A simulation-based decision support tool for arctic field logistics

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Marine Technology (2-year)
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Norwegian University of Science and Technology
Department of Marine Technology
MASTER THESIS TASK DESCRIPTION

for

Mads Ulstein

A simulation-based decision support tool for arctic field logistics and transit transport

It is estimated that 22% of the world’s undiscovered petroleum resources are located in the Arctic, 84% projected to be offshore in at least partially ice-covered waters, majority in West and Eastern Siberian Basin (US Geology Survey, 2008). Furthermore, the current trend of diminishing ice coverage in the high north allows for extended operational windows, but also introduces new challenges such as drifting ice features close to the continuous ice edge. In addition, the distinct conditions of Arctic Sea, such as remoteness or the lack of marine infrastructure, represent a challenge to be surpassed in order to ensure a safe and economical feasibility. Furthermore, the preferences of the arctic stakeholders will significantly influence technical solutions required to achieve economical feasibility for safe operations. Hence, this project is concerned with the development of a simulation-based decision support tool for arctic field logistics. By doing so, environmental conditions shall be incorporated into the simulation model to assess the sensitivity to the operational duration of Platform Supply Vessels (PSVs). The thesis shall focus on the production phase of an oilfield in the Barents Sea.

The following aspects shall be considered for the simulation-based decision support tool:

- Select KPI’s and variables for arctic field logistics
- Identify arctic field logistic specific requirements
- Identify arctic environmental conditions and operational limitations

The work shall be carried out in the following steps

1) Familiarization with the Arctic Sea region, especially the Barents Sea
2) Literature review of simulation methods for value chains suitable for arctic field logistics
3) Development of a simulation based decision support tool for Arctic field logistics
4) Development of a simulation base case for the North sea
   - Gap analysis comparing the base case with the challenges found for the arctic sea
5) Presentation of the findings and results, both on a generally applicable level as well as with the use of the case studies
6) The conditions, assumptions and limitations of your study shall be discussed with respect to physical relevance
7) Conclusions and recommendations for further work

Literature studies of specific topics relevant to the thesis work may be included. The work scope may prove to be larger than initially anticipated. Subject to approval from the supervisors, topics may be deleted from the list above or reduced in extent.
In the thesis the candidate shall present his personal contribution to the resolution of problems within the scope of the thesis work. Theories and conclusions should be based on mathematical derivations and/or logic reasoning identifying the various steps in the deduction. The candidate should utilise the existing possibilities for obtaining relevant literature.

**Thesis format**
The thesis should be organised in a rational manner to give a clear exposition of objective, results, assessments, and conclusions. The text should be brief and to the point, with a clear language and the objective to be published in a conference article and/or scientific journal. Telegraphic language should be avoided.
The thesis shall contain the following elements: An executive summary, list of symbols and acronyms, followed by the main body of the thesis consisting of a brief background introduction, selection of scientific method, a state of the art defining the knowledge gaps defining the scope or work and limitations, the actual contribution chapters, conclusions with recommendations for further work, references and (optional) appendices. All figures, tables and equations shall be numerated.
The supervisors may require that the candidate, in an early stage of the work, to present a written plan for the completion of the work. The plan may include a budget for the use of computer and laboratory resources if applicable, which will be charged to the department. Overruns shall be reported to the supervisors.
The original contribution of the candidate and material taken from other sources shall be clearly defined following basic academic principles and an acknowledged referencing system, which includes the name of the referred authors followed by the publication year in the text. The subsequent reference list can thus be alphabetical.

The report shall be submitted in two copies:
- Signed by the candidate
- The text defining the scope included
- In bound volume(s)
- Drawings and/or computer prints, which cannot be bound should be organised in a separate folder.
- The report shall also be submitted in PDF along with essential input files for computer analysis, spread sheets, MATLAB files etc. in digital format.

**Ownership**
NTNU has according to the present rules the ownership of the thesis. Any use of the thesis has to be approved by NTNU (or external partner when this applies). The department has the right to use the thesis as if a NTNU employee carried out the work, if nothing else has been agreed in advance.

**Thesis supervisor**

Professor Sören Ehlers

**Deadline: June 10 2014**
Preface

This Master thesis has been written by Mads Ulstein during the spring semester of 2012 at Norwegian University of Science and Technology, Department of Marine Technology.

The objective of the thesis was to investigate the possibility of developing a simulation based decision support tool for Arctic field logistics. Collection of environmental data required an effort, and the model development proved to be more time consuming than first anticipated.

The author would like to express his gratitude to Professor Soren Ehlers for great help and support during the work. Ehlers has always been arranging the best opportunity to complete my thesis successfully. In addition I would like to thank Knut Aaneland and the PhD candidates Martin Bergstrom and Aleksandar-Sasa Milakovic for valuable input and discussions throughout the work.

Trondheim, 9th June 2014

Mads Ulstein
Abstract

As the global demand for energy continues to rise, the oil and gas industry investigates new opportunities for oil and gas production in more remote areas. Promising estimation of oil and gas reserves in the Arctic areas has resulted in an increased focus on oil extraction in the Higher Norths. For the logistic providers and ship yards, this area represent a new era in offshore operations and vessel design. The Arctic area offers challenges to offshore vessels but also to the offshore operation itself. Increased distances to shore and harsh environmental conditions sets new demands to the offshore supply chain.

Platform supply vessels (PSVs) are an important part of the offshore logistic supply chain, providing offshore installations with necessary cargo and personnel. Accurate delivery is of high importance in order to ensure continuously production. Weather or not an offshore operation can be conducted, is restricted by environmental conditions at site. Exceedance of these limitations will affect the feasibility and duration of a voyage. In such cases, an oil operator may be forced to hire a vessel from the spot-marked. Although, offshore field logistics represent an important segment in offshore operations, the literature is scarce on the business side. It is clear that the current situation require new technological solutions, but also new and improved business models to ensure sustainability.

In this paper we address the impact of the Arctic environment on PSVs. It has been investigated if a simulation model could be used to determine the operational duration and optimal fleet composition of PSVs in the Arctic environment. To determine the capability of the model, two case studies were presented.
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Chapter 1

Introduction

The current trend of melting ice in the Arctic will allow for an extended operational window, but also introduce new challenges to offshore operations. The Barents sea is the part of the Arctic Ocean bound by Novaja Semlja in the east, Frans Josefs in the north and Svalbard in west, covering an area of 1.4 million $km^2$. The majority of the Barents Sea is located within Norwegian and Russian boarders. The boarder has been a disputed area for decades, but was finally settled in 2011. The planned extraction of oil and gas resources in the area may require development of new technology and solutions. To ensure safe and feasible operations in the northern areas, challenges and gaps between the North Sea and Barents Sea needs to be identified.

Exploration and Production is a highly capital intensive business. Production loss and down-time can result in a huge financial loss. Accurate delivery of cargo and personnel is therefore of high importance in order to ensure continuously production.

The infrastructure in the North Sea has been developed over decades and consist of an advanced system of, offshore platforms, supply bases and specialized vessels. The offshore oilfield consists of a variety of floating and fixed production units. Each units has its own characteristic cargo requirement depending on type of operation, fuel consumption, personnel on board, storage capacity and technical specification. Offshore logistics compromise the process of transporting cargo and personnel back and fourth these installations. Supply bases are an important hub to ensure that equipment and personnel are delivered to the offshore installations. These bases monitor the offshore operations by radar, Automatic Identification System (AIS), and regulate communication by satellite-based email and telephone. The distance from supply bases to the offshore field are in general not more than 200-300 km. Specially designed Platform Supply Vessels (PSVs) has been developed to transport cargo between the supply base and the offshore installations. The vessels have a large open deck-space aft, and various specialized tanks for liquid cargo transportation. During production phase of an oil field, PSVs usually stay out 1-2 days. During drilling exploration, PSVs can be used as construction support vessel to continuously supply drill rigs with equipment. These
activities are time consuming and can require a vessel to stay for weeks. Oil companies usually hire PSVs from shipowners or ship-brokers. Hired vessels, are refereed to as time-charter vessels. The amount of time-charter vessels in the fleet varies from year to year, depending on the amount of activity offshore.

Whether or not an offshore operation can be conducted, is restricted by the environmental conditions at site. Certain threshold values, refereed to as operational limitations, are set to ensure the safety of personnel and assets. Operational limitations includes restrictions in allowable wave-height, wind speed and visibility. Exceedance of these limitations will affect the duration of a voyage, refereed to as the operational duration, and result in delayed deliveries. In such cases, the oilfield operator may be forced to hire a vessel from the spot-marked. Frequent use of spot-vessels, can result in huge additional cost for the operator. Deciding the amount of time-charter vessels a year ahead is therefore of great importance to reduce the cost of operating vessels. In addition, the required size of these vessels must be thoroughly investigated to reduce the total fuel cost. The number of vessels and their size, is refereed to as the fleet composition. With years of experience, the fleet composition in the North Sea is optimized to operate in a well known environment with a high degree of predictability in the cargo demand.

