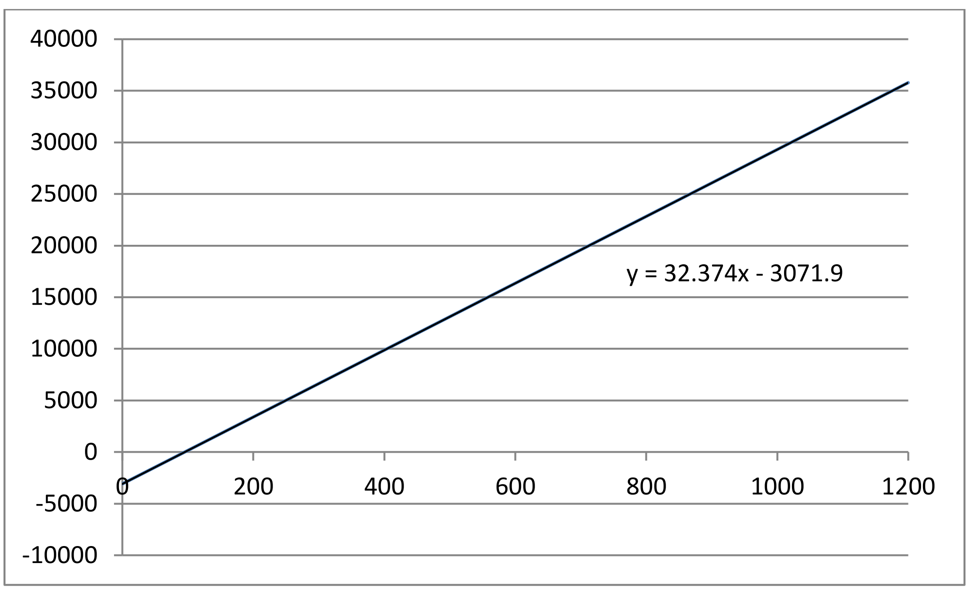
Average PSV North Sea spot rates from www.seabrokers.co.uk (25.04.2013). Converted from GBP to USD, with assuming 1 USD = 0.65 GBP (25.04.2013).

PSVs <800 m2	jan	feb	mar	apr	mai	jun	jul	aug	sep	okt	nov	des	Avereage
2011	£3 536	£5 412	£8 465	£10 355	£10 923	£19 838	£16 574	£13 828	£16 894	£13 023	£10 870	£8 448	**£11 514**
2012	£7 833	£7 804	£17 121	£17 543	£9 554	£13 017	£9 139	£5 457	£12 907	£9 240	£4 639	£4 915	**£10 962**
PSVs >800m2													
2011	£7 639	£6 396	£9 514	£11 330	£16 813	£20 208	£20 309	£19 922	£19 834	£17 263	£12 735	£9 704	**£14 306**
2012	£9 032	£9 786	£18 983	£19 405	£11 783	£16 014	£10 980	£7 337	£13 791	£10 196	£7 402	£6 836	**£12 731**

USD

PSVs <800 m2	jan	feb	mar	apr	mai	jun	jul	aug	sep	okt	nov	des	Average
2011	$5 440	$8 326	$13 023	$15 931	$16 805	$30 520	$25 498	$21 274	$25 991	$20 035	$16 723	$12 997	**$17 714**
2012	$12 051	$12 006	$26 340	$26 989	$14 698	$20 026	$14 060	$8 395	$19 857	$14 215			**$16 864**
PSVs >800m2													
2011	$11 752	$9 840	$14 637	$17 431	$25 866	$31 089	$31 245	$30 649	$30 514	$26 558	$19 592	$14 929	**$22 009**
2012	$13 895	$15 055	$29 205	$29 854	$18 128	$24 637	$16 892	$11 288	$21 217	$15 686	$11 388	$10 517	**$19 586**

Below is the charter rates plotted against deck size of the vessels. The graph is calculated based on rate of 17000 USD for a ship of size 620 square meters and a rate of 35 000 USD for a ship of size 1176 square meters. We only use the graph between 620 and 1176 square meters. Day rates are on the y-axis and deck size is on the x-axis.



Appendix 6 Demand data for installations

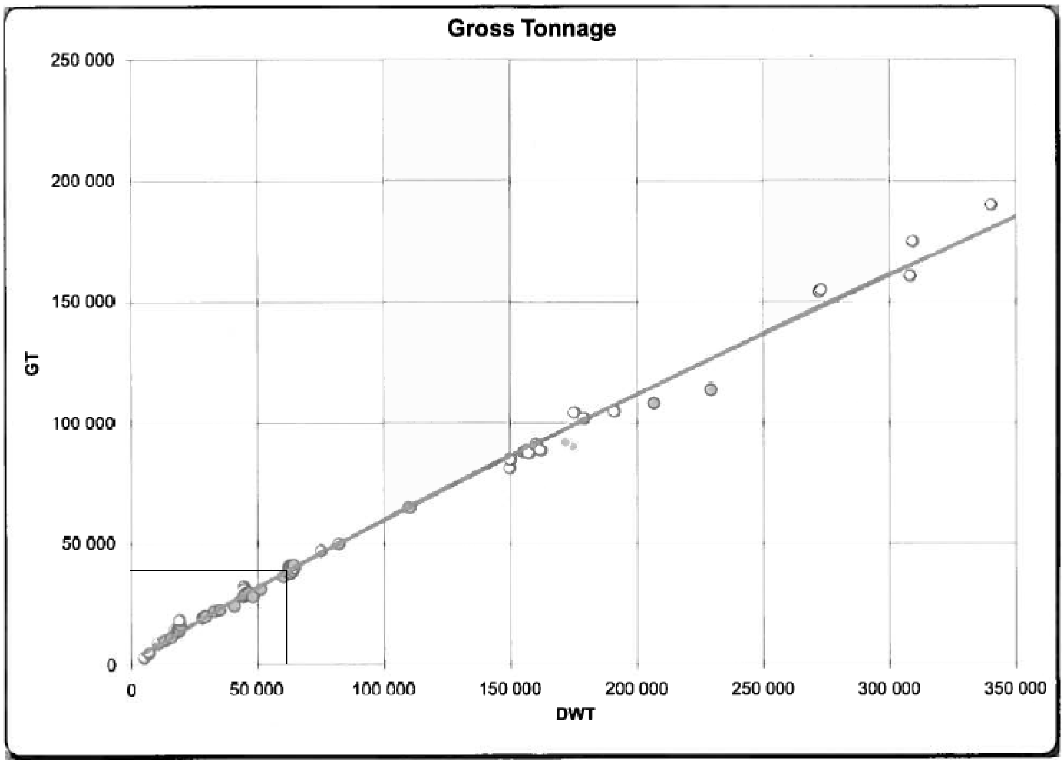
Below are some average demand data for some installations presented. The conversion factor from getting from ton to square meters for deck cargo is 0.56 ton/m^2.

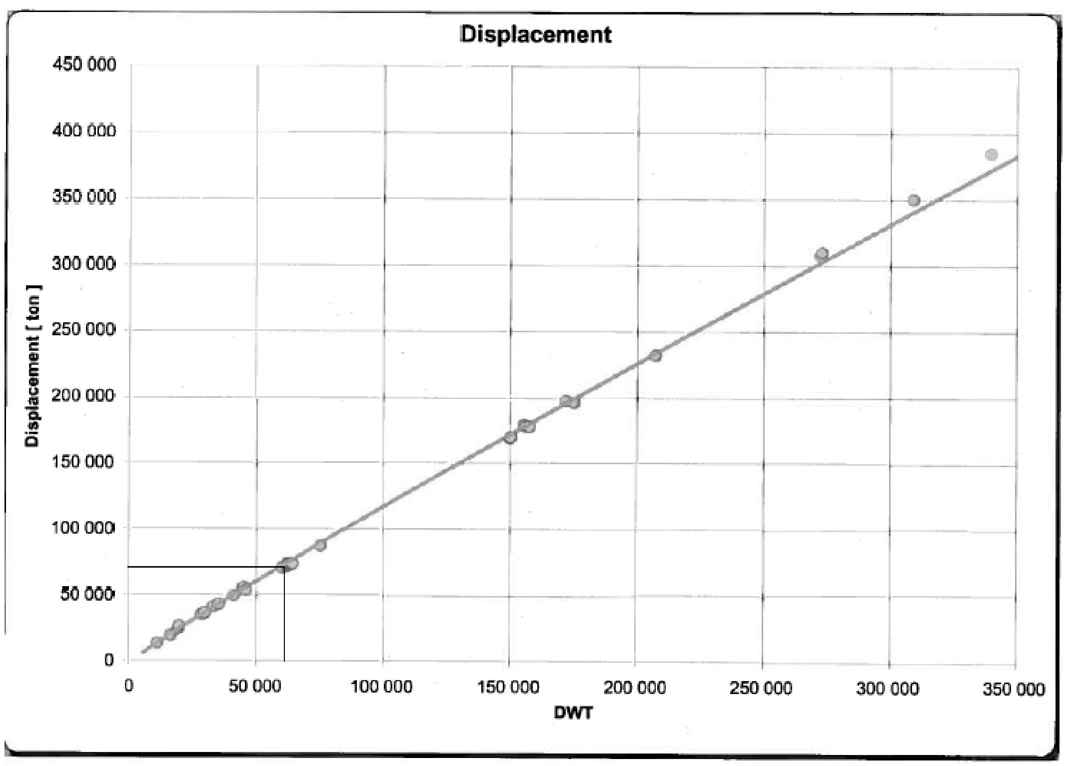
These data is been given by Professor Bjørn Egil Asbjørnslett for analytical purposes and is not time related.

