NTNU – Trondheim
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A simulation-based decision support tool for arctic field logistics

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Marine Technology (2-year)
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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 Arcitic, 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. Resent 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 excludes 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 effected by particular events occurring at a particular time. The times which an event effect 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 Gribkovskaia [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.

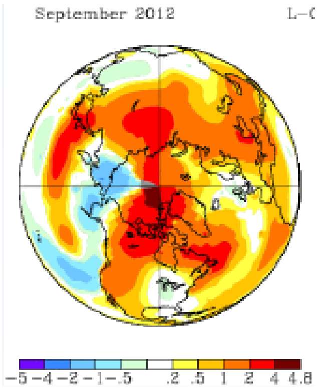


Figure 2.1: Trend in mean surface temperature

The temperature in the Arctic can fall significantly bellow 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 bellow -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 luncher. 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 hight of 5.5 meters at 35 m/s. In the areas were 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 **??** show that the average wave hight is largest in the Barents Sea, and inclines further east and south. This can be seen in context with the occurrence of polar lows.

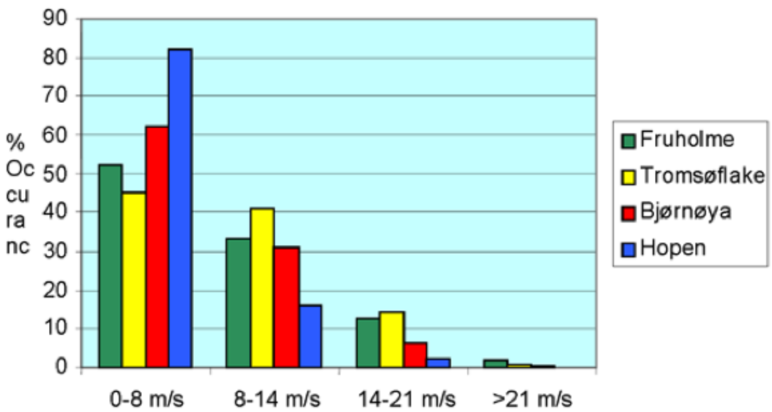


Figure 2.2: Wind speed in the Barents Sea

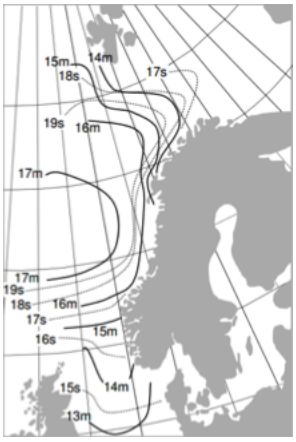


Figure 2.3: Average wave height

2.4 Ice conditions

The National Snow and Ice Data Center [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 km2 less then the previous record in 2007, and 3.3 million km2 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 km2 from March to September, also represent the largest number of ice extent loss during one year.

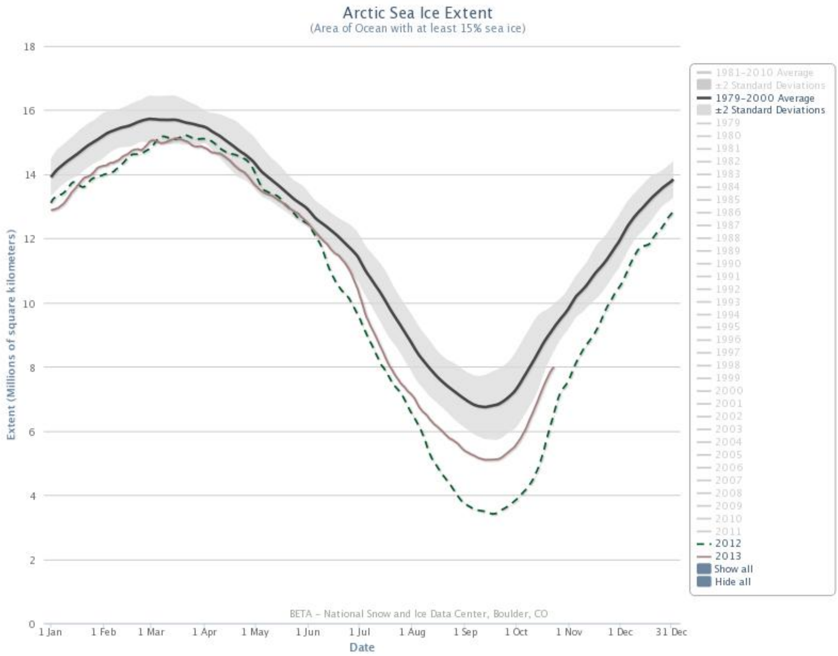


Figure 2.4: 2013 Arctic Sea Ice Extent, Source: [2],

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 states 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 depend 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 firs-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 a 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.