As the oil & gas companies move their operations further north, extreme environmental conditions and increased distance to shore will oppose challenges to the supply vessels operational duration. To predict the future fleet composition of PSVs in the Arctic, strategic planning and analysis of the environmental conditions must be done. Due to the stochastic nature of the environment on the operational duration, fleet composition can be hard solve by traditional methods. Development of new decision support systems is therefore necessary.

Different approaches has been developed for the maritime industry in order to optimize the fleet composition. The use of spreadsheet is the simplest, but also the most frequently used approach for dealing with such problems. These spreadsheets are developed by planners within the companies with long experience in the maritime industry. Numerous literature has been written trying to replace shipowners use of spreadsheets with optimization based decision support systems. A frequently used method is by applying optimization based on an mixed-integer programming model (MIP). Marine technology centre in Trondheim [15] developed computer based MIP model for optimizing the fleet composition in shipping companies. The result was a programme, which incorporated optimization algorithm with a user-friendly interface, enabling shipping companies to easily optimize their vessel schedules. Resent literature includes Fagerholt et. al. [6] who presented a voyage based model for optimal fleet composition and periodic routing of offshore supply vessels.

Such IP models can also be solved by using search heuristics. Search heuristics are often used to solve complex IP problems, within a limited amount of time. The solution are often near optimal, but there is no guaranty of the quality. One type of search heuristics previously applied to MIP problems is the Genetic Algorithm. The GA solves constrained optimization problems based on natural selection by repeatedly modifying
a population of individual solutions. The algorithm selects individuals to produce "children" for the next generation. Through evolution, the population develops to an optimal solution. The first to develop algorithms for optimization in the maritime industry were Golden et. al [8]. They adapted the Clark and Wright [5] savings technique, originally designed for routing of trucks, to solve a fleet size and mix problem. Recent literature include Salhi et al. [18] who presented a multi-level search heuristic for fleet size and mix problems; Liu et al. [13] who implemented a Genetic Algorithm (GA) based heuristic to determine fleet size and mix problems in linear shipping.

A major challenge with using optimization models is that they exclude stochastic elements, e.g. environmental conditions. In order to assess the operational duration and fleet composition of the PSV vessels, it is therefore necessary to look into alternative methods, such as simulation modelling.

Simulation modelling is the process of designing a model of a real system and conducting experiments with this model in order understand the behaviour and thereby evaluate various strategies for the operation of the system. A simulation model is a decision support technique for solving business problems with complex interactions of stochastic variables. It works as a framework in integrating multiple input parameters in order to understand their interactions and consequences. The type of simulation method to be used, depends on the type of problem in mind. Offshore field logistics can be categorised as an event-driven system.

Discrete event simulation is a quantitative, mathematical, computer model consisting of numerous equations and variables. In a discrete event model, the state of the system will only be affected by particular events occurring at a particular time. The times which an event affect the system is called event times. The occurrence of an event, can initiate processes, activities or trigger new events. Typical events in offshore logistics may be the arrival of vessels in harbour. This event may again trigger an time dependent activity such as loading of cargo. The scheduled arrival of an event in the harbour is calculated based on statistics or stochastic distributions, such as environmental conditions. The discrete event simulation contains discrete items called entities. Entities represent an object, such as a vessel. Each entity can be assigned specific properties called attributes. Examples include speed, cargo capacities or fuel consumption. Entities passing through a block, represent a discrete incident, which changes the state of variable, outputs or occurrence of next event. A resource is an attribute that sets constraints to the system or an entity. A resource can represent a finite capacity, such as allowable number of vessels in port, or a restriction, such as operational limitations. Discrete event models usually contains some kind of random variation, introduced by stochastically distributed activities or input. Detailed analysis of the results is therefore necessary before a decision is made. Most of the research done has focused on control of transportation systems such as fleet scheduling and supply chains for transit logistics. Nevertheless, it seems like there is an increasing focus on the importance of simulating operational duration of PSVs. The newly published article by Maisiuk and Gribkovskaja [14] present a discrete-event simulation model for evaluation of alternative fleet size configurations, while also taking into account uncertainty in weather conditions and spot rates. Glover et al. [7]
developed an approach that combines simulation models and optimization models, by using an optimization algorithm on top of a simulation model. The simulation model was used as a black-box evaluation function. Almeder and Preusser [1] presented an approach, where the solution of the optimization model was translated into decision rules for the discrete-event simulation model. They concluded that an iterative combination of simulation and linear programming is competitive compared to deterministic MIP-models.

It is clear that the use of simulation and optimization methods has been discussed in literature before. Nevertheless, the possibility of developing a simulation model for offshore vessels in the Arctic environment has not been investigated. Needless to say, less attention has been given to combining simulation and optimization methods to optimize the fleet composition. Based on the lack of research done in this area, this thesis will investigate if it possible to develop a simulation based decision support system for Arctic field logistics.

The simulation model should be able to include complex interactions from the stochastic environment, including waves, wind, visibility, jet streams, temperature, polar lows and drifting ice. Resource constraints in form of operational limitations should be implemented to determine the resulting impact on the PSVs operational duration in Arctic environments. The model should be able to illustrate the most critical environmental components of the operational duration. It will also be investigated if the simulation model can be used in combination with a genetic algorithm to find the optimal fleet composition. The model should determine the optimal fleet composition by minimizing the total fuel costs, based on a built in resistance calculation method. A major aim of this thesis is to provide a good starting point for further research in the Arctic area. The model should therefore be able to analyse gaps in both operational duration, as well as fleet composition between the North Sea and The Barents Sea.

The thesis is divided in three main sections. First, an analysis of the general conditions in the Arctic is conducted, including a summary of which environmental conditions that should be implemented in the simulation model. Further, the development of the simulation model will be described followed by two case studies illustrating the capability of the simulation model. Last, a discussion of the suitability of the simulation model will be given.

1.1 Limitations

The simulation of the operational duration is limited to waves, wind, visibility, jet streams, temperature, polar lows and drifting ice. Communication, opening hours at supply base and periodic maintenance of the vessels are therefore not included. Optimization of the fleet composition is based on fuel consumption only. Investment cost, ice-class, and charter rates are not included. The model, as it stands, is limited to the
operational duration of PSVs only.
Chapter 2

Challenges in the Arctic

The environmental conditions in the High North represent a challenge to the offshore supply chain. Sudden changes in the environmental conditions may cause large delays and result in increased operational duration of PSV vessels. In order to include necessary environmental input in the simulation model, the following chapter aims to identify key challenges which are found in the Barents Sea. The identified challenges will be summarised at the end.

2.1 Temperature and icing

The temperature in the Arctic has increased significantly during the last 30 years. Figure 2.1 show the trend in mean surface temperature. The red and dark red colour found in the Arctic areas indicates a temperature increase of 1 - 4.8 degrees over the last 50 years. The temperature in the Arctic is increasing faster than in other parts of the world. Nevertheless, current operations still needs to take into account high temperature variations.
CHAPTER 2. CHALLENGES IN THE ARCTIC

Figure 2.1: Trend in mean surface temperature

The temperature in the Arctic can fall significantly below zero, causing additional challenges for the operations. Icing on seagoing vessels and offshore structures are caused by the accumulation of ice. This is a usual phenomena in the Arctic, and can have huge impact on the protection of personnel, safety and vessel operation. The degree of icing depends on the temperature, salinity in the water, waves and wind conditions at the location, and most frequently occur in open sea. Icing are often divided in tow categories depending on their origin. Atmospheric icing is caused by the meteorological conditions at site. The accumulation of cooled rain, snow or fog on the vessel is a result of atmospheric icing. As new technology has been developed, this form of icing is not generally a problem for Arctic vessels. Sea-spray icing is a result of green sea freezing at the deck. Sea-spray induced icing is most likely to occur when the surface temperature decreases below -1 degree, in combination with wind speeds above 10 m/s.

If subjected to severe icing, weight of the ice can shift the center of gravity of the vessel, resulting in a decrease in stability and sea-keeping ability. The risk of freezing ballast water, is also a concern when operating in cold climates. In addition to slippery decks and rails, icing can also lead to blocking of escape routes and frozen lifeboat launcher. Fire fighting can be problematic if the water freeze in the pipes. Ventilation ducts can be blocked, resulting in accumulation of hydrocarbons in closed areas. Great effort has been put into reduce icing problems on ships. Elimination of dead ended pipes and insulation are done in order to maintaining water flow in pipes. Systems for adding air bubbles in the ballast tanks have been proven as efficient to prevent ballast freezing. In the case of severe icing during operation, de-icing of the vessel must be conducted.