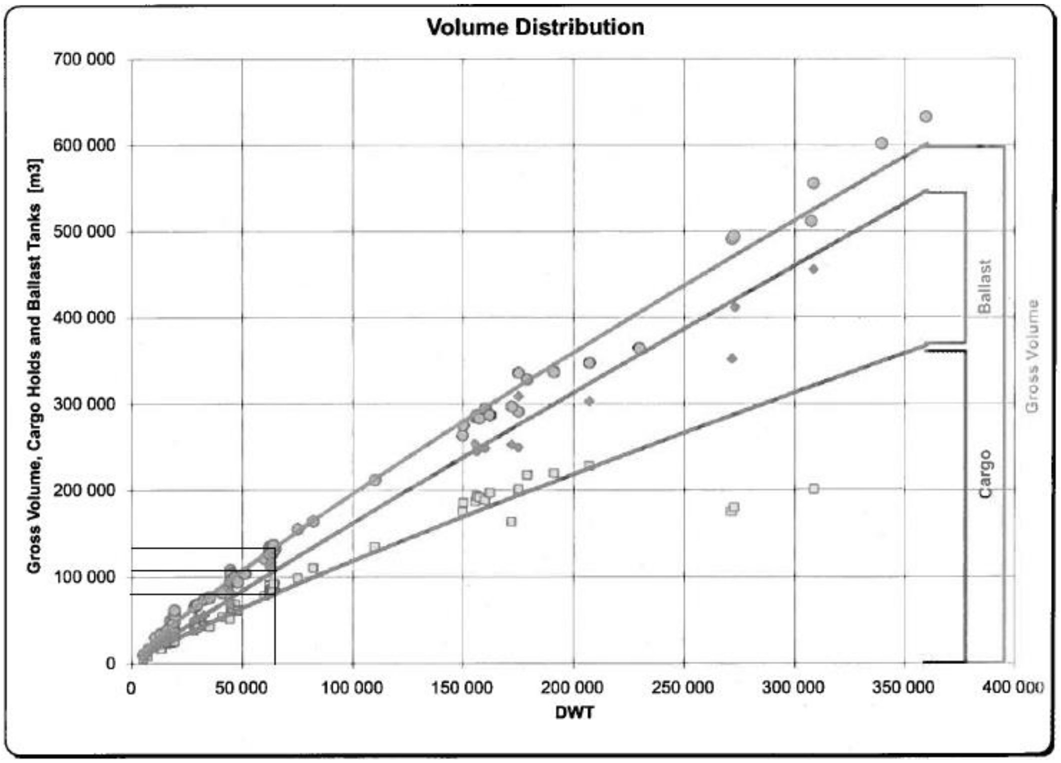
Activity	Date	No. Months	Average visits per week	Total loading and unloading time	Dry bulk	Mud	Brine	Fuel	Mineral oil	Water	Sum tons	Square meters
Production	Jan. - May	5	2.3	6	0	0	0	16	0	65	82	118
Production	Jan. - May	5	3.8	18	82	77	238	27	0	133	558	571
Production	Jan. - April	4	3.2	10	40	6	12	60	0	167	285	200
Exploration drilling	Jan. - May	5	4.3	29	123	289	227	164	0	304	1106	671
Exploration drilling	Jan, April, May	3	3.8	24	37	21	193	78	0	99	428	251
Exploration drilling	Jan. - May	5	3.6	21	68	95	58	123	0	154	498	405
Exploration drilling	Jan. - May	5	2.7	14	124	68	39	97	0	249	577	321
Sum per week			3.4	124	474	555	768	565	0	1171	3533	2 536

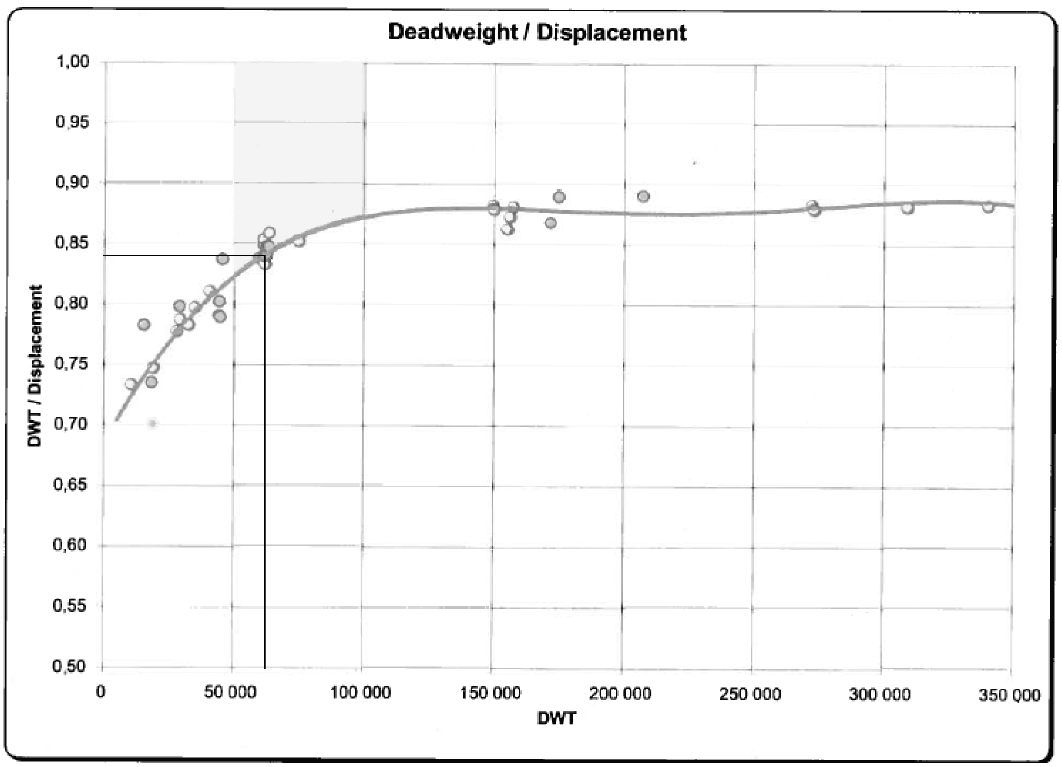
Appendix 7 Bulk carrier statistics (Levander, 2009)

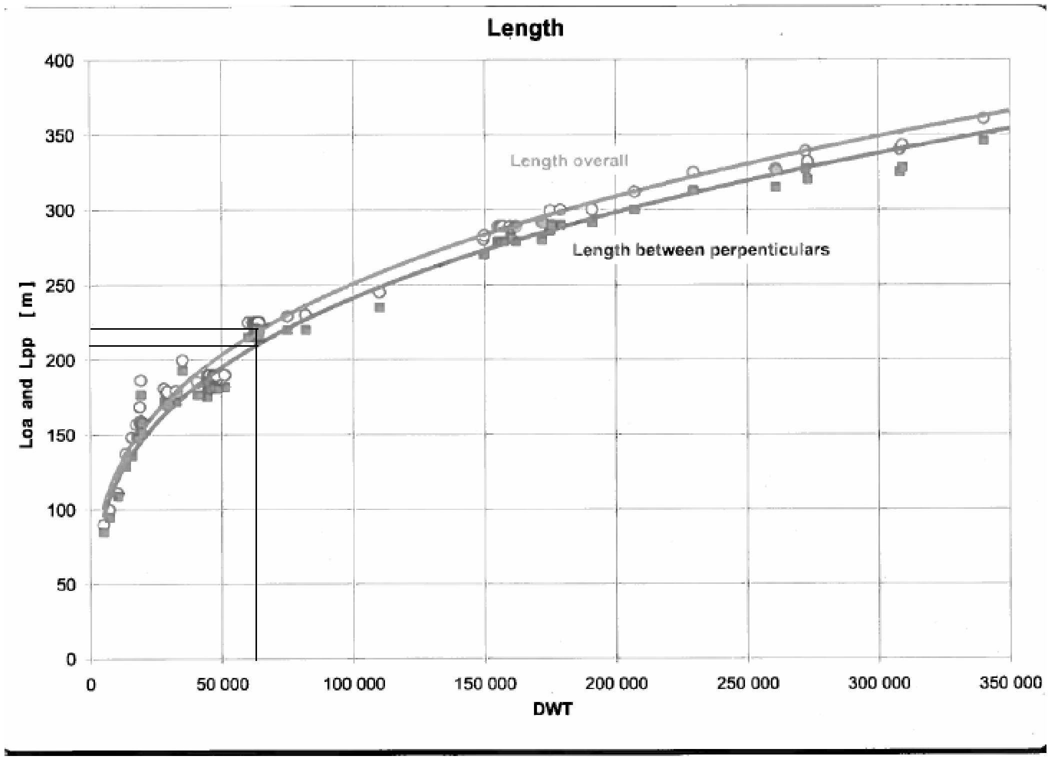
Graphs used to estimate data for bulk carriers.

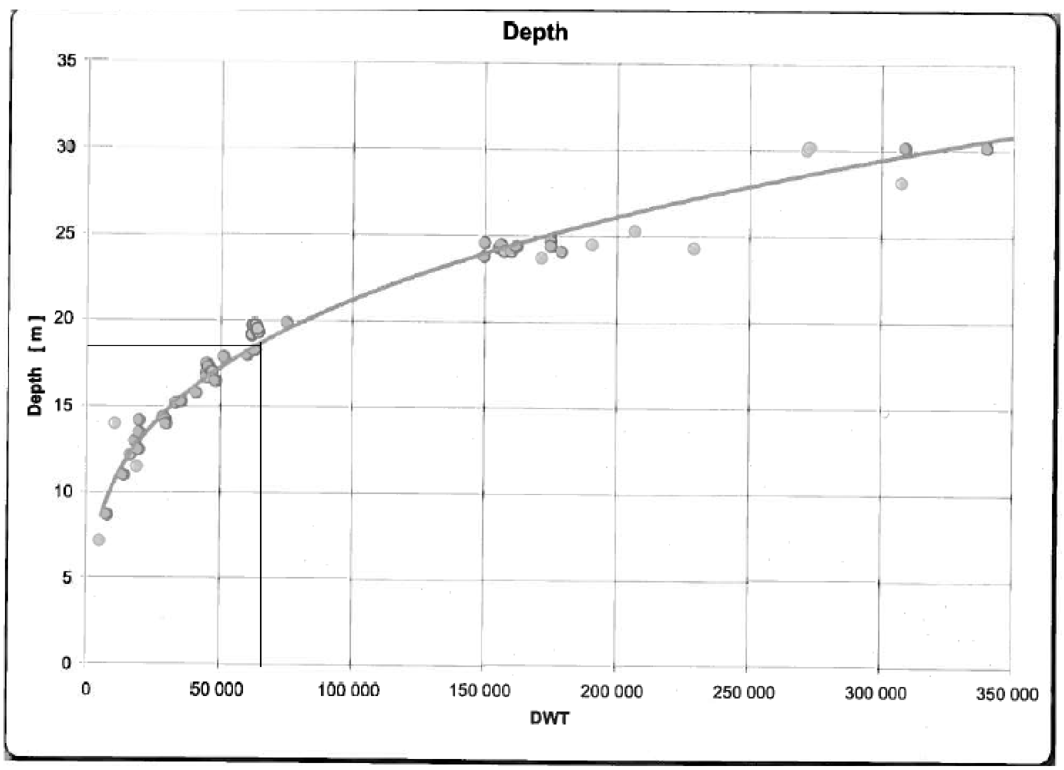


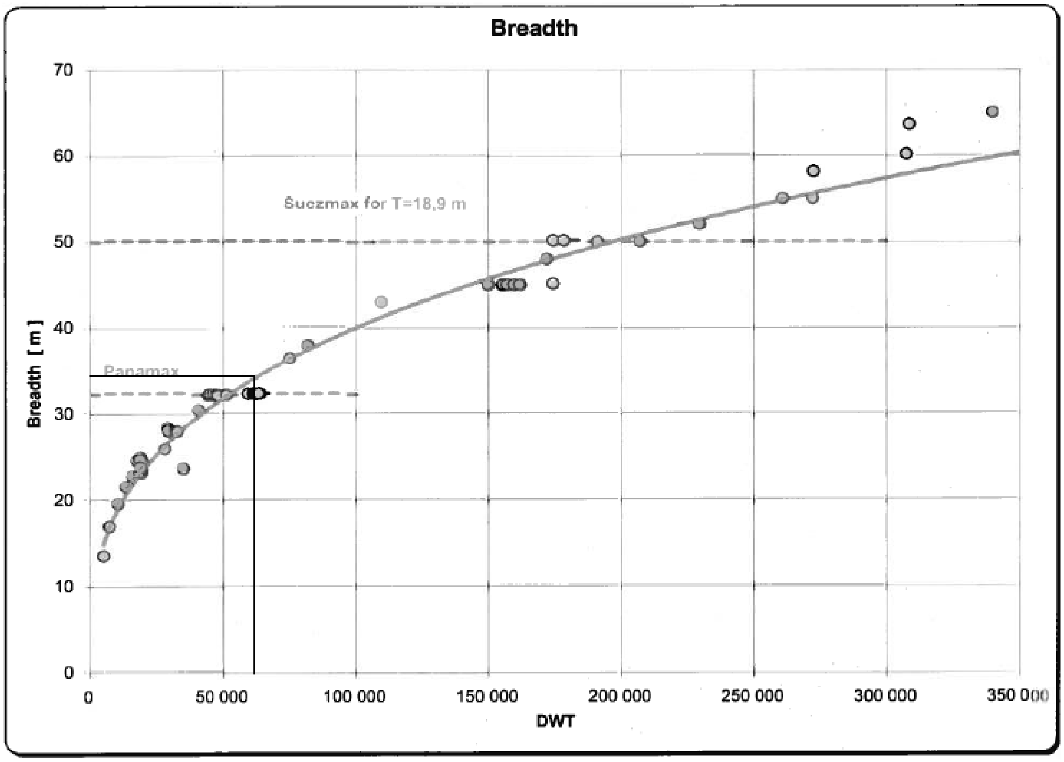



Volume Distribution
Gross Volume, Cargo Holds and Ballast Tanks [m3]
DWT
Ballast
Cargo
Gross Volume