2.2 Polar lows

Polar lows form when cold Arctic air flows over the warm water surface. The Barents Sea is especially exposed for polar lows due to the warm Gulf Stream coincide with the cold air from the Arctic. In the Barents Sea, sea ice isolates the warm ocean from the
atmosphere, and the warm air gets cooled down. In some cases, cold air from the Arctic flows southward. The interaction between cold air and warm water results in polar lows. They constitute a huge risk to marine operations, as they are hard to predict and develop quickly. Polar lows vary in size from 100 to 500 km, with a wind speed average of 22 m/s. Occasionally, they can reach speeds up to 35 m/s. When the polar low is stationary, they can develop significant wave height of 5.5 meters at 35 m/s. In the areas where the travel direction of the polar flow is the same as the wind direction, even larger wave heights can be developed [8]. They reach maximum speed within 12 to 24 hours, but usually don’t last for more than 24 to 48 hours. Polar lows only occur during winter season from October to May, with highest rate during January and March. When observed on radar pictures, they tend to look pretty similar to hurricanes.

2.3 Wind and waves

Wind speed in the Arctic basin has an average between 4-6 m/s. The winds are strongest in the winter season with an average of 7-12 m/s, and weakest in the summer season with an average of 5-7 m/s. Maximum wind speeds can exceed 50 m/s during the winter season. The strongest average winds are found in Baffin Bay, Bering and Chukchi Sea. Figure 2.3 shows that the Barents Sea are exposed to relatively high winds compared with the average in the Arctic. Approximately 20 percent of the time it is found wind speeds between 8-14 m/s. Large wave heights are often a result of large wind speeds. Figure 2.3 show that the average wave height is largest in the Barents Sea, and inclines further east and south. This can be seen in context with the occurrence of polar lows.

![Figure 2.2: Wind speed in the Barents Sea](image-url)
2.4 Ice conditions

The National Snow and Ice Data Center \cite{2} supports research into the Arctic climate. NSIDC distributes more than 500 cryospheric data sets for researchers, from both satellite and ground observations. They began satellite monitoring of the Arctic in 1979, and possess a large number of scientific contributions related to the Arctic environment. In mid September 2012, Arctic sea extent was recorded with a record low level with 3.4 million km$^2$. Recorded ice extent was 760,000 km$^2$ less then the previous record in 2007, and 3.3 million km$^2$ bellow the 1979 to 2000 average. This is the lowest ice extent since the recording started in 1976, and indicates a trend of melting ice in the Arctic region. An ice extent loss of 11.8 million km$^2$ from March to September, also represent the largest number of ice extent loss during one year.
Different models have been developed by scientists trying to model the future ice extent in the Arctic area. By combining sea ice data and climate models, they try to forecast the ice development for years into the future. Some models state that the Arctic will be ice-free in the summers at the end of the century [17], while others later or even sooner [12]. Prediction of the future ice extension heavily depends on the weight given to the data, understanding of Arctic change processes and the use of model projections. So far, few of these models have showed accurate results, which result in continuous update of previous models. Event though the models differ in the prediction of when it will occur, they all conclude that it will happen sooner or later.

Major parts of the Barents Sea are exposed to floating ice or icebergs. Different forms of floating ice can occur at sea, where the most extensive form of floating ice is sea ice. Sea ice is developed by the freezing of sea water and usually reaches its minimum in September and maximum in March [16]. The ice developed during the last winter is called first-year ice. First-year ice is up to 120 cm thick. Ice that has survived one or more summers is called multi-year ice, and can be up to 300 cm thick. Multi-year ice tends to be more compressed than first-year ice, resulting in larger impact on ships and offshore structures. Large masses of floating ice originating from glaciers are called icebergs. Icebergs come in different types and sizes. Bergy bits and growlers are especially dangerous for ship operations, since they are very hard to detect. The ice can be categorised on the basis of their distinctive characteristics [9]. Level-ice is found wherever sea ice is present. It is formed under calm conditions, and has a uniform...
thickness. Rafted ice is the result of two pieces of ice that overrides another. Ice ridges are formed by a wall of broken ice which due to the thermal forces creates a sail and a keel on the ice sheet. The keel are a great hazard to pipelines and sub-sea installations. The strength of the ridges is also a problem for offshore structures.

2.5 Operational differences between the North Sea and Arctic

The uncertainty of Arctic operations in combination with an increased number of stakeholders, regulations and conflicting interests, will result in an increased complexity of the operations. Large distances to shore limits the search and rescue capacity, requiring increased cooperation and communication between the vessels. Uncertainty in the weather conditions may lead increased operational duration, and more frequent delays. Table 2.1 present the main challenges between operations in the North Sea and the Arctic.

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<td>Yes</td>
<td>Delays</td>
<td>Drive around, forecast, ice management</td>
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<td>Temperature</td>
<td>Yes</td>
<td>Can cause icing in combination with sea spray</td>
<td>Proper equipment, deicing</td>
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<td>Wind</td>
<td>Yes</td>
<td>Large delays, emergency preparedness, operational hazard, disconnect</td>
<td>Risk assessment, reduce distances</td>
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<td>Waves</td>
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<td>Large delays, emergency preparedness, operational hazard, disconnect</td>
<td>Risk assessment, reduce distances</td>
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<td>Polar lows</td>
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<td>Large delays, operational hazard, disconnect</td>
<td>More frequent weather forecast</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>Yes</td>
<td>Larger distances</td>
<td>Floating supply base, multipurpose vessel</td>
</tr>
</tbody>
</table>

Table 2.1: Operational triggers
Chapter 3

The simulation model

The simulation model is developed as a "transaction-based" system, with an event-driven behaviour. The system state will only be affected by discrete events. The simulation model contains discrete items called entities. Each entity are assigned specific properties called attributes. Entities passing through a block, represent a discrete incident, which changes the state of variable, outputs or occurrence of next event.

The simulation model contains an integrated simulation and optimization environment. The development has been done by combining non-linear and stochastic elements from simulation with an mixed-integer genetic algorithm for optimization. The simulation model is developed in the Matlab software SimEvents. An overview of the main components in the simulation model is presented in Figure 3.1. The vessels operate in a round-trip systems, where PSVs are transferring cargo back and fourth the supply base.

![Figure 3.1: Overview of the simulation transport system](image)

The supply base consists of three main functions, which is to generate new vessels, assign orders from platforms and load/unload vessels in port. The vessels wait in a queue until an order is assigned. Low cargo volume results in vessel queue, while high cargo volume results in cargo queue. The platform that has the largest backlog of cargo, will be prioritised when assigning cargo. Rest capacity will be assigned remaining platforms. The arrival of an vessel in the supply base is modelled as an event. This event will again
CHAPTER 3. THE SIMULATION MODEL

trigger a process, which is to load cargo. After cargo loading, the vessels sail from the supply base to the oilfield. The transit time is a function of the wave-height and given by the following distribution:

\[
TransitTime = \frac{\text{Distance}}{\text{Speed}} 1.02^{Hs}
\]  

(3.1)

The vessels unload their cargo offshore, and continue to the next platform, before heading back to the supply base. The rate each location has to load/offload is set by a service rate. The rate increase exponentially with wave the wave height.

\[
\text{ServiceRate} = \frac{\text{Cargo}}{3500} 1.04^{Hs}
\]  

(3.2)

Offloading can only take place if the environmental conditions does not exceed the operational limitations. The operational duration, is defined as the time a vessel use between loading cargo at the supply base, until it is back in the harbour.

The simulation model has been developed in five steps containing: vessel generation, order generation, load/offload cargo, transit, environmental input and operational limitations. Detailed description and illustration of the steps are given in Appendix A.

3.1 Simulation input

Simulation input has been divided in six groups. Each group consist of multiple input parameters, which are feed into the model during simulation.

![Figure 3.2: Simulation input](image)

Wave and wind conditions at the location are updated each third hour, and implemented with stochastic variation using various distributions. Figure 3.3 illustrates the process of transforming environmental conditions to stochastic distributed input in the simulation model.
CHAPTER 3. THE SIMULATION MODEL

Figure 3.3: Transformation to stochastically distributed input

Wave data is implemented with a log-normal distribution. The log-normal distribution describes the distribution of a stochastic variable where its logarithm is normally distributed. If \( Y \) is a normally distributed stochastic variable, then \( X \) is log-normal distributed. A log-normal distribution can be described by the density function, where \( \theta \) is the threshold parameter.

\[
f(x) = \begin{cases} 
\frac{e^{\frac{-((\ln x - \theta) - \mu)^2}{2\sigma^2}}}{(x-\theta)\sigma\sqrt{2\pi}} & \text{for } x > \theta \\
0 & \text{otherwise}
\end{cases} 
\]  

(3.3)

Wind data containing both regular wind and jet streams, is implemented with a Gaussian distribution. The distribution is closely connected to the central limit theorem, which states that the sum of a large number of independent random variables are, under certain conditions, approximately normal distributed. A Gaussian distribution can be described by the following equation, where \( \mu \) is the mean parameter and \( \sigma \) is the standard deviation parameter.

\[
f(x) = \frac{exp(-(x-\mu^2/2\sigma^2))}{\sigma\sqrt{2\pi}} 
\]  

(3.4)

Polar lows, visibility, and drifting ice is implemented using the Bernoulli distribution. The Bernoulli distribution is a statistical method of calculating the probability distribution of a random variable which takes the value 1 for success and 0 for failure. The distribution is a special case of binomial distribution in which the number of trials is 1. The distribution can be expressed with the following equation, where \( \rho \) is the probability of 1.
CHAPTER 3. THE SIMULATION MODEL

\[ f(x) = \begin{cases} p^x(1-p)^{1-x} & \text{if } x = 0 \\ 0 & \text{otherwise} \end{cases} \quad (3.5) \]

Fleet size and vessel particulars are inserted as attributes. These values are set at simulation start and kept constant during simulation. Location of the supply base and oilfield, and the distances between them are inserted. The oilfields respective transport demand is established on the basis of the cargo type and frequency. The order is generated by entities where attributes determine the size of each order. The orders are registered as global variables which allows for accumulation of cargo and modification anywhere in the system. In practise, this means that if there are two orders in the base, which one vessel can carry alone, it will load both of the orders.

### 3.2 Operational limitations

Limitations to the vessels ability to perform offloading operations are set by an operational limitations parameter. Waves, wind and visibility are given threshold values. Polar lows, and drifting ice are either allowed, or not allowed. The operational limitation is modelled as a resource, which introduce a constraint to the system. The operational limitations are as follow:

- Wave height: 4 meter significant wave height
- Wind speed incl. jet stream: 30 knots
- Visibility: <200m
- Temperature: -1
- Polar lows: Within a radius of 500 km
- Drifting ice: Within 1km

If the wave height or wind speed exceeds the operational limitation, the vessel will wait for appropriate weather conditions. Wave and wind is updated each third hour. Visibility is given a mean waiting time of three hours with a standard deviation of 30 minutes. Time to de-ice if the temperature is bellow -1 is set as 30 minutes. If an polar low occurs within 500km, the time spent waiting is given by a random number between 24-48 hours. Detailed explanation of the operational limitations including user interface is given in Appendix A.7

### 3.3 Simulation environment

The simulation input is received at various stages during simulation. The interaction between the input and output is displayed in Figure 3.4, where the number represent the
simulation input explained in section 3.1. In the supply base, information about the fleet composition and vessel particulars are set. Resistance and required propulsion power for each vessel in the fleet are then calculated using the Holtrop & Mennen method [10], and outputted from the model. The supply base also reads required transport demand and cargo capacity. The model then calculates the level of cargo at base, and the time used to load cargo. The operational duration of each vessel is registered and outputted. During sailing, the simulation model reads information about service speed, distance and wave conditions. In combination with the Required engine power, it outputs the vessels sailing time and fuel consumption.

Figure 3.4: Simulation environment: Input and output
3.4 Optimization environment

The simulation model contains an environment for optimizing stochastic discrete event simulation. In addition to increasing the flexibility in modifying the objective function, it also makes it easy to run parallel discrete event simulation and optimization without using multiple software. The genetic algorithm solves constrained optimization problems based on natural selection by repeatedly modifying a population of individual solutions. The algorithm selects individuals to produce "children" for the next generation. In each generation, the populations fitness is evaluated and modified. The optimal solution is found when a satisfactory fitness level has been found, or when the maximum number of generations has been conducted. The genetic algorithm supports mixed integer programming and optimization problems where the objective function is stochastic.

The feature has been utilized to minimize the operational costs by selecting the most optimal composition of vessels in the fleet. The objective function is constrained by a maximum allowed backlog of cargo at the platforms. Figure [3.5] show the interaction between the simulation environment and the optimization environment. Upon simulation start, six different vessel sizes are implemented in the fleet. The simulation environment calculates the resistance and required propulsion power for each vessel. At the end of the simulation run, the fuel consumption is registered and used as input in the optimization algorithm. In an iterative process, the genetic algorithm runs the simulation model with varying vessels in the fleet. When the combination of vessels that correspond to the lowest operational cost is found, the process stops. To speed up the system, the MATLAB configuration Parallel Computing Toolbox has been utilized. The implementation allows for running parallel simulations using multiple processors in the computer cluster. During simulation, information about the penalty values and current best fleet composition is displayed in two plots. Detailed information about the optimization script is found in Appendix A.8.
Figure 3.5: Optimization environment: Input and output
Chapter 4

Case studies

To illustrate the capability of the simulation model, two case studies will be presented. The case studies will investigate if the simulation model can be used to illustrate gaps between the North Sea and the Barents Sea. One representative oilfield has been selected on each location. The Balder oilfield represent the North Sea, while the Apollo oil field represent the Barents Sea. Each case study will be compared with a North Sea base case. Environmental conditions are analysed and transformed into probability density functions for the simulation model. The first case study will investigated if the simulation model is capable to measure environmental impact on the operational duration, cargo hold and number of vessels needed. In the second case study, we investigate if the simulation model can utilize discrete event simulation in combination with the genetic algorithm to determine the optimal composition of vessels in the fleet.

Figure 4.1 illustrates the expected outcome in each case study, where blue indicates case study I and, orange case study II.
Figure 4.1: Expected outcome case study. Blue=case study I, orange=case study II
4.1 Environmental input

Time series of significant wave height (Hs) and one hour wind speed at 10 m above sea level (u10) at the two oilfield locations has been provided by BMT ARGOSS [2]. Data is measured each third hour from 1999 - 2012, and is based on underlying databases compromising of long-term global and regional model hind-cast and satellite observations. The data include wind and wave conditions resulting from Polar lows and Jet streams. In order to implement stochastic variations of wave height in the simulation model, the time-series has been transformed into a probability density function and fitted with a log-normal distribution. Distribution for each month is given in Appendix B. Figure 4.2 show the expected mean Hs during one year. The Barents Sea location is exposed to larger wave-heights than North Sea location. At both locations, the wave-heights are largest during the winter months November-February, and lowest during the summer months June-August.

![Figure 4.2: Mean Hs](image)

Time series of mean wind speed 10m above sea level (u10) has been fitted with a Gaussian distribution for each month. The wind data also represent wind conditions resulting from Polar lows and Jet streams. Distribution fitting for each month is given in Appendix B. We can expect wind speeds in the range 25-30 m/s in March, October and December in the Barents Sea, and in the moths January, February, October, and November in the North Sea. Figure 4.3 illustrate the mean values after distribution fitting. Balder has a higher mean wind speed, with an exception of the moths March - May.
Visibility statistics has been provided by the Norwegian Metrological Institute [11]. Fog has been set as visibility below 1000m, and has been divided into three groups according to the length of sight. Poor visibility is visibility in the interval 0-199m, moderate visibility is visibility with up to 499m sight, good visibility is less than 1000m sight. The probability of each group is given in Appendix E while Figure 4.4 illustrates the probability of fog on each location. We can see that July is the most critical month, where we have fog up to 20% of the time, where 4.5% is good visibility, 11.6% is moderate visibility and 3.47% is bad visibility.

Estimation of drifting ice has been done by collecting data from two different sources. Probability of ice occurrence has been collected from The Norwegian Petroleum Safety Authority [3]. To detect variations during the year, number of weeks with sea ice at 1 degree North of the oilfield has been collected from U.S. National Ice Center [4]. The collected data indicates that there will be ice occurrence from November to June. The results can be seen in Figure 4.4 while data collection is given in Appendix D.
Observations and daily registrations of polar lows in the period 2003-2011 are provided by the Norwegian Metrological Institute [11]. The observations are given in Appendix F. The probability of polar low occurrence has been derived by counting the number of occurrences within a radius of 500km of the location. January and December is the most critical months with a total of 24 incidents. In the summer months, June-September, no polar lows were observed. The highest mean wind speed of the polar lows was during February, with an average of 24 m/s. There were no observed polar lows in the southern part of the north sea.

Sea temperature in the period 2008-2013 has been provided by Norwegian Metrological Institute [11]. Figure 4.7 show that there are large differences in temperature between the two locations. In the Barents Sea, almost 100% of the measured values during the winter months was between -1.9 and 2 degrees. In the same period in the North Sea, the measured values was between 6.1-10 degrees.


4.2 Case I: Operational duration

In the following case study, we investigate if the simulation model is capable of identify operational gaps between the North Sea and the Barents Sea. The comparison is based on the locations ability to meet the criteria of zero cargo waiting time, and one contingency vessel in supply base throughout the year. The average operational time, and the level of cargo at the base is simulated and analysed. The output from the North Sea location will be summarised as key performance indicators in the end.

For the sake of simplicity, we consider one production platform Balder in the North Sea, and one future platform, Apollo, in the Barents Sea. The Balder FPSO is located 68 nautical miles from Korst supply base, while the Apollo FPSO is located 209 nautical miles from Hammerfest. The fleet of vessel consists of 3500DWT PSVs with an deck cargo capacity of 600 m$^2$. The production platform is assumed to have a constant cargo demand of 1200 m$^2$ per day. The transport system is simulated over one year.