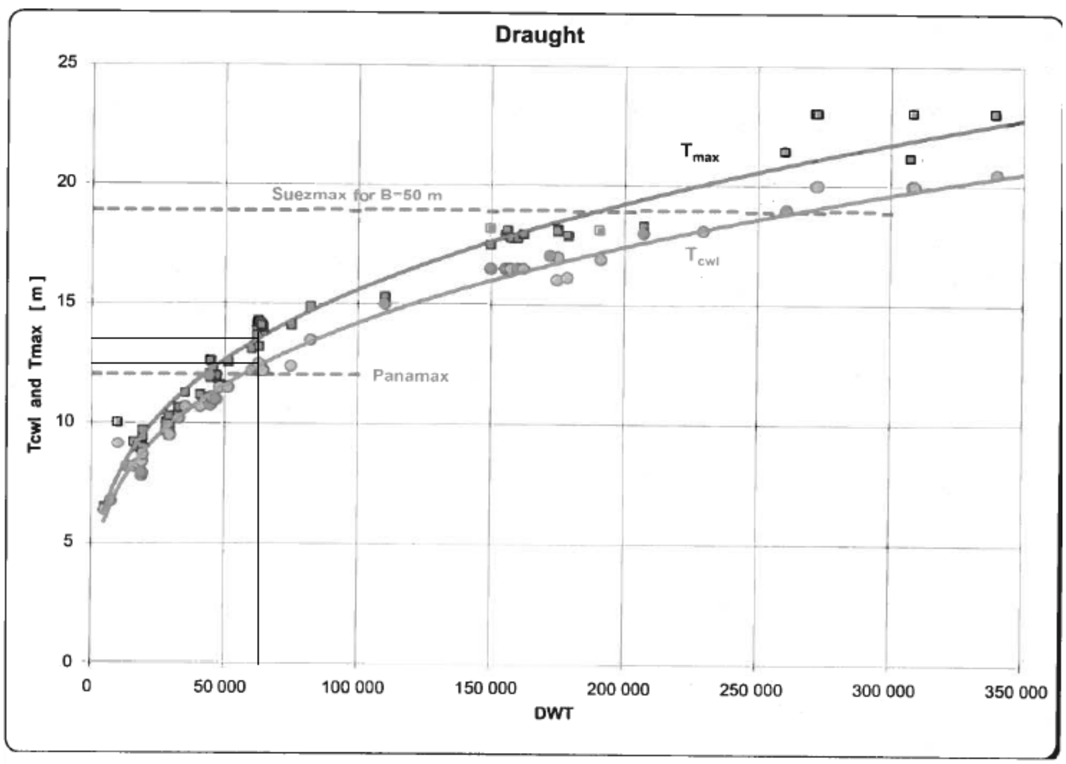

Deadweight / Displacement
DWT / Displacement
DWT


Length
Length overall
Length between perpenticulars
Loa and Lpp [m]
400
350
300
250
200
150
100
50
0
0
50 000
100 000
150 000
200 000
250 000
300 000
350 000
DWT

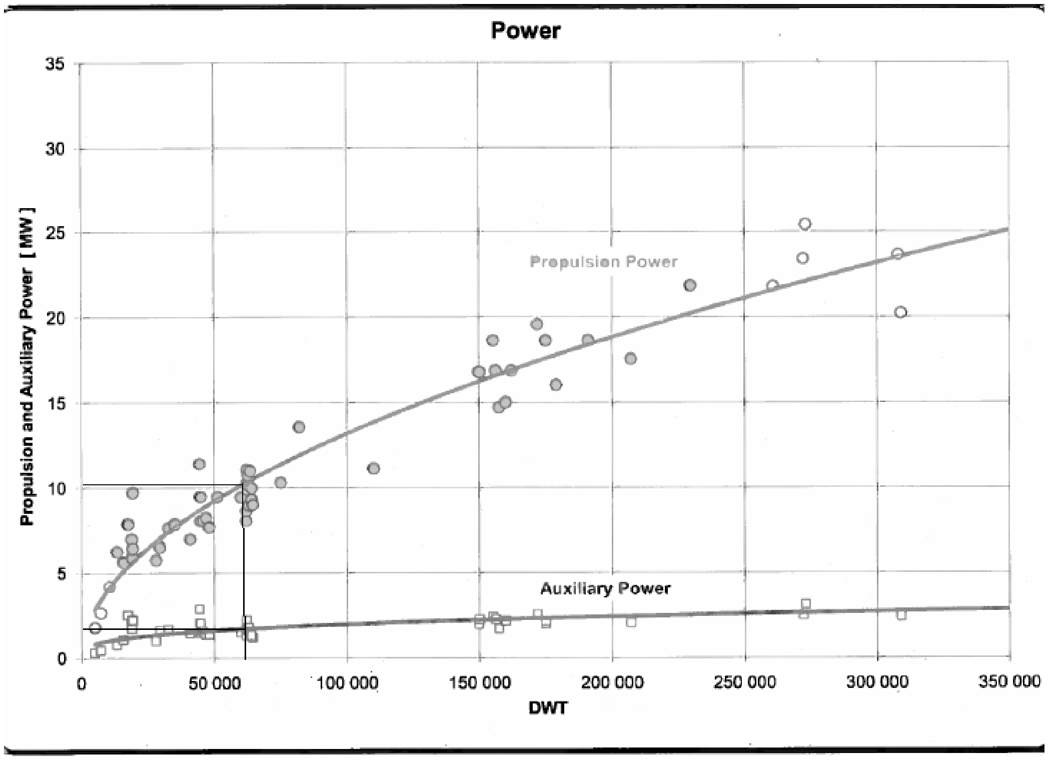

Depth
Depth [m]
35
30
25
20
15
10
5
0
0
50 000
100 000
150 000
200 000
250 000
300 000
350 000
DWT

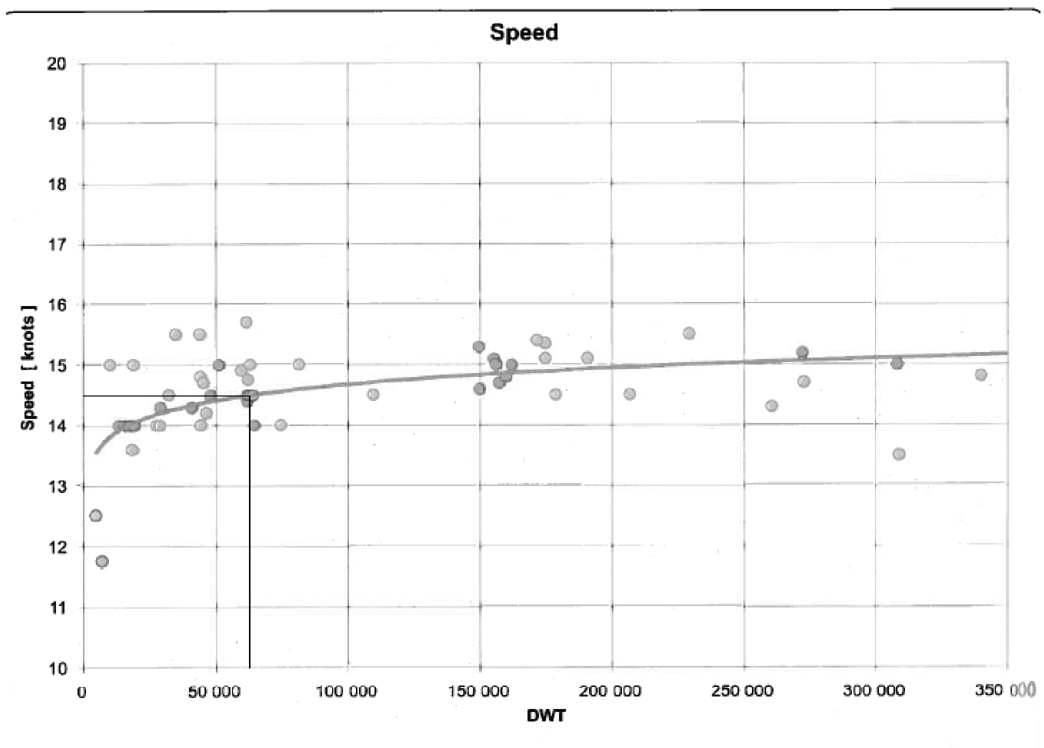


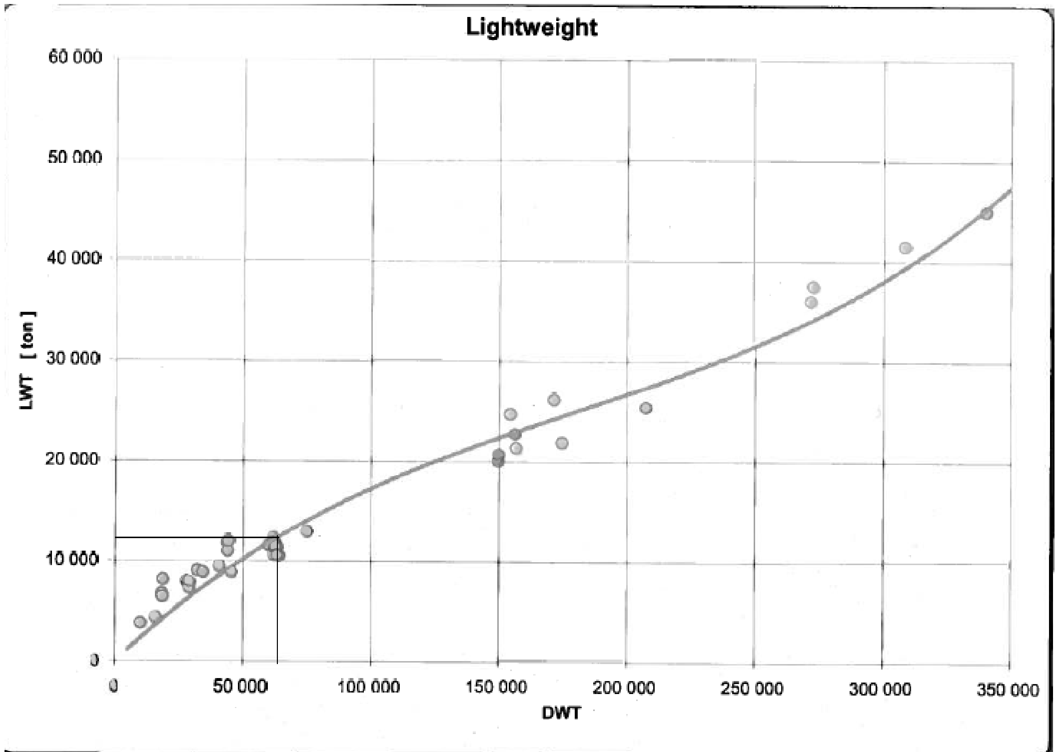
Breadth
Suezmax for T=18,9 m
Panamax
Breadth [m]
DWT
0
10
20
30
40
50
60
70
0
50 000
100 000
150 000
200 000
250 000
300 000
350 000