![Figure 4.7: Sea temperature](image)

(a) North Sea  
(b) Barents Sea

Figure 4.7: Sea temperature
4.3 Result Case I

The simulation model has been run 5 times with varying seeds on the environmental conditions. The results from the North Sea show that 6 vessels are required in order to have zero order waiting time and one contingency vessel for emergency operations. Figure 4.9a illustrates that the fleet is able to utilize sufficient capacity in each month given the assumed cargo demand. The corresponding results for the Barents Sea illustrates that fleet is neither capable of keeping up with the required cargo demand, nor provide an an stationary vessel for contingency. The deviations are largest during January, February and October, where we can see a shortage of 600m2 capacity. The number of vessels in supply base and average waiting time for cargo is found in Appendix G.1.

![Figure 4.8: Location of the oilfield in the North Sea and Barents Sea](image)

![Figure 4.9: Transport capacity robustness](image)

(a) North Sea  
(b) Barents Sea

Figure 4.9: Transport capacity robustness
The results indicate that the environmental conditions are challenging the integrity of the supply chain during the winter months. In average, the operational duration in the North Sea lasts for 22.6 hours. 21% of the time is spent waiting for appropriate weather conditions, while 32% is spent on loading/offloading, and 47% during sailing (Appendix G.2). Figure 4.10a illustrates that the environmental impact of the operational duration is highest during the winter months, and peaks in February. No additional waiting time was registered in August. In the Barents Sea, the mean time spent during operation were 48 hours, where 71% of the time is spent during sailing. 17% loading/offload and 13% of waiting for weather. Through out the year, an average of 5 hours is used to wait for appropriate weather conditions. Figure 4.10b illustrates that there are large fluctuations of the environmental impact to the operational duration. February has an average of 7 hours waiting time, while August is the most favourable month with approximately 0 waiting time.

By decomposing the time spent waiting for weather, we can see that the major share in the North Sea is due to large waves and high wind speeds during the winter months. Visibility has the lowest share, and mainly affect the operations during the summer months, when wave height and wind speed is low. In the Barents Sea, Figure 4.11b shows that the transport system was impacted by polar lows during February, May and December. Even though these events cause large operational downtime for a particular transport, it has relatively small impact on the total average delivery time through the month. De-icing contributed to increase the loading/offloading time for all months except July-October. Drifting ice had large impact in December, contributing with almost 1 hour. Even though, we can see that large wave heights also are the most critical factor in the Barents Sea as well.
In general, it can be seen that there is a large gap between the operational duration between the two locations. The increased distance and resulting transit time, is by far the most critical contribution to the increased operational duration.

<table>
<thead>
<tr>
<th>KPI</th>
<th>North Sea</th>
<th>Barents Sea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational duration</td>
<td>22.6 [h]</td>
<td>48.2 [h]</td>
</tr>
<tr>
<td>Transit</td>
<td>11.8 [h]</td>
<td>36.5 [h]</td>
</tr>
<tr>
<td>Waiting for weather</td>
<td>1.9 [h]</td>
<td>2.2 [h]</td>
</tr>
<tr>
<td>Waves</td>
<td>0.7 [h]</td>
<td>0.8 [h]</td>
</tr>
<tr>
<td>Wind</td>
<td>0.1 [h]</td>
<td>0.2 [h]</td>
</tr>
<tr>
<td>Visibility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polar lows</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drifting ice</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Since PSV vessels are rarely used for supplying only one platform, we therefore introduce two platforms with a hypothetical cargo demand. The cargo demand and frequency is modelled with a Gaussian distribution, presented in table 4.1. The allowable backlog of cargo is set as 500m².
CHAPTER 4. CASE STUDIES

Table 4.1: Required cargo demand

The available pool of vessel consists of six different types, classified according to their dead-weight. Average size and cargo capacities has been found by conducting a parametric study of the current fleet of PSVs in the North Sea. The upper bound is set to 10 vessels of each vessel type. The average values are listed in Table 4.1. The input service speed is set at 12 knots, and consumption of $2 \text{ g/kwh}$.

Table 4.2: Available pool of vessels

<table>
<thead>
<tr>
<th>Vessel type</th>
<th>Length o.a. [m]</th>
<th>Beam [m]</th>
<th>Max draft [m]</th>
<th>Displacement</th>
<th>Deck area [m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSV 2500</td>
<td>68</td>
<td>15,6</td>
<td>5,4</td>
<td>3900</td>
<td>490</td>
</tr>
<tr>
<td>PSV 3000</td>
<td>70</td>
<td>16,0</td>
<td>5,7</td>
<td>4680</td>
<td>540</td>
</tr>
<tr>
<td>PSV 3500</td>
<td>75</td>
<td>16,4</td>
<td>5,9</td>
<td>5460</td>
<td>610</td>
</tr>
<tr>
<td>PSV 4000</td>
<td>83</td>
<td>17,5</td>
<td>6,1</td>
<td>6240</td>
<td>720</td>
</tr>
<tr>
<td>PSV 4500</td>
<td>87</td>
<td>18,0</td>
<td>6,2</td>
<td>7020</td>
<td>825</td>
</tr>
<tr>
<td>PSV 5000</td>
<td>89</td>
<td>18,4</td>
<td>6,5</td>
<td>7800</td>
<td>910</td>
</tr>
</tbody>
</table>

4.5 Result Case II

Figure 4.13 show the resulting fuel consumption [ton/day] for each vessel together with its respective cargo capacity. It can be seen that the largest vessels have the highest fuel consumption, but are able to carry more cargo per ton consumed. The balance between size and consumption, is the key when the genetic algorithm decides the optimal composition of vessels. The calculated power requirement for each vessel is given in Appendix G.2.
The results from the North Sea optimization process took 2019 seconds and found the optimal fleet composition of 2 PSV 4000 and 1 PSV 2500. There are 1000000 number of different compositions in the fleet, but the genetic algorithm found a suitable after trying 676 compositions.

The results from the Barents Sea optimization process took 3129 seconds and found the optimal fleet composition of 4 PSV 4000 and 1 PSV 4500. The genetic algorithm found a suitable after trying 900 different compositions.

Figure 4.14 illustrates the optimal composition of vessels in the North Sea and in the Barents sea. The average fuel consumption per round-trip was 82.5 tonne in the North Sea and 42.3 tonne in the Barents Sea. Average fuel cost in Figure 4.14 is based in a fuel price of 600$/tonne. The results indicate that the increased operational duration will not only require more vessels in the fleet, but also larger vessels.
The utilization of the vessels available was observed to be higher in the North Sea. This can be seen in context with the higher variation in operational duration during the winter months. In general, the relatively low utilization of the cargo deck, can be seen in context with the strict constraint of cargo backlog. In a real life transport scenario, it would possible to include lower penalty if the cargo backlog exceeded the given constraint. This is expected to give a higher utilization of the deck area.

<table>
<thead>
<tr>
<th></th>
<th>Utilization deck area [%]</th>
<th>Fuel consumption [tonne]</th>
<th>Fuel cost [$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Sea</td>
<td>75 %</td>
<td>82.5</td>
<td>49500</td>
</tr>
<tr>
<td>Barents Sea</td>
<td>69 %</td>
<td>42.3</td>
<td>25380</td>
</tr>
</tbody>
</table>

Table 4.3: Average utilization of cargo deck and fuel consumption per round-trip

The results from the case study indicates that the fleet composition has been heavily influenced by the cargo frequency. In a real life situation, including additional platforms, it is expected that the difference in vessel size would be larger for the Barents Sea. Nevertheless, the optimization environment proved to deliver reliable results, under the assumptions made.
Chapter 5

Discussion

The thesis presented, has proven that it is possible to develop a simulation based decision support tool for Arctic field logistics. When that is said, there should also be stressed that there are aspects of the model which could be improved in future development. The following section aims to highlight different aspects of the model.

The use of the genetic algorithm turned out to be a very powerful tool in the case of fleet optimization. A combination of the previously discussed optimization method from Lui et al. [13] with the discrete-event simulation model, was found to be a successful approach to optimize the fleet composition. Compared to the black box optimization approach previously discussed by Glover et al. [7], this model will contain the advantage of combining exact solutions from the optimization algorithm with stochastic variations in the simulation model. In the case of fleet optimization, this model also posses a major benefit, as it is possible to run simulation and optimization without the need for additional optimization software. As previously discussed, the genetic algorithm is an effective heuristic for solving complex optimization problems, nevertheless there are some aspects that should be considered. Due to the limitation of computational time, the algorithm does not guarantee a global optimal. Using a GA therefore impose a risk of finding sub-optimal solutions. A validation of the model could be done by comparing the result with the previously discussed approach of Almeider and Preusser [1]. In order to optimize the fleet composition, the simulation model was built based on global variables instead of traditional entity combining techniques. From the authors experience, this approach seemed to be much more time consuming than the traditional approach. In addition, as the complexity of the model grew, the simulation run time increased drastically.

By using discrete event-simulation it was possible to obtain good estimations of the environmental impact on the vessels operational duration. The transit time was approximated as a function of wave height, which gave reasonable results. Lubkovsky [19] has developed a formula for speed reduction, which takes into account the bow radius, wave angle, dead weight and wave height. This seems like a more precise way of estimat-
ing the transit time and fuel consumption, and could be a promising implementation in further development. The simulation model only included waiting time at the oilfield. In some cases, were the environmental conditions are to severe, the vessels will not leave port. This is recommended in further development.

Data of the stochastic environmental conditions were successfully collected and implemented in the model. Wave and wind distribution were implemented by transforming time-series into stochastic distributions. This seems to be a solid way of implementing such data. Nevertheless, wind data was expected to include occurrence of jet streams. This may not be valid in all cases, and an approach for separating these two conditions may be a more accurate in a future implementation. A risk of implementing the environmental conditions by random number generation, is that the randomized sequence of seeds is to closely linked to the simulation software. An alternative way of implementing wave and wind conditions could be by developing a hybrid system of continuous and discrete event simulation. This is would possibly provide a more realistic simulation of the weather duration. The relevance of such an implementation, should thus be carefully considered as it would require high accuracy of the input data in addition to high computational effort. Reliable statistics of drifting ice during the year was near impossible to obtain. From the authors experience, more research in this area must be done in order to provide a future simulation model with reliable input.

Collection and modelling of environmental conditions required an effort. Before a future simulation model is built, it is recommended to have a clear view of not only the relevant input, but also the degree of accuracy the input should have. Data collection can easily turn out to be a major time thief during the model development. Scarce knowledge about the Arctic conditions is, from the authors view, the most challenging part of developing simulation models for Arctic environments. As the output is no better then the input, it is expected that future decisions must require a higher accuracy of environmental input. The simulation software chosen was SimEvents. The strength of SimEvents, is from the authors experience, also part of its weakness. It is a low-level simulation package that allows for highly customized models. This also means that many simple and standardised operations, such as making a realistic cargo accumulation turned out to be quite complex and time consuming.

It is hoped that this paper has succeeded in providing a good starting point for further research on decision support systems in the Arctic area.
Chapter 6

Conclusion

The uncertainty of the Arctic environment in combination with the large distance to shore, will result in increased complexity of offshore operations. The sudden occurrence of extreme weather conditions will impose a challenge for the operational schedule of platform supply vessels. In order to sustain the integrity of the offshore supply chain, new decision support systems must be developed.

This thesis presented a simulation based decision support tool for Arctic field logistics. The decision support system has been developed by including complex interactions from the environment in a discrete-event simulation model. Resource constraints in form of operational limitations has been implemented to determine the environmental impact on platform supply vessels operational duration. An integrated infrastructure for optimizing stochastic events has been implemented by using a genetic algorithm.

To illustrate the capability of the model, two case studies were presented. The results from the first case study confirmed that the simulation model was capable analysing environmental impact on the platform supply vessels operational duration. The results from the second case study confirmed that it was possible to combine discrete-event simulation model with an genetic algorithm to optimize the fleet of platform supply vessels. The presented decision support tool can be used to analyse operational gaps between the North Sea and the Barents Sea.
Bibliography

[1] Preusser M. Almeder C., *Simulation and optimization of supply chains: alternative or complementary approaches?*

[2] BMT ARGOSS.


Appendix
Appendix A

Simulation model in SimEvents
A.1 Overview of the simulation model

The model is configured with two platforms, one supply base and one terminal for oil offloading. PSVs transport cargo between the supply base and the platforms, while shuttle tankers transport oil from the FPSO to the terminal. Intermediate transit is shown in blue.
A.2 Vessel generation

Vessels are generated as entities. Each vessel is assigned vessel particulars in form of attributes. Upon simulation start, vessel particulars need to be set. The configuration allows for up to six different vessel configurations in the fleet. By clicking on their respective icon, a box will appear on the screen. Number of vessels, size, capacities, service speed and fuel price will need to be inserted.
A.3 Order generation

Orders are generated as entities. The size of each order is set as an attribute. Whenever an order is generated, its value will be saved as a global variable. By using global variables, it is possible to accumulate the level at cargo in base, needed for the fleet optimization. The global variable can, in contrast to local variables, be modified anywhere in the system. This allows for building the simulation model without combining entities. The interface allows for setting order frequency, size and destination for two platforms.
A.4 Load cargo

The vessels will wait in a queue until an order is assigned. The level of deck- and liquid cargo is read from the global data store read block, and feed into a state-flow chart. The state-flow chart outputs 1 if there are orders in the base and 0 if there is no orders in base. The enabled gate releases a vessel if the control value is 1. If the value is 0, vessels will stand in queue until an order is assigned. After being released from the queue, the vessels load cargo on deck or in specialized tanks underneath the deck. The vessels will prioritize loading cargo to the platform that has the largest backlog of orders. If both are equal, or the vessel has large enough cargo capacity, the vessel will sail to both platforms.
A.5 Sailing

The time spent sailing is a function of speed distance and wave-height. The "sailing" block allows for setting distances to the oilfields.
A.6 Environmental input

Environmental conditions are implemented in the simulation model by using a "random number" generator. The random number is log-normal and normally distributed for wave and wind conditions. Polar low, visibility, ice and temperature is implemented by the Bernoulli equation. By using 12 "random number" generators, the environment is simulated over one year. Based on the month of the year, a Matlab function determine which of the 12 numbers will be used as input.
APPENDIX A. SIMULATION MODEL IN SIMEVENTS
A.7 Operational limitations

The operational limitations are set as attributes. If the corresponding attribute of the environmental conditions exceed the value of the operational limitations, the vessel will wait until the environmental conditions is below the threshold value. By clicking on the ”Wait for weather” block, environmental limitations can be set for wave, wind and visibility. Polar lows are either excepted or not.
A.8 Optimization environment

The first line sets up the code for the optimization. \texttt{lb} sets the lower bound of the optimization variables and \texttt{ub} sets the upper bound of the variables. This means that the allowable number of vessels of each size must be between 0 and 10. \texttt{IntCon} determine which variables containing integers. The fleet must, off-course, consist of integer vessels, so all six vessels are set. The next line is where the genetic algorithm is being called from the Matlab optimization toolbox. The objective function is the function which the genetic algorithm is minimizing. Variables to the number of vessels are then set to each vessel. \texttt{Setparam} indicates that the number of vessels will be changed in the simulation model. \texttt{simOut} is simulating the model and saves the value to a variable called \texttt{backlogValuesCargo}. \texttt{fuel} is the line were the were the fuel consumption for each vessel is assigned to the variables. The objective function is then minimized, were an infinite values is set if the backlog exceeds the threshold value given in the simulation model.

```matlab
function fleetcomposition=sim()

%

opts=gacestset('PlotFcns',@gaplotbestf; @gaplotbestindiv; @gaplotstopping);...
'Generations',150,'StallGenLimit',20,'UseParallel','always');

%%
lb=[0 0 0 0 0 0];
%%
ub=[10 10 10 10 10 10];
%%
IntCon=[1 2 3 4 5 6];
tic

[fleetcomposition,~,exitflag]=ga(@fuelCost,6,[],[],[],lb,ub,[],IntCon,opts);
toc
```
function obj=fuelCost(x)

Vessel1=x(1);
Vessel2=x(2);
Vessel3=x(3);
Vessel4=x(4);
Vessel5=x(5);
Vessel6=x(6);

set_param('NS_opt_V2_1/Order generation and cargo loading/Vessel generation', ...
    'n', num2str(Vessel1));
set_param('NS_opt_V2_1/Order generation and cargo loading/Vessel generation1', ...
    'n', num2str(Vessel2));
set_param('NS_opt_V2_1/Order generation and cargo loading/Vessel generation2', ...
    'n', num2str(Vessel3));
set_param('NS_opt_V2_1/Order generation and cargo loading/Vessel generation3', ...
    'n', num2str(Vessel4));
set_param('NS_opt_V2_1/Order generation and cargo loading/Vessel generation4', ...
    'n', num2str(Vessel5));
set_param('NS_opt_V2_1/Order generation and cargo loading/Vessel generation5', ...
    'n', num2str(Vessel6));

simOut=sim('NS_opt_V2_1','SaveOutput','on',...
    'OutputSaveName','backlogValuesCargo');

z=simOut.get('backlogValuesF');
z=simOut.get('FuelCost1');
z=simOut.get('FuelCost2');
z=simOut.get('FuelCost3');
z=simOut.get('FuelCost4');
z=simOut.get('FuelCost5');
z=simOut.get('FuelCost6');
backlogCargo=z(end);
FuelCost1=z(end);
FuelCost2=z(end);
FuelCost3=z(end);
FuelCost4=z(end);
FuelCost5=z(end);
FuelCost6=z(end);

obj=(backlogCargo*inf)+fuel
end
A.9 Order generation script

```matlab
function fcn(Deck_cargo_P1, Deck_cargo_P2, Liquid_cargo_p1, Liquid_cargo_p2 )

% accumulate cargo. Set as global variables

global level_fuel_p1
if isempty(level_fuel_p1)
    level_fuel_p1 = 0; % Initialise Total Cargo
end
level_fuel_p1 = level_fuel_p1 + Fuel; % Calculate cumulative total

global level_fuel_p2
if isempty(level_fuel_p2)
    level_fuel_p2 = 0; % Initialise Total Cargo
end
level_fuel_p2 = level_fuel_p2 + Fuel_p2; % Calculate cumulative total

global level_fd_p1
if isempty(level_fd_p1)
    level_fd_p1 = 0; % Initialise Total Cargo
end
level_fd_p1 = level_fd_p1 + FandD; % Calculate cumulative total

global level_fd_p2
if isempty(level_fd_p2)
    level_fd_p2 = 0; % Initialise Total Cargo
end
level_fd_p2 = level_fd_p2 + FandD_p2; % Calculate cumulative total

level_fuel_p1 = Deck_cargo_P1
level_fuel_p2 = Deck_cargo_P2
level_fd_p1 = Liquid_cargo_p1
level_fd_p2 = Liquid_cargo_p2
```
APPENDIX A. SIMULATION MODEL IN SIMEVENTS