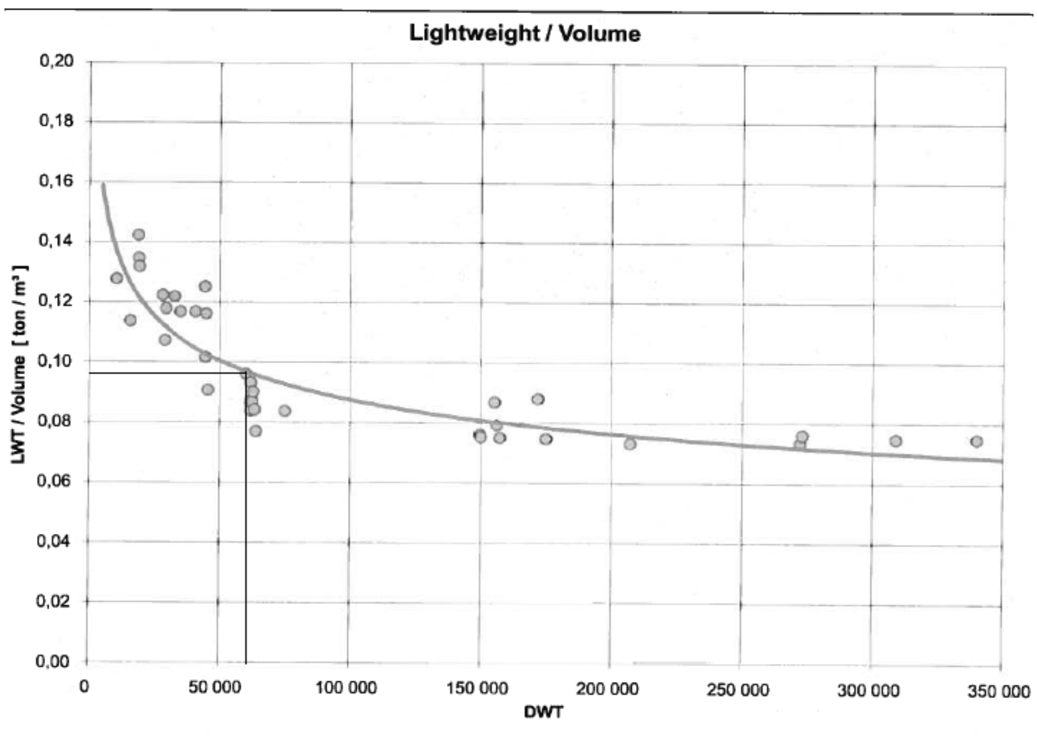


Draught
Suezmax for B=50 m
Panamax
T_{max}
T_{cwl}
Tcwl and Tmax [m]
DWT
0
5
10
15
20
25
0
50 000
100 000
150 000
200 000
250 000
300 000
350 000


Power
Propulsion and Auxiliary Power [MW]
Propulsion Power
Auxiliary Power
DWT
0
5
10
15
20
25
30
35
50 000
100 000
150 000
200 000
250 000
300 000
350 000


Speed
Speed [knots]
DWT
10
11
12
13
14
15
16
17
18
19
20
0
50 000
100 000
150 000
200 000
250 000
300 000
350 000


Lightweight
60 000
50 000
40 000
30 000
20 000
10 000
0
LWT [ton]
0
50 000
100 000
150 000
200 000
250 000
300 000
350 000
DWT


Lightweight / Volume
0,20
0,18
0,16
0,14
0,12
0,10
0,08
0,06
0,04
0,02
0,00
LWT / Volume [ton / m³]
0
50 000
100 000
150 000
200 000
250 000
300 000
350 000
DWT

Appendix 8 Storage capacity calculations

Time in operation = 2 weeks

No inst. max = 8

No. PSVs max = 5

Safety margin for peak demand = 50 %

The supply demand data from Appendix 6 are used as a basis for the calculations. The rest of the values are based on assumptions.

Average demand	Drilling	Production		Density	
Fuel	164	60	Tons	0.83	ton/m3
Fresh water	304	167	Tons	1	ton/m3
Liquid mud	289	77	Tons	1.2	ton/m3
Cement	400	200	Tons	1.5	ton/m3
Base oil	300	200	Tons	0.85	ton/m3
Methanol	200	200	Tons	0.8	ton/m3
Dry Bulk	124	82	Tons	2	ton/m3
Deck cargo	671	571	m2	0.56	ton/m2

Demand from PSVs				
Demand from PSVs				
Crew members	10	[-]		
Fuel	84	Tons per week	0.83	ton/m3
Fresh water	4.9	Tons per week	1	ton/m3
General supplies	3	m2	0.56	ton/m2

Demand from PSVs	[tons]
Fuel	840
Fresh water	49
General supplies	30
Total	**919**

Demand from PSVs	[m3]
Fuel	1012
Fresh water	49
General supplies	107
Total	**1168**

Demand from own use				
Crew members	25			
Fuel	220	Tons per week	0.83	ton/m3
Lube oil	22	Tons per week	0.83	ton/m3
Fresh water	12.25	Tons per week	1	ton/m3
General supplies	10	m2	0.56	ton/m2

Demand from Own use	**[tons]**
Fuel	440
Lube oil	44
Fresh water	25
General supplies	20
Total	**529**

Demand from Own use	**[m3]**
Fuel	530
Lube oil	53
Fresh water	25
General supplies	71
Total	**679**

Demand from installations [tons]	**Drilling**		**Production**	
	Average	**Peak**	**Average**	**Peak**
Fuel	2618	3927	960	1440
Fresh water	4864	7296	2672	4008
Liquid mud	4617	6925	1232	1848
Cement	6400	9600	3200	4800
Base oil	4800	7200	3200	4800
Methanol	3200	4800	3200	4800
Dry Bulk	1984	2976	1312	1968
Deck cargo	6012	9018	5116	7674.24
Total	**34494**	**51742**	**20892**	**31338**

Demand from installations [m3]	95 % Average	Maximum tank usage Drilling Peak	Production Average	Peak
Fuel	3320	4980	1218	1826
Fresh water	5120	7680	2813	4219
Liquid mud	4050	6075	1081	1621
Cement	4491	6737	2246	3368
Base oil	5944	8916	3963	5944
Methanol	4211	6316	4211	6316
Dry Bulk	1044	1566	691	1036
Deck cargo	21472	32208	18272	27408
Total	**49652**	**74478**	**34492**	**51739**
m2 for deck cargo	**10736**	**16104**	**9136**	**13704**

Appendix 9 Conversion cost estimate

Prices have been converted from NOK to USD with an exchange rate of 5.85.

The method to calculate the conversion cost is based on the one presented by (Levander, 2009). The cost coefficients for the cost groups, General, Hull structure cargo and Machinery is also taken from (Levander, 2009).

The cost of the OR equipment including dispersant is given by Trond Mauritzen at NOFO.

The cost of the Helicopter deck and DP system is based on own assumptions, it has not been possible to get any accurate estimate of these numbers. The price set here should include labor cost.

Due to the uncertainty of all the numbers it has been set a 50 % safety margin on all the material and labor costs.

Cost group	Unit	Value	USD/unit	h/unit	Material M USD	Labor h
General	LWT (ton)	2800	342	5	1.0	14000
Hull structure, Cargo	LWT (ton)	2800	1026	30	2.9	84000
Machinery	Aux (kW)	7000	1026	2	7.2	14000
OR Equipment	[-]				5.5	
Helicopter deck	[-]				5.0	
DP system	[-]				10.0	
Total					31.5	112000
Reserve	%		50 %	50 %	15.7	56000
Total Material and labor					47.2	168000

This gives a total material cost of 47.2 M USD. The total price of the conversion has to include the cost of labor, design, building financing, profit to the yard, financing the payment cost and broker fees. Again the example in (Levander, 2009) is followed.

Price estimation		h/LWT	Hours	USD/h	Price M USD
Design		10	28000	60	1.7
Labor + Overhead		36	168000	68.38	11.5
Material					47.2
Building time financing		6 %	Months	12	1.8
Total Production Cost					62.2
Profit	5 %				3.1
Financing, payment	3 %				1.9
Broker fees	1 %				0.6
Conversion price					**68**
Buy cost					**45**
Total project cost					**113**

This gives a total conversion price of 68 M USD, including buying the vessel at 45 M USD, the total project will have an investment cost of 113 M USD.

Appendix 10 Day rate calculations

The day rate cost for the oil company of hiring the vessel does not include fuel and port fees; these are added on top of the day rate when calculating the cost of having the storage unit for the oil company. The calculation method here are based on an example by (Pruyn, 2012).

Input data	
Engine [kW]	10000
Average DP [kW]	5000
Number of crew	25
Investment cost [USD]	113000000
Sale value at end of life	0
Depreciation time	20
Profit	20 %

The engine sizes are needed for calculating the fuel consumptions in the different modes. The number of crews is used to calculate the manning cost. The investment cost include buying the vessel and conversion work. There is assumed that the vessel will have no value at the end of its lifetime. It is assumed that the ship owner want 20 % profit on his investment.

General data:		
Port fees (assumed)	50000	USD
Assumed fuel consumption		
Fuel consumption sailing	*185*	*g/kWhr*
Fuel consumption DP	*185*	*g/kWhr*
Fuel consumption standby	*37*	*g/kWhr*
Fuel consumption port	*18.5*	*g/kWhr*
Fuel price	900	dollar/tonn
Crew costs	60000	dollar/person
Average interest rate	5 %	per year
Repayment period	20	years
Own capital, 20 % of Price	22600000	dollar
Sailing days per year	160	
Days per year	365	
Time per trip	6	weeks
Weeks in 1 year	52	

The interest rate for the loan on the vessel is set to 5 %. It is expected that the ship owner will pay 20 % of the investment upfront.

Schedule		
Time in port	48	[h]
Sailing time	100	[h]
DP	240	[h]
Standby	96	[h]
Total time	484	[h]
Not in operation	188	[h]
Trips per year	13	

This schedule is used to calculate the fuel consumption.