A.10 Load deck cargo script

```matlab
function [Cargo_f_p1, Cargo_f_p2] = laster(Capacity_f)
% Cargo_f_p1 = Deck_cargo_loaded_p1
% Cargo_f_p2 = Deck_cargo_loaded_p2
%--------Alt. 1
% If level in tank for orders to platform 1 is larger than level for
% platform 2 - priority loading is given to platform 1.
global level_fuel_p1
global level_fuel_p2
if Capacity_f > 0
    if level_fuel_p2 <= level_fuel_p1
        if level_fuel_p1 <= 0
            Cargo_f_p1 = 0;
        elseif (0 < level_fuel_p1) && (level_fuel_p1 < Capacity_f)
            Cargo_f_p1 = level_fuel_p1;
        else
            Cargo_f_p1 = Capacity_f;
        end
        rest_capacity_f = Capacity_f - Cargo_f_p1;
        if rest_capacity_f > 0
            if level_fuel_p2 <= 0
                Cargo_f_p2 = 0;
            elseif (0 < level_fuel_p2) && (level_fuel_p2 < rest_capacity_f)
                Cargo_f_p2 = level_fuel_p2;
            else
                Cargo_f_p2 = rest_capacity_f;
            end
        else
            Cargo_f_p2 = 0;
        end
    end
    %--------Alt. 2
elseif level_fuel_p2 > level_fuel_p1
    if level_fuel_p2 <= 0
        Cargo_f_p2 = 0;
    elseif (0 < level_fuel_p2) && (level_fuel_p2 < Capacity_f)
        Cargo_f_p2 = level_fuel_p2;
    else
        Cargo_f_p2 = Capacity_f;
    end
    rest_capacity_f = Capacity_f - Cargo_f_p2;
    if rest_capacity_f > 0
        if level_fuel_p1 <= 0
            Cargo_f_p1 = 0;
        elseif (0 < level_fuel_p1) && (level_fuel_p1 < rest_capacity_f)
            Cargo_f_p1 = level_fuel_p1;
        else
            Cargo_f_p1 = rest_capacity_f;
        end
    else
        Cargo_f_p1 = 0;
    end
end
```
$\text{-----------------Divided}$

\begin{verbatim}
elseif level_fuel_p1 + level_fuel_p2 <= \text{Capacity}_F
    Cargo_f_p1 = level_fuel_p1
    Cargo_f_p2 = level_fuel_p2
else
    Cargo_f_p1 = \text{disp(‘error’)}
    Cargo_f_p2 = \text{disp(‘error’)}
end
level_fuel_p1 = level_fuel_p1 - Cargo_f_p1
level_fuel_p2 = level_fuel_p2 - Cargo_f_p2
end
\end{verbatim}
A.11 Liquid deck cargo script

```
function [Cargo_fd_p1,Cargo_fd_p2] = laster(Capacity_fd)

%Cargo_fd_p1=Liquid cargo P1
%Cargo_fd_p2=Liquid cargo P2

global level_fd_p1
global level_fd_p2

%-------Ship 1
%If level in tank for orders to platform 1 is larger than level for
%platform 2 - priority loading is given to platform 1.
if Capacity_fd>0
    if level_fd_p2<=level_fd_p1

    if level_fd_p1<=0
        Cargo_fd_p1=0;

    elseif (0<level_fd_p1)&&(level_fd_p1<Capacity_fd)
        Cargo_fd_p1=level_fd_p1;

    else
        Cargo_fd_p1=Capacity_fd;
    end

    rest_capacity_f=Capacity_fd-Cargo_fd_p1;

    if rest_capacity_f>0
        if level_fd_p2<=0
            Cargo_fd_p2=0;

        elseif (0<level_fd_p2)&&(level_fd_p2<rest_capacity_f)
            Cargo_fd_p2=level_fd_p2;

        else
            Cargo_fd_p2=rest_capacity_f;
        end

    else
        Cargo_fd_p2=0
    end

end
```

APPENDIX A. SIMULATION MODEL IN SIMEVENTS

%--------Ship 2

elseif level_fd_p2>level_fd_p1

    if level_fd_p2<=0
        Cargo_fd_p2=0;
    elseif (0<level_fd_p2)&&(level_fd_p2<Capacity_fd)
        Cargo_fd_p2=level_fd_p2
    else
        Cargo_fd_p2=Capacity_fd;
    end

rest_capacity_f=Capacity_fd-Cargo_fd_p2;

    if rest_capacity_f>0
        if level_fd_p1<=0
            Cargo_fd_p1=0;
        elseif (0<level_fd_p1)&&(level_fd_p1<rest_capacity_f)
            Cargo_fd_p1=level_fd_p1;
        else
            Cargo_fd_p1=rest_capacity_f;
        end
    else
        Cargo_fd_p1=0
    end