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average
Total loan left	90.4	85.9	81.4	76.8	72.3	67.8	63.3	58.8	54.2	49.7	45.2	40.7	36.2	31.6	27.1	22.6	18.1	13.6	9.0	4.5	
Interest paid	4.5	4.3	4.1	3.8	3.6	3.4	3.2	2.9	2.7	2.5	2.3	2.0	1.8	1.6	1.4	1.1	0.9	0.7	0.5	0.2	2.37
Value	113.0	107.4	101.7	96.1	90.4	84.8	79.1	73.5	67.8	62.2	56.5	50.9	45.2	39.6	33.9	28.3	22.6	17.0	11.3	5.7	

The tables above show how the loan will be paid back over the 20 year lifetime. This gives average yearly interest costs of 2.37 M USD.

Dry bulk	Handymax	Supramax	Panamax
Total Manning cost	667950	844245	886220
Total Insurance	287985	308060	314265
Total stores and lubes	248565	258420	306235
Repair and maintenance	636560	715400	817235
Total other	251850	270830	289810
Total operating cost [USD]	2093275	2396955	2602815

The table above shows what the average operating costs of different types of bulk ships. The numbers are based on a Ship Operating Costs Annual Review and Forecast 2012/13 report by DREWRY. Here it is assumed that out vessel will have similar operating cost as a Supramax bulk carrier. Manning cost is likely to be higher here due to a larger crew. The vessels are depreciated linearly over the lifetime.

Day rate calculations	[USD]
Maintenance	715400
Manning	1500000
Insurance	308060
Stores and lubes	258420
Other	270830
Interest	2373000
Depreciation	5650000
Total cost	11075710
Profit	2215142
Needed income	13290852
Day rate	**36413**

Based on the operating costs of the vessel the ship owner needs to take a day rate around 36 500 USD from the oil company. In addition come fuel consumption, see calculations below.

Fuel consumption per trip		
Port	8.88	[tones]
Sailing	185	[tones]
DP	222	[tones]
Standby	35.52	[tones]
Total	451.4	[tones]

These numbers are based on the schedule of the vessel.

Fuel cost per trip		
Total fuel cost per trip	406260	[USD]
Total fuel cost per year	5281380	[USD]
Fuel cost per day	14470	[USD]

With a fuel price of 900 USD per ton, the average fuel cost per day should be around 14 500 USD. In addition the oil company has to pay for port fees. Assuming that the cost of visiting the port costs 50 000 USD and with 13 trips to port per year, this gives yearly port fee costs of 650 000 USD. The average port fees per day are 1781 USD.

Adding up the day rate for the ship owner, fuel costs and port fees, the oil company will have to pay 52 664 USD per day for each vessel. When using the number it will be rounded up to 53 000 USD.

Appendix 11 Xpress models for setup 1

```
!THIS IS THE MAIN MODEL, SAME AS THE ONEDISCUSSED IN CHAPTER 4.1.1

model Model1
uses "mmxprs", "mmsystem"; !gain access to the Xpress-Optimizer solver

options explterm
! This option means that all commands must end with a ;
options noimplicit
! This option means that everything must be declared before it is used

parameters
	DataFile = 'GeneralDataInput.dat';
	RouteGeneration = 'TESTING.dat';
end-parameters
! it is necessary to have two data files, one general and one generated by the route generation model file

declarations
	nVessels:		integer;
	nInstallations:		integer;
	vessels:		set of integer;
	vesselTypes:		set of integer;
	vesselType:		dynamic array(vessels)of integer;
	vesselsOfType:		dynamic array(vesselTypes) of set of integer;
	numVesselsOfType :	integer;
	installations:		set of integer;
end-declarations
!Data describing the size of the problem

initializations from DataFile
	nVessels;
	nInstallations;
end-initializations

vesselTypes := 1..nVessels;
numVesselsOfType := 4;

forall(i in vesselTypes, j in 1..numVesselsOfType)do
	vesselsOfType(i) += {j+((i-1)*numVesselsOfType)};
	vessels+={j+((i-1)*numVesselsOfType)};
	vesselType(j+((i-1)*numVesselsOfType)):=i;
end-do
!Have several copies of each type vessel in the model

installations := 1..nInstallations;

declarations
nSchedules:		dynamic array(vessels) of integer;
schedules:		dynamic array(vessels) of set of integer;
end-declarations
!Defining the shedules for each vessel
```

```
initializations from RouteGeneration
	nSchedules;
end-initializations

forall (vv in vessels, ii in 1..nSchedules(vesselType(vv))) do
	schedules(vv) += {ii} ;
end-do
!Making the set of routes for each vessel

declarations
totalTime:	dynamic array(vessels,integer)			of real;
serviceA:	dynamic array(vessels,integer,installations)	of integer;
freqS:		array(installations)				of integer;
charterC:	array(vessels)					of integer;
serviceC:	dynamic array(vessels,integer)			of real;
largeNumber:							integer;
end-declarations

!"totalTime" will be generated in step 1 and is the total time i nhours of schedule r for ship k
!"serviceA" will be generated in step 1 ans is a constant that is equal to 1 if vessel v service
!installation i on schedule r
!"freqS" is the minimum number of weekly services for installation i
!"charterC" is the cost of using supply vessel v
!"serviceC" will be generated in step 1 and is the service cost of sailing route r with vessel v

initializations from RouteGeneration
	totalTime;
	serviceA;
	serviceC;
end-initializations

initializations from DataFile
	freqS;
	charterC;
	largeNumber;
end-initializations

declarations
	X:		dynamic array(vessels,integer)		of mpvar;
	Y:		dynamic array(vessels)			of mpvar;
	FreqCon:	dynamic array(installations)		of linctr;
	TimeCon:	dynamic array(vessels)			of linctr;
	ConnectCon:	dynamic array(vessels)			of linctr;
end-declarations
! X is an integer variable indicating the number of times in the timer period ship v sails its schedule r
! Y is a binary variable that is equal to 1 if vessel v is used in the optimal solution, 0 otherwise
! FreqCon = Constraint (2) in the report
! TimeCon = Constraint (3) in the report
! ConnectCon = Constraint (4) in the report

forall (vv in vessels, rr in schedules(vv)) do
	create(X(vv,rr));
end-do
```

```
forall (vv in vessels) do
	create(Y(vv));
end-do

declarations
	TotalCost:		linctr;
end-declarations
! TotalCost = The value of the objective function

TotalCost :=
sum(vv in vessels) 7*charterC(vesselType(vv)) * Y(vv) + sum(vv in vessels, rr in schedules(vv))
serviceC(vesselType(vv),rr) * X(vv,rr);
!This is the objective function, to be minimized


forall (ii in installations) do
FreqCon(ii):= sum(vv in vessels, rr in schedules(vv))serviceA(vesselType(vv),rr,ii)*X(vv,rr) >= freqS(ii);
end-do
!This constraint ensures that each offshore installation is service at least the minimum number if times

forall (vv in vessels) do
TimeCon(vv) := sum(rr in schedules(vv)) totalTime(vesselType(vv),rr) * X(vv,rr) <= 168;
end-do
!This constraint ensure that the sum of the total time of the schedules for a given vessel does not exceed 168 hours
! in this case 1 week, change number if longer time period.

forall (vv in vessels) do
	ConnectCon(vv) := sum(rr in schedules(vv)) X(vv,rr) - largeNumber * Y(vv) <= 0;
end-do
!Ensure that if at least one schedule is selecte, then the corresponding binary variable for the vessel must be equal
to one

declarations
	tempVessels: set of integer;
end-declarations

forall(tt in vesselTypes)do
	tempVessels := vesselsOfType(tt);
	tempVessels -={tempVessels(1)};
	forall( vv in tempVessels)do
		sum(rr in schedules(vv)) X(vv,rr)<= sum(rr in schedules(vv-1)) X(vv-1,rr);
	end-do
end-do
!Symmetry constraints

forall(vv in vessels, rr in schedules(vv)) X(vv,rr) is_integer;
!make the X variable integer, tells how many times per week, the vessel sails its schedule

forall(vv in vessels) Y(vv) is_binary;
!make the Y variable binary
setparam('xprs_verbose',true);
declarations
```

```
        solutiontime:       real;
end-declarations

  solutiontime := gettime;
        minimize(TotalCost);

writeln;
writeln('Optimal objective value : ', getobjval);

forall(vv in vessels,rr in schedules(vv))do
if(getsol(X(vv,rr))>=1)then
writeln("X(",vv, ",",rr, "): ", getsol(X(vv,rr)));
end-if
end-do
!Write out the x variables that are in the solution

writeln(" The solution time        : ", strfmt(gettime - solutiontime,7,2));
!Find the solution time for the model


end-model
```

```
!THIS IS THE MODEL FOR THE ROUTE GENERATION
model Routes
uses "mmjobs","mmjobs","mmsystem";

options explterm
options noimplicit

parameters
	DataFile = 'GeneralDataInput.dat';
end-parameters

declarations
	solutiontime:	real;
end-declarations
 solutiontime := gettime;

declarations
	nVessels:		integer;		!nVessels, Number of vessels
	nInstallations:		integer;		!nInstallation, Number of installations
	vessels:		set of integer;	!vessels, describing the set of vessels
	installations:		set of integer;	!installations, describing the set of installations
	npath:			integer;		!Counter for the number of paths created
	serviceT:		integer;		!Time to service 1 installation
	v:			integer;		!v, Sailing speed of all vessels
	depotT:			integer;		!Time to load ship at depot
	DIST:			array(integer,integer) of integer;	!Distance matrix
	fuelC:			integer;				!fuelC, Cost per ton of fuel
	fuelh:			array(vessels)	of real;		!Fuel consumption per hour
	DEMAND:			array(installations) of integer;	!Demand at each installations
	CAP:			array(vessels)	of integer;		!Capacity of each vessel
end-declarations

 declarations
	nSchedules:	dynamic array(vessels)			of integer;
	!Number of schedules generated for each vessel
	totalTime:	dynamic array(vessels,integer)			of real;
	!The time vessel v uses on schedule r
	serviceA:	dynamic array(vessels,integer,installations)  of integer;
	!Service matrix
	serviceC:	dynamic array(vessels,integer)			of real;
	!Cost of route r for vessel v
end-declarations

initializations from DataFile
	nVessels;
	nInstallations;
	serviceT;
	v;
	fuelC;
	DIST;
	depotT;
end-initializations
```

```
vessels            := 1..nVessels;
installations      := 1..nInstallations;
!node              := 1..nNodes;

initializations from DataFile
        DEMAND;
        CAP;
        fuelh;
end-initializations

!***********************************************************************************
! Model declarations
!***********************************************************************************
 declarations
                Sub_TSP:        Model;  !Define the TSP model
                modelfile:      string;
                inputfile:      string;
                outputfile:     string;
                OUTPUT:         string;
end-declarations
!Defining the subproblem and the data files that will be used

                modelfile := "tsp1";
                inputfile :=  "raw:";
                outputfile :=  "raw:";
                OUTPUT := 'TESTING.dat'; !File to write out route data to
!***********************************************************************************
! ROUTE GENERATION
!***********************************************************************************
declarations

                PATH =  record          !PATH is the paths/routes for each ship
                        V:              integer;                !vessel that is used for this path
                        N:              set of integer;         !nodes included in this path
                        D:              real;                   !Total demand for this route
                        T:              real;                   !Total time for this route
                end-record;

                PPATH:                  dynamic array(vessels,integer) of PATH;
                PP:                     array(vessels) of set of integer;
                NP:                     array(vessels) of set of integer;
                partial: integer;       !Partial paths
                pos_partial: PATH;
                p_counter: integer;     !Number of routes generated
                PPP: set of integer;
                pos_inst : set of integer;
                NN: set of integer;     !Nodes that should be sent to the sub problem
                TT: real;               !the time of the path sent from the sub problem
                N: set of integer;
end-declarations

forall(vv in vessels)do
```

```
    p_counter:=1;

    forall(ii in installations)do           !Here all the initial values for the paths are created
            PPATH(vv,p_counter).N :={ii};
            PPATH(vv,p_counter).D :=DEMAND(ii);
            PPATH(vv,p_counter).T :=0;
            PPATH(vv,p_counter).V :=vv;
            PP(vv) +={p_counter};
            p_counter+=1;
    end-do

while(getsize(PP(vv))<>0)do                 !continue the operation as long as PP is not empty

            PPP := PP(vv);
            partial := PPP(1);
            PP(vv)-={partial};              !Reduce PP with the partial path
            NP(vv)+={partial};              !Add the partial path to NP
            pos_inst := installations;
            pos_inst -= PPATH(vv,partial).N;
                    forall(ii in pos_inst | ii > max(j in PPATH(vv,partial).N)j )do
                     !Here we go through all the nodes not in PPATH(vv,partial).N

                            PPATH(vv,p_counter).N :=PPATH(vv,partial).N;
                            PPATH(vv,p_counter).D :=PPATH(vv,partial).D;
                            PPATH(vv,p_counter).T :=PPATH(vv,partial).T;
                            PPATH(vv,p_counter).V :=PPATH(vv,partial).V;



                            PPATH(vv,p_counter).N +={ii};               !Add the node ii to PPATH
                            PPATH(vv,p_counter).D += DEMAND(ii);        !Add the demand of the node ii

                            if(PPATH(vv,p_counter).D<=CAP(vv))then
                            !Check if capacity constraint is okay

                                    NN := PPATH(vv,p_counter).N;


                                    initializations to inputfile
                                            NN as "shmem:NN";
                                    end-initializations
                                    !Send the P to the inputfile, so it can be used in the tsp model

                            !solve the subproblem for the nodes in P.N and get P.T
                            if compile("tsp1.mos")<>0 then exit(1); end-if
                            load(Sub_TSP, "tsp1.bim"); ! Load the bim file
                            run(Sub_TSP); ! Start model execution
                            wait(1); ! Wait 1 second for an event
                            if isqueueempty then ! No event has been sent: model still runs
                            writeln("Stopping the submodel");
                            stop(Sub_TSP); ! Stop the model
                            wait(1); ! Wait for model termination
                            end-if
```

```
                        dropnextevent; ! Ignore termination event message

                        initializations from outputfile
                                TT as "shmem:TT";
                        end-initializations
                        !Get the time of the route back from the tsp model

                        PPATH(vv,p_counter).T :=TT;
                        !Update the time of the path

                        if(PPATH(vv,p_counter).T<=168)then
                        !Check that the time of the route is less than one week

                        PP(vv)+={p_counter};        !If the path is feasible we extend PP(vv)
                        p_counter += 1;   !The number of routes will be increased by 1

                        end-if

                        end-if
                end-do
        end-do
end-do

forall(vv in vessels, nn in NP(vv))do

        nSchedules(vv) +=1;
        if(getsize(PPATH(vv,nn).N)=1)then
        !Update the time for the routes with only one installation
        !these are not taken care of in the sub problem
        N :={};
        N :=PPATH(vv,nn).N;
        totalTime(vv,nn) :=DIST(N(1),9)*2/v+serviceT+depotT;
        PPATH(vv,nn).T :=totalTime(vv,nn);
        end-if

        totalTime(vv,nn) :=PPATH(vv,nn).T;
        serviceC(vv,nn) :=totalTime(vv,nn)*fuelh(vv)*fuelC;
        writeln;
        writeln('Path : ', PPATH(vv,nn)); !Write out the feasible paths we have
end-do

forall(vv in vessels, nn in NP(vv), ii in installations)do

forall(aa in PPATH(vv,nn).N          |ii=aa)do
serviceA(vv,nn,ii):=1;        !Update the service matrix to be sent to the datafile for the main problem
end-do
end-do

forall(vv in vessels)do
writeln('Number of schedules : ', nSchedules(vv));
end-do
```

```
!********************************************************************************************! POST
PROCESSING OF DATA, WRITE OUT TO FILE FOR MASTER PROBLEM
!********************************************************************************************

 !Make the data ready for the masterproblem
  initializations to OUTPUT
        nSchedules      as      "nSchedules";

        totalTime       as      "totalTime";

        serviceA as     "serviceA";

        serviceC as     "serviceC";
 end-initializations

writeln(" The solution time      : ", strfmt(gettime - solutiontime,7,2));
!Get time to generate the routes

end-model
```

```
!MODEL FOR THE TRAVELLING SALESMAN PROBLEM
model Sub
uses "mmxprs","mmjobs","mmsystem", "mmive" ; !gain access to the Xpress-Optimizer solver

forward procedure break_subtour
forward procedure print_sol

declarations
	node:					set of integer;
	DIST:		dynamic array(integer,integer) of integer;
	nextnode:	dynamic array(node)	of integer;
	v:					real;		!sailing speed
	serviceT:				real;		!time to service on installation
	depotT:					real;		!time to load cargo at the depot
	nNodes:					integer;
	TT:					real;	!Time of route
	DD: real;				!Distance of route
	x: dynamic array(node,node) of mpvar; !Variable for each arc between nodes
	NNN: set of integer;
	inputfile:	string;
	outputfile: string;
end-declarations

inputfile :=  "raw:";
outputfile :=  "raw:";
!Get the data from the route model
NNN :={};

initializations from inputfile
			NNN as "shmem:NN";
end-initializations

initializations from 'GeneralDataInput.dat'
	DIST;
	v;
	serviceT;
	depotT;
end-initializations

node :=NNN;
node +={9}; !9 is the land depot

nNodes :=getsize(node);
forall(ii in node,jj in node | ii<jj) DIST(jj,ii):=DIST(ii,jj) !Symmetric distance matrix
forall(ii in node,jj in node | exists(DIST(ii,jj)))do
	create(x(ii,jj));
	x(ii,jj) is_binary;
end-do

! Objective: total distance
 TotalDist:= sum(ii,jj in node | ii<>jj) DIST(ii,jj)*x(ii,jj)

! Visit every city once
```

```
 forall(ii in node) OneVisitI(ii):= sum(jj in node | ii<>jj) x(ii,jj) = 1
 forall(jj in node) OneVisitJ(jj):= sum(ii in node | ii<>jj) x(ii,jj) = 1

forall(ii,jj in node | ii<>jj) x(ii,jj) is_binary

! Solve the problem
minimize(TotalDist)

 break_subtour
!Use the subtour breaking procedure

!-----------------------------------------------------------------
!Destroy subtours by adding constraints
!The model file tsp.m from the xpress example file has been used as a basis
 procedure break_subtour
  declarations
   TOUR,SMALLEST,ALLCITIES: set of integer
  end-declarations

  forall(ii in node)
   nextnode(ii):= integer(round(getsol(sum(jj in node) jj*x(ii,jj) )))

print_sol

! Get (sub)tour containing the first node
  TOUR:={}

  first:=node(1)
  repeat
   TOUR+={first}
   first:=nextnode(first)
  until first=node(1)
  size:=getsize(TOUR)

! Find smallest subtour
  if size < nNodes then
   SMALLEST:=TOUR
   if size>2 then
    ALLCITIES:=TOUR
    forall(ii in node) do
     if(ii not in ALLCITIES) then
      TOUR:={}
      first:=ii
      repeat
       TOUR+={first}
       first:=nextnode(first)
      until first=ii
      ALLCITIES+=TOUR
      if getsize(TOUR)<size then
       SMALLEST:=TOUR
       size:=getsize(SMALLEST)
      end-if
      if size=2 then
```

```
      break
     end-if
    end-if
   end-do
  end-if

! Add a subtour breaking constraint
 sum(ii in SMALLEST) x(ii,nextnode(ii)) <= getsize(SMALLEST) - 1

! Re-solve the problem
  minimize(TotalDist)

  break_subtour
 end-if
end-procedure
!-----------------------------------------------------------------
!Write out the solution
procedure print_sol
 declarations
  ALLCITIES: set of integer
 end-declarations
 forall(i in node, j in node)do
          if(getsol(x(i,j))>0.999)then
                    nextnode(i):=j;
          end-if
 end-do

 writeln("Total distance: ", getobjval)
 ALLCITIES:={}
 forall(ii in node) do
  if(ii not in ALLCITIES) then
   write(ii)
   first:=ii
   repeat
    ALLCITIES+={first}
    write(" - ", nextnode(first))
    first:=nextnode(first)
   until first=ii
   writeln
  end-if
 end-do
end-procedure

DD :=getobjval;

TT := DD/v+serviceT*getsize(NNN)+depotT;
!Find the time of the route

initializations to outputfile
                    TT as "shmem:TT";
end-initializations
!Send the data to the route generation model
end-model
```

```
!GENERALDATA INPUT FILE

nVessels            : 10
!Number of vessel types
nInstallations      : 8
!Number of installations to service
freqS     : [ 3, 3, 3, 3, 3, 3, 3, 3 ]
!Visiting frequency for each installation
charterC            : [ 17000 , 19687 , 22827 , 23151 , 27392 , 28590 , 30014 , 30791 , 31597 , 35000 ]
!Daily charter cost per vessel type
largeNumber: 2
!Maximum number of routes per vessel

fuelh: [0.38 , 0.35 , 0.31 , 0.38 , 0.52 , 0.46 , 0.48 , 0.35 , 0.40 , 0.42]
!Fuel cnsumption for each ship per hour in tons
fuelC: 900
!Fuel cost per ton

v: 12
!Speed of the vessels in knots

serviceT: 4
!Assuming same service time for each installation,

depotT: 8
!ASsuming that it takes 8 hours to load cargo at the depot

DIST: [(1 9) 533 (2 9) 577 (3 9) 649 (4 9) 580 (5 9) 610 (6 9) 635 (7 9) 581 (8 9) 542
       (1 2) 95 (1 3) 163 (1 4) 62 (1 5) 97 (1 6) 131 (1 7) 58 (1 8) 28
       (2 3) 84 (2 4) 38 (2 5) 33 (2 6) 59 (2 7) 74 (2 8) 64
                   (3 4) 96 (3 5) 60 (3 6) 30 (3 7) 111 (3 8) 131
                          (4 5) 35 (4 6) 99 (4 7) 38 (4 8) 37
                                     (5 6) 64 (5 7) 61 (5 8) 70
                                            (6 7) 89 (6 8) 107
                                                   (7 8) 42]
!9 is the land depot
!Distance matrix

CAP: [620 703 800 810 941 978 1022 1046 1082 1176]
!Deck cargo capacity of vessel v

DEMAND: [250 250 250 250 250 250 250 250]
!Demand of deck cargo for installation ii, m2, per visit
```