%--------Delt

elseif level_fd_p1+level_fd_p2<=Capacity_fd

    Cargo_fd_p1=level_fd_p1
    Cargo_fd_p2=level_fd_p2

else
    Cargo_fd_p1=66
    Cargo_fd_p2=66

end

else
    Cargo_fd_p1=0
    Cargo_fd_p2=0
end

level_fd_p1=level_fd_p1-Cargo_fd_p1
level_fd_p2=level_fd_p2-Cargo_fd_p2
A.12 Transit script

```matlab
function [sailing_time, additional_sailing_time] = fcn(speed, distance, Wave_h)
% Calculate sailing time + additional sailing time due to waves
sailing_time = (distance/speed)/24
additional_sailing_time = ((distance/speed)/24)*1.02*Wave_h - sailing_time

%-------Divided
elseif level_fuel_p1 + level_fuel_p2 <= Capacity_f
    Cargo_f_p1 = level_fuel_p1
    Cargo_f_p2 = level_fuel_p2
else
    disp('error')
    Cargo_f_p1 = disp('error')
end
level_fuel_p1 = level_fuel_p1 - Cargo_f_p1
level_fuel_p2 = level_fuel_p2 - Cargo_f_p2
end
```
A.13 Wave and wind script

```matlab
function w = fcn(SimTime,w1,w2,w3,w4,w5,w6,w7,w8,w9,w10,w11,w12)
%#codegen
%Determine the wave height for each month
if (SimTime>=0) && (SimTime<=30)
    w = w1;
elseif (SimTime>30) && (SimTime<=60)
    w = w2;
elseif (SimTime>60) && (SimTime<=90)
    w = w3;
elseif (SimTime>90) && (SimTime<=120)
    w = w4;
elseif (SimTime>120) && (SimTime<=150)
    w = w5;
elseif (SimTime>150) && (SimTime<=180)
    w = w6;
elseif (SimTime>180) && (SimTime<=210)
    w = w7;
elseif (SimTime>210) && (SimTime<=240)
    w = w8;
elseif (SimTime>240) && (SimTime<=270)
    w = w9;
elseif (SimTime>270) && (SimTime<=300)
    w = w10;
elseif (SimTime>300) && (SimTime<=330)
    w = w11;
elseif (SimTime>330) && (SimTime<=360)
    w = w12;
else
    w = 300;
end
```
A.14 Polar low input script

```matlab
function p = fcn(SimTime, p1, p2, p3, p4, p5, p6, p7, p8, p9, p10, p11, p12)
  %#codegen
  if (SimTime>=0) && (SimTime<=30)
    p = p1;
  elseif (SimTime>30) && (SimTime<=50)
    p = p2;
  elseif (SimTime>50) && (SimTime<=90)
    p = p3;
  elseif (SimTime>90) && (SimTime<=120)
    p = p4;
  elseif (SimTime>120) && (SimTime<=150)
    p = p5;
  elseif (SimTime>150) && (SimTime<=180)
    p = p6;
  elseif (SimTime>180) && (SimTime<=210)
    p = p7;
  elseif (SimTime>210) && (SimTime<=240)
    p = p8;
  elseif (SimTime>240) && (SimTime<=270)
    p = p9;
  elseif (SimTime>270) && (SimTime<=300)
    p = p10;
  elseif (SimTime>300) && (SimTime<=330)
    p = p11;
  elseif (SimTime>330) && (SimTime<=360)
    p = p12;
  else
    p = 300
  end
```
A.15 Visibility script

```matlab
function visibility = fcn(SimTime,
    v1_1,v1_2,v1_3,v2_1,v2_2,v2_3,v3_1,v3_2,v3_3,
    v4_1,v4_2,v4_3,v5_1,v5_2,v5_3,v6_1,v6_2,v6_3,
    v7_1,v7_2,v7_3,v8_1,v8_2,v8_3,v9_1,v9_2,v9_3,
    v10_1,v10_2,v10_3,v11_1,v11_2,v11_3,v12_1,v12_2,v12_3);

 %#Visibility values
 low = 199;
 medium = 499;
 high = 999;
 unlimited = 1200;

 if (SimTime<=0) & (SimTime<=30)
    if v1_1==1
       visibility = low;
    elseif v1_2==1
       visibility = medium;
    elseif v1_3==1
       visibility = high;
    else
       visibility = unlimited;
    end
 else if (SimTime>30) & (SimTime<=60)
    if v2_1==1
       visibility = low;
    elseif v2_2==1
       visibility = medium;
    elseif v2_3==1
       visibility = high;
    else
       visibility = unlimited;
    end
 else if (SimTime>60) & (SimTime<=90)
    if v3_1==1
       visibility = low;
    elseif v3_2==1
       visibility = medium;
    elseif v3_3==1
       visibility = high;
    else
       visibility = unlimited;
    end
 else if (SimTime>90) & (SimTime<=120)
    if v4_1==1
       visibility = low;
    elseif v4_2==1
       visibility = medium;
    elseif v4_3==1
       visibility = high;
    else
       visibility = unlimited;
    end
```
APPENDIX A. SIMULATION MODEL IN SIMEVENTS

```plaintext
elseif (SimTime>120) && (SimTime<=150)
    if v5_1==1
        visibility=low
    elseif v5_2==1
        visibility=medium
    elseif v5_3==1
        visibility=high
    else
        visibility=unlimited
    end

elseif (SimTime>150) && (SimTime<=180)
    if v6_1==1
        visibility=low
    elseif v6_2==1
        visibility=medium
    elseif v6_3==1
        visibility=high
    else
        visibility=unlimited
    end

elseif (SimTime>180) && (SimTime<=210)
    if v7_1==1
        visibility=low
    elseif v7_2==1
        visibility=medium
    elseif v7_3==1
        visibility=high
    else
        visibility=unlimited
    end

elseif (SimTime>210) && (SimTime<=240)
    if v8_1==1
        visibility=low
    elseif v8_2==1
        visibility=medium
    elseif v8_3==1
        visibility=high
    else
        visibility=unlimited
    end
```
APPENDIX A. SIMULATION MODEL IN SIMEVENTS

```plaintext
elseif (SimTime>=240) && (SimTime<=270)
    if v9_1==1
        visibility=low
    elseif v9_2==1
        visibility=medium
    elseif v9_3==1
        visibility=high
    else
        visibility=unlimited
    end

elseif (SimTime>270) && (SimTime<=300)
    if v10_1==1
        visibility=low
    elseif v10_2==1
        visibility=medium
    elseif v10_3==1
        visibility=high
    else
        visibility=unlimited
    end

elseif (SimTime>300) && (SimTime<=330)
    if v11_1==1
        visibility=low
    elseif v11_2==1
        visibility=medium
    elseif v11_3==1
        visibility=high
    else
        visibility=unlimited
    end

elseif (SimTime>330) && (SimTime<=360)
    if v12_1==1
        visibility=low
    elseif v12_2==1
        visibility=medium
    elseif v12_3==1
        visibility=high
    else
        visibility=unlimited
    end

else
    visibility=0
end
```
Appendix B

Lognormal distribution of wave conditions

Time series of significant wave height has been transformed to a probability density function and fitted with a log-normal distribution.

Figure B.1: January-December, Balder

Figure B.2: January-December, Ringhorne
APPENDIX B. LOGNORMAL DISTRIBUTION OF WAVE CONDITIONS

B.1 Barents Sea

Figure B.3: January
APPENDIX B. LOGNORMAL DISTRIBUTION OF WAVE CONDITIONS

Figure B.4: February

Figure B.5: March
APPENDIX B. LOGNORMAL DISTRIBUTION OF WAVE CONDITIONS

Figure B.6: April

Figure B.7: May
APPENDIX B. LOGNORMAL DISTRIBUTION OF WAVE CONDITIONS

Figure B.8: June

Figure B.9: July
APPENDIX B. LOGNORMAL DISTRIBUTION OF WAVE CONDITIONS

Figure B.10: August

Figure B.11: September
APPENDIX B. LOGNORMAL DISTRIBUTION OF WAVE CONDITIONS

Figure B.12: October

Figure B.13: November
Figure B.14: December
B.2 North Sea

Figure B.15: December
APPENDIX B. LOGNORMAL DISTRIBUTION OF WAVE CONDITIONS

Figure B.16: February

Figure B.17: March
APPENDIX B. LOGNORMAL DISTRIBUTION OF WAVE CONDITIONS

Figure B.18: April

Figure B.19: May
APPENDIX B. LOGNORMAL DISTRIBUTION OF WAVE CONDITIONS

Figure B.20: June

Figure B.21: July
APPENDIX B. LOGNORMAL DISTRIBUTION OF WAVE CONDITIONS

Figure B.22: August

Figure B.23: September
APPENDIX B. LOGNORMAL DISTRIBUTION OF WAVE CONDITIONS

Figure B.24: October

Figure B.25: November
Figure B.26: December
Appendix C

Gaussian distribution of wind conditions

Figure C.1: January
APPENDIX C. GAUSSIAN DISTRIBUTION OF WIND CONDITIONS

Figure C.2: February

Figure C.3: March
APPENDIX C. GAUSSIAN DISTRIBUTION OF WIND CONDITIONS

Figure C.4: April

Figure C.5: May
Figure C.6: June

Figure C.7: July
APPENDIX C. GAUSSIAN DISTRIBUTION OF WIND CONDITIONS

Figure C.8: August

Figure C.9: September
APPENDIX C. GAUSSIAN DISTRIBUTION OF WIND CONDITIONS

Figure C.10: October

Figure C.11: November
C.1 Barents Sea
C.2 North Sea

Figure C.13: January
APPENDIX C. GAUSSIAN DISTRIBUTION OF WIND CONDITIONS

Figure C.14: February

Figure C.15: March
APPENDIX C. GAUSSIAN DISTRIBUTION OF WIND CONDITIONS

Figure C.16: April

Figure C.17: May
APPENDIX C. GAUSSIAN DISTRIBUTION OF WIND CONDITIONS

Figure C.18: June

Figure C.19: July
APPENDIX C. GAUSSIAN DISTRIBUTION OF WIND CONDITIONS

Figure C.20: August

Figure C.21: September
Figure C.22: October

Figure C.23: November
Figure C.24: December
Appendix D

Ice occurrence

Figure D.1: Ice occurrence 76 degrees North
Figure D.2: Limits of sea ice with an annual probability of exceedance
Appendix E

Visibility

![Visibility North Sea Graph](image1)

![Visibility Barents Sea Graph](image2)
Appendix F

Polar lows

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UTC)</th>
<th>Lat.</th>
<th>Long.</th>
<th>Remark</th>
<th>Min. SLP (hPa)</th>
<th>Max wind (kt)</th>
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<td>18E</td>
<td></td>
<td>989</td>
<td>45</td>
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<td>72.5N</td>
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<td>50</td>
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<td>21E</td>
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<td>33-40</td>
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<td>03W</td>
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<td>40</td>
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Appendix G

Case studies

G.1 Case study I

Number of vessels in the supply base during the year for the North Sea and the Barents Sea (at time 0 there are 0 vessel).

![Number of vessels in Supply base](image1.png)  ![Number of vessels in Supply base](image2.png)

(a) North Sea  (b) Barents Sea

Figure G.1: Number of vessels in Supply base

Average cargo wait in North Sea and Barents sea.
APPENDIX G. CASE STUDIES

Percent contribution to operational duration in the North Sea and Barents Sea.

(a) North Sea

(b) Barents Sea

Figure G.2: Contribution to operational duration

G.2 Case study II

Calculated power requirement for each vessel in the fleet.
### APPENDIX G. CASE STUDIES

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<th>Power at service speed [kW]</th>
<th>Consumption in service speed [ton/day]</th>
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<td>PSV 5000</td>
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</table>
Figure G.3: PSV2500
Figure G.4: PSV3000
Figure G.5: PSV3500
Figure G.6: PSV4000
Figure G.7: PSV4500
Figure G.8: PSV5000
Figure G.9: Optimal fleet composition North Sea

Figure G.10: Optimal fleet composition North Sea