Appendix 12 Xpress models for setup 3

!THIS IS THE MAIN MODEL, SAME AS THE ONEDISCUSSED IN CHAPTER 4.1.1

```
model model2
uses "mmxprs", "mmsystem"; !gain access to the Xpress-Optimizer solver

options explterm
! This option means that all commands must end with a ;
options noimplicit
! This option means that everything must be declared before it is used

parameters
	DataFile = 'GeneralDataInput2.dat';
	RouteGeneration = 'TESTING.dat';
end-parameters
! it is necessary to have two datafiles, one general and one generatd by the route generation model file

declarations
	nVessels:		integer;		!Number of vessels in the model
	nInstallations:	integer;		!Number of installations to supply
	nLocations:		integer;		!Number of location for storage unit
	vessels:		set of integer;	!Set of vessels
	vesselTypes:	set of integer;	!Set of vessel types
	vesselType:		dynamic array(vessels)		of integer;
	vesselsOfType:	dynamic array(vesselTypes)	of set of integer;
	numVesselsOfType :	integer;
	installations:	set of integer;	!Set of installations
	locations:		set of integer;	!Set of locations
end-declarations
!Data describing the size of the problem

initializations from DataFile
	nVessels;
	nInstallations;
	nLocations;
end-initializations


vesselTypes := 1..nVessels;
numVesselsOfType := 4;

forall(i in vesselTypes, j in 1..numVesselsOfType)do
	vesselsOfType(i) += {j+((i-1)*numVesselsOfType)};
	vessels+={j+((i-1)*numVesselsOfType)};
	vesselType(j+((i-1)*numVesselsOfType)):=i;
end-do
!Makes it possible to have more than 1 vessel of each type

installations := 1..nInstallations;
locations := 1..nLocations;
```

```
declarations
nSchedules:             dynamic array(vessels,locations) of integer;
schedules:              dynamic array(vessels,locations) of set of integer;
end-declarations
!Defining the shedules for each vessel



initializations from RouteGeneration
        nSchedules;
end-initializations


forall (vv in vessels,ll in locations, ii in 1..nSchedules(vesselType(vv),ll)) do
        schedules(vv,ll) += {ii} ;
end-do
!Making the set of routes for each vessel

declarations
totalTime:      dynamic array(vessels,integer,locations)                of real;
serviceA:       dynamic array(vessels,integer,installations,locations) of integer;
freqS:          array(installations)                                    of integer;
charterC:       array(vessels)                                          of integer;
serviceC:       dynamic array(vessels,integer,locations)                of real;
locationC:                                                              real;
largeNumber:                                                            integer;
end-declarations

!"totalTime" will be generated in step 1 and is the total time i nhours of schedule r for ship k
!"serviceA" will be generated in step 1 ans is a constant that is equal to 1 if vessel v service
!installation i on schedule r
!"freqS" is the minimum number of weekly services for installation i
!"charterC" is the cost of using supply vessel v
!"serviceC" will be generated in step 1 and is the service cost of sailing route r with vessel v
!locationC is the cost of using the storage units
!LargeNumber is how many route a ship can be used for

initializations from RouteGeneration
        totalTime;
        serviceA;
        serviceC;
end-initializations

initializations from DataFile
        freqS;
        charterC;
        largeNumber;
        locationC;
end-initializations

declarations
        X:              dynamic array(vessels,integer,locations)        of mpvar;
```

```
		Y:			dynamic array(vessels)			of mpvar;
		Z:			dynamic array(locations)			of mpvar;
		FreqCon:		dynamic array(installations,locations)	of linctr;
		TimeCon:		dynamic array(vessels,locations)		of linctr;
		ConnectCon:	dynamic array(vessels,locations)		of linctr;
		zCon:									linctr;
end-declarations
! X is an integer variable indicating the number of times in the timer period ship v sails its schedule r
! Y is a binary variable that is equal to 1 if vessel v is used in the optimal solution, 0 otherwise
! Z is a binary variable that is equal to 1 if the storage unit is used at location l, 0 otherwise
! Constraint (16) in the report
! Constraint (17) in the report
! Constraint (18) in the report
! Constraint (19) in the report

forall (vv in vessels,ll in locations, rr in schedules(vv,ll)) do
		create(X(vv,rr,ll));
end-do


forall (vv in vessels) do
		create(Y(vv));
end-do

forall (ll in locations) do
		create(Z(ll));
end-do

declarations
		TotalCost:				linctr;
end-declarations
! TotalCost = The value of the objective function

TotalCost :=
sum(vv in vessels) 7*charterC(vesselType(vv)) * Y(vv) + sum(vv in vessels,ll in locations, rr in schedules(vv,ll))
serviceC(vesselType(vv),rr,ll) * X(vv,rr,ll) +sum(ll in locations) locationC * Z(ll);
!This is the objective function, to be minimized


forall (ii in installations,ll in locations) do
FreqCon(ii,ll):= sum(vv in vessels, rr in schedules(vv,ll))serviceA(vesselType(vv),rr,ii,ll)*X(vv,rr,ll)  >= freqS(ii)-(1-
Z(ll))*freqS(ii);
end-do
!This constraint ensures that each offshore installation is serviced at least the minimum number of times

forall (vv in vessels, ll in locations) do
TimeCon(vv,ll) := sum(rr in schedules(vv,ll)) totalTime(vesselType(vv),rr,ll) * X(vv,rr,ll) <= 168*Z(ll);
end-do
!This constraint ensure that the sum of the total time of the schedules for a given vessel does not exceed 168 hours
! in this case 1 week, change number if longer time period.

forall (vv in vessels,ll in locations) do
		ConnectCon(vv,ll) := sum(rr in schedules(vv,ll)) X(vv,rr,ll) - largeNumber * Y(vv) <= 0;
```

```
end-do
!Ensure that if at least one schedule is selecte, then the corresponding binary variable for the vessel must be equal to one

zCon := sum(ll in locations) Z(ll) >=1;

declarations
		tempVessels: set of integer;
end-declarations

forall(tt in vesselTypes)do
		tempVessels := vesselsOfType(tt);
		tempVessels -={tempVessels(1)};
		forall( vv in tempVessels,ll in locations)do
				sum(rr in schedules(vv,ll)) X(vv,rr,ll)<= sum(rr in schedules(vv-1,ll)) X(vv-1,rr,ll);
		end-do
end-do
!Symmetry constraints for vessels of the same type


forall(vv in vessels,ll in locations, rr in schedules(vv,ll)) X(vv,rr,ll) is_integer;
!make the X variable integer, tells how many times per week, the vessel sails its schedule

forall(vv in vessels) Y(vv) is_binary;
!make the Y variable binary

forall(ll in locations) Z(ll) is_binary;
!make the Z variable binary

setparam('xprs_verbose',true);
!Get solution details

declarations
		solutiontime:		real;
end-declarations

  solutiontime := gettime;
		minimize(TotalCost);

writeln;
writeln('Optimal objective value : ', getobjval);

forall(vv in vessels,ll in locations,rr in schedules(vv,ll))do
if(getsol(X(vv,rr,ll))>=1)then
writeln("X(",vv," ", rr," ",ll, "): ", getsol(X(vv,rr,ll)));
end-if
end-do
!Write out the solution

writeln(" The solution time		: ", strfmt(gettime - solutiontime,7,2));
!FInd the time of running the model

end-model
```

```
!THIS IS THE MODEL FOR THE ROUTE GENERATION
model Routes
uses "mmjobs","mmjobs","mmsystem";

options explterm
options noimplicit

parameters
	DataFile = 'GeneralDataInput2.dat';
end-parameters

declarations
	solutiontime:	real;
end-declarations
 solutiontime := gettime;

declarations
	nVessels:		integer;		!nVessels, Number of vessels
	nInstallations:		integer;		!nInstallation, Number of installations
	nLocations:		integer;		!nLocations, number of locations
	vessels:		set of integer;	!vessels, describing the set of vessels
	installations:		set of integer;	!installations, describing the set of installations
	locations:		set of integer;	!Set of location for the storage unit
	npath:			integer;		!Counter for the number of paths created

	serviceT:		integer;
	v:			integer;		!v, Sailing speed of all vessels,
	depotT:			integer;		!Time to load a PSV
	DIST:			array(integer,integer) of integer;
	fuelC:			integer;		!fuelC, Cost per ton of fuel
	fuelh:			array(vessels)	of real;
	DEMAND:			array(installations) of integer;	!Demand at each installations
	CAP:			array(vessels)	of integer;	!Capacity of each vessel
end-declarations

 declarations
	nSchedules:	dynamic array(vessels,locations)			of integer;
	totalTime:	dynamic array(vessels,integer,locations)		of real;
	serviceA:	dynamic array(vessels,integer,installations,locations) of integer;
	serviceC:	dynamic array(vessels,integer,locations)		of real;
end-declarations
 !This is the data that will be sent to the main model
```

```
initializations from DataFile
        nVessels;
        nInstallations;
        nLocations;
        serviceT;
        v;
        fuelC;
        DIST;
        depotT;
end-initializations


vessels         := 1..nVessels;
installations   := 1..nInstallations;
locations       := 1..nLocations;

initializations from DataFile
        DEMAND;
        CAP;
        fuelh;
end-initializations

!***************************************************************************************
! Model declarations
!***************************************************************************************

 declarations
                Sub_TSP:        Model;
                modelfile:      string;
                inputfile:      string;
                outputfile:     string;
                OUTPUT:                 string;
end-declarations
!Defining the subproblem and the data files that will be used

                modelfile := "tsp2";
                inputfile :=  "raw:";
                outputfile :=  "raw:";
                OUTPUT := 'TESTING.dat'; !File to write out route data to
```

```
!*************************************************************************************
! ROUTE GENERATION
!*************************************************************************************

declarations

                    PATH =   record              !PATH is the paths/routes for each ship
                             V:                  integer;                  !vessel that is used for this path
                             N:                  set of integer;           !nodes incldued in this path
                             D:                  real;                     !Total demand for this route
                             T:                  real;                     !Total time for this route
                    end-record;

PPATH:              dynamic array(vessels,integer,locations) of PATH;
PP:                 array(vessels,locations) of set of integer;
NP:                 array(vessels,locations) of set of integer;

partial: integer; !Partial paths
pos_partial: PATH;
p_counter: integer;          !Number of routes generated
PPP: set of integer;
pos_inst : set of integer;

NN:       set of integer;      !Nodes that should be sent to the sub problem
TT:       real;                !the time of the path sent from the sub problem
N:        set of integer;
end-declarations


forall(vv in vessels,ll in locations)do
          p_counter:=1;



          forall(ii in installations)do              !Here all the initial values for the paths are created
                    PPATH(vv,p_counter,ll).N :={ii};
                    PPATH(vv,p_counter,ll).D :=DEMAND(ii);
                    PPATH(vv,p_counter,ll).T :=0;
                    PPATH(vv,p_counter,ll).V :=vv;
                    PP(vv,ll) +={p_counter};
                    p_counter+=1;
          end-do
```

```
while(getsize(PP(vv,ll))<>0)do                    !continue the operation as long as PP is not empty

            PPP := PP(vv,ll);
            partial := PPP(1);
            PP(vv,ll)-={partial};                  !Reduce PP with the partial path
            NP(vv,ll)+={partial};                  !Add the partial path to NP
            pos_inst := installations;
            pos_inst -= PPATH(vv,partial,ll).N;
            forall(ii in pos_inst | ii > max(j in PPATH(vv,partial,ll).N)j )do
            !here we go through all the nodes not in PPATH(vv,partial).N

                  PPATH(vv,p_counter,ll).N :=PPATH(vv,partial,ll).N;
                  PPATH(vv,p_counter,ll).D :=PPATH(vv,partial,ll).D;
                  PPATH(vv,p_counter,ll).T :=PPATH(vv,partial,ll).T;
                  PPATH(vv,p_counter,ll).V :=PPATH(vv,partial,ll).V;



                  PPATH(vv,p_counter,ll).N +={ii};      !Add the node ii to PPATH
                  PPATH(vv,p_counter,ll).D += DEMAND(ii);     !Add the demand of the node ii

                        if(PPATH(vv,p_counter,ll).D<=CAP(vv))then
                        !Check that capacity of vessel is not broken
                        NN := PPATH(vv,p_counter,ll).N;


                        initializations to inputfile
                        NN as "shmem:NN";
                        ll as "shmem:ll";
                        end-initializations
                        !Send the data to the inputfile, so it can be used in the tsp model

                        !solve the subproblem for the nodes in P.N and get P.T
                        if compile("tsp2.mos")<>0 then exit(1); end-if
                        load(Sub_TSP, "tsp2.bim"); ! Load the bim file
                        run(Sub_TSP); ! Start model execution
                        wait(1); ! Wait 1 second for an event
                        if isqueueempty then ! No event has been sent: model still runs
                        writeln("Stopping the submodel");
                        stop(Sub_TSP); ! Stop the model
                        wait(1); ! Wait for model termination
                        end-if
                        dropnextevent; ! Ignore termination event message


                              initializations from outputfile
                                    TT as "shmem:TT";
                              end-initializations
                              !Get TT back from the tsp model

                              PPATH(vv,p_counter,ll).T :=TT;
                              !Update the time of the path
```

```
                                if(PPATH(vv,p_counter,ll).T<=168)then
                                !Check that the time of the route is less than one week

                                PP(vv,ll)+={p_counter};     !If the path is feasible we extend PP(vv)
                                p_counter += 1;             !The number of routes will be increased by 1
                                end-if
                        end-if
                end-do
        end-do
end-do

forall(vv in vessels,ll in locations, nn in NP(vv,ll))do

nSchedules(vv,ll) +=1;
if(getsize(PPATH(vv,nn,ll).N)=1)then        !Update the time for the routes with only one installation
N :={};                                     !these are not taken care of in the sub problem
N :=PPATH(vv,nn,ll).N;
totalTime(vv,nn,ll) :=DIST(N(1),ll+8)*2/v+serviceT+depotT;
PPATH(vv,nn,ll).T :=totalTime(vv,nn,ll);
end-if

        totalTime(vv,nn,ll) :=PPATH(vv,nn,ll).T;
        serviceC(vv,nn,ll) :=totalTime(vv,nn,ll)*fuelh(vv)*fuelC;
        writeln;
        writeln('Path : ', PPATH(vv,nn,ll)); !Write out the feasible paths we have
end-do

forall(vv in vessels,ll in locations, nn in NP(vv,ll), ii in installations)do

forall(aa in PPATH(vv,nn,ll).N        |ii=aa)do
serviceA(vv,nn,ii,ll):=1;         !Update the service matrix to be sent to the datafile for the main problem
end-do
end-do

!*************************************************************************************
! POST PROCESSING OF DATA, WRITE OUT TO FILE FOR MASTER PROBLEM
!*************************************************************************************

initializations to OUTPUT
        nSchedules      as      "nSchedules";

        totalTime       as      "totalTime";

        serviceA as     "serviceA";

        serviceC as     "serviceC";
 end-initializations

writeln(" The solution time       : ", strfmt(gettime - solutiontime,7,2));
!Get the solution time

end-model
```

```
!MODEL FOR SOLVING THE TSP SUB-PROBLEM
model Sub
uses "mmxprs","mmjobs","mmsystem", "mmive" ; !gain access to the Xpress-Optimizer solver

forward procedure break_subtour
forward procedure print_sol

declarations
	node:		set of integer;
	DIST:		dynamic array(integer,integer) of integer;
	nextnode:	array(node) of integer;
	v:		real;		!sailing speed
	serviceT:	real;		!time to service on installation
	depotT:		real;		!time to load cargo at the depot
	nNodes:		integer;


	TT: real;	!Time of route
	DD: real;	!Distance of route

	x: dynamic array(node,node) of mpvar;

	NNN:		set of integer;
	ll:		integer;  !Location number
	inputfile:	string;
	outputfile:	string;
end-declarations

inputfile :=  "raw:";
outputfile :=  "raw:";
!Get the data from the route model
NNN :={};

initializations from inputfile
		NNN as "shmem:NN";
		ll as "shmem:ll"
end-initializations
!Get node and location data from the route model

initializations from 'GeneralDataInput2.dat'
	DIST;
	v;
	serviceT;
	depotT;
end-initializations

node :=NNN;
node +={8+ll}; !This describes the depot (location of storage unit)

nNodes :=getsize(node);
forall(ii in node,jj in node | ii<jj) DIST(jj,ii):=DIST(ii,jj)		!Symetric distance matrix
forall(ii in node,jj in node | exists(DIST(ii,jj)))do
	create(x(ii,jj));
```

```
            x(ii,jj) is_binary;
end-do

! Objective: total distance
 TotalDist:= sum(ii,jj in node | ii<>jj) DIST(ii,jj)*x(ii,jj)

! Visit every city once
 forall(ii in node) OneVisitI(ii):= sum(jj in node | ii<>jj) x(ii,jj) = 1
 forall(jj in node) OneVisitJ(jj):= sum(ii in node | ii<>jj) x(ii,jj) = 1

 forall(ii,jj in node | ii<>jj) x(ii,jj) is_binary

! Solve the problem
 minimize(TotalDist)

 break_subtour
!Use the subtour breaking procedure
!------------------------------------------------------------------
!Destroy subtours by adding constraints
!The model file tsp.m from the xpress example file has been used as a basis

 procedure break_subtour
  declarations
   TOUR,SMALLEST,ALLCITIES: set of integer
  end-declarations

  forall(ii in node)
   nextnode(ii):= integer(round(getsol(sum(jj in node) jj*x(ii,jj) )))

print_sol

! Get (sub)tour containing city 1
  TOUR:={}
  first:=node(1);
  repeat
   TOUR+={first}
   first:=nextnode(first)
  until first=node(1)
  size:=getsize(TOUR)

! Find smallest subtour
  if size < nNodes then
   SMALLEST:=TOUR
   if size>2 then
    ALLCITIES:=TOUR
    forall(ii in node) do
     if(ii not in ALLCITIES) then
      TOUR:={}
      first:=ii
      repeat
       TOUR+={first}
       first:=nextnode(first)
      until first=ii
```

```
     ALLCITIES+=TOUR
     if getsize(TOUR)<size then
      SMALLEST:=TOUR
      size:=getsize(SMALLEST)
     end-if
     if size=2 then
      break
     end-if
    end-if
   end-do
  end-if

! Add a subtour breaking constraint
 sum(ii in SMALLEST) x(ii,nextnode(ii)) <= getsize(SMALLEST) - 1

! Re-solve the problem
  minimize(TotalDist)

  break_subtour
 end-if
end-procedure
!-----------------------------------------------------------------
!Write out the solution
procedure print_sol
 declarations
  ALLCITIES: set of integer
 end-declarations

 writeln("Total distance: ", getobjval)
 ALLCITIES:={}
 forall(ii in node) do
  if(ii not in ALLCITIES) then
   write(ii)
   first:=ii
   repeat
    ALLCITIES+={first}
    write(" - ", nextnode(first))
    first:=nextnode(first)
   until first=ii
   writeln
  end-if
 end-do
end-procedure

DD :=getobjval;

TT := DD/v+serviceT*getsize(NNN)+depotT;
writeln(TT);
 initializations to outputfile
                    TT as "shmem:TT";
 end-initializations

 end-model
```

```
!GENERALDATA INPUT FILE
nVessels          : 10                    !Number of vessel types
nInstallations    : 8                     !Number of installations to service
nLocations                : 8             !Number of possible location for the storage unit
freqS     : [ 3, 3, 3, 3, 3, 3, 3, 3 ]    !Visiting frequency for each installation
charterC : [ 17000 , 19687 , 22827 , 23151 , 27392 , 28590 , 30014 , 30791 , 31597 , 35000 ]
!Daily charter cost per vessel type

largeNumber: 4                            !Maximum number of routes per vessel
locationC:         700000                 !Cost of the storage unit
fuelh: [0.38 , 0.35 , 0.31 , 0.38 , 0.52 , 0.46 , 0.48 , 0.35 , 0.40 , 0.42]
!Fuel cnsumption for each ship per hour in tons

fuelC: 900                                !Fuel cost per ton

v: 12                                     !Speed of the vessels in knots

serviceT: 4                               !Assuming same service time for each installation,

depotT: 8                                 !ASsuming that it takes 8 hours to load cargo at the depot

DIST: [
(1 9) 16 (1 10) 43 (1 11) 45 (1 12) 87 (1 13) 82 (1 14) 120 (1 15) 116 (1 16) 142
(2 9) 86 (2 10) 21 (2 11) 59 (2 12) 15 (2 13) 44 (2 14) 41 (2 15) 57 (2 16) 65
(3 9) 161 (3 10) 122 (3 11) 120 (3 12) 78 (3 13) 74 (3 14) 41 (3 15) 42 (3 16) 16
(4 9) 68 (4 10) 32 (4 11) 24 (4 12) 30 (4 13) 22 (4 14) 61 (4 15) 53 (4 16) 79
(5 9) 99 (5 10) 61 (5 11) 57 (5 12) 20 (5 13) 20 (5 14) 27 (5 15) 22 (5 16) 46
(6 9) 133 (6 10) 94 (6 11) 88 (6 12) 50 (6 13) 49 (6 14) 20 (6 15) 19 (6 16) 13
(7 9) 72 (7 10) 54 (7 11) 20 (7 12) 62 (7 13) 40 (7 14) 85 (7 15) 71 (7 16) 100
(8 9) 35 (8 10) 22 (8 11) 21 (8 12) 62 (8 13) 58 (8 14) 95 (8 15) 89 (8 16) 115
    (1 2) 95 (1 3) 163 (1 4) 62 (1 5) 97 (1 6) 131 (1 7) 58 (1 8) 28
   (2 3) 84 (2 4) 38 (2 5) 33 (2 6) 59 (2 7) 74 (2 8) 64
          (3 4) 96 (3 5) 60 (3 6) 30 (3 7) 111 (3 8) 131
               (4 5) 35 (4 6) 99 (4 7) 38 (4 8) 37
                         (5 6) 64 (5 7) 61 (5 8) 70
                              (6 7) 89 (6 8) 107
                                   (7 8) 42]
!Distance matrix


CAP: [620 703 800 810 941 978 1022 1046 1082 1176]
!Deck cargo capacity of vessel v

DEMAND: [250 250 250 250 250 250 250 250]
!Demand of deck cargo for installation ii, m2, per visit
```