Triggers	**Challange**	**Operation**	**Consideration**
Drifting ice	Yes	Delays	Drive around, forceast, ice management
Temperature	Yes	Can cause icingin combination with sea spray	Propper equipment, deicinbg
Wind	Yes	Large delays, emergency preparedness, operational hazard, disconnect	Risk assesment, reduce distances
Waves	Yes, Sudden change in wave conditions	Large delays, emergency preparedness, operational hazard, disconnect	Risk assesment, reduce distances
Polar lows	Yes	Large delays, operational hazard, disconnect	More frequent weather forecast
Infastructure	Yes	Larger distances	Floating supply base, multipurpose vessel

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.

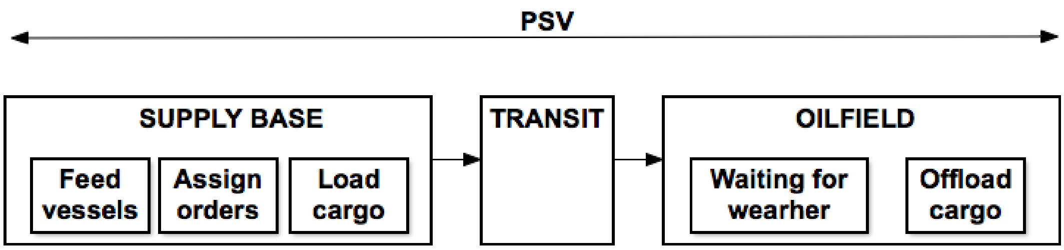


Figure 3.1: Overview of the simulation transport system

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 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:

$$TransitTime = \frac{Distance}{Speed} 1.02^{Hs} \tag{3.1}$$

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.

$$ServiceRate = \frac{Cargo}{3500} 1.04^{Hs} \tag{3.2}$$

Offloading can only take place if the environmental conditions does not exceed the operational limitations. The operational duration, is defined as the time a vessels 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.

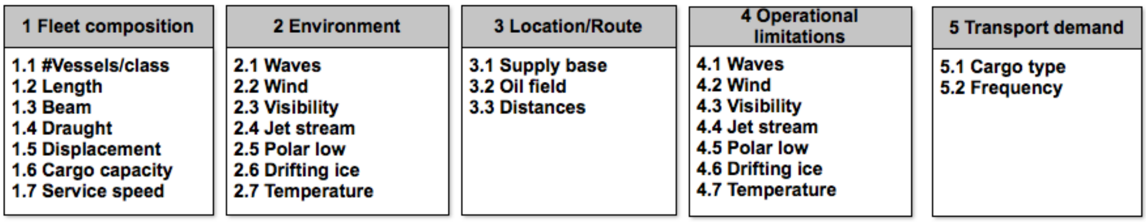


Figure 3.2: Simulation input

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.

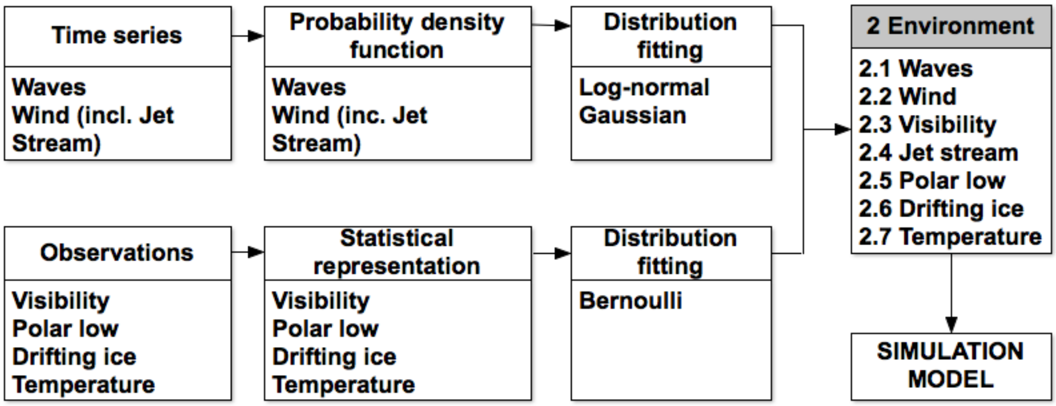


Figure 3.3: Transformation to stochastically distributed input

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 θ is the threshold parameter.

$$f(x) = \begin{cases} \dfrac{exp[\dfrac{-(ln(x-\theta)-\mu^2]}{2\sigma^2}]}{(x-\theta)\sigma\sqrt{2x}} \\ 0 \end{cases} \tag{3.3}$$

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 μ is the mean parameter and σ is the standard deviation parameter.

$$f(x) = \frac{exp(-(x-\mu^2/2\sigma^2)}{\sigma\sqrt{2\pi}} \tag{3.4}$$

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 ρ is the probability of 1.

$$f(x) = \begin{cases} p^x(1-p)1-x \\ 0 \end{cases} \tag{3.5}$$

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 vessels in the fleet are then calculated using the Holtrop& Mennen method [10], and outputted from the model. The supply base also read 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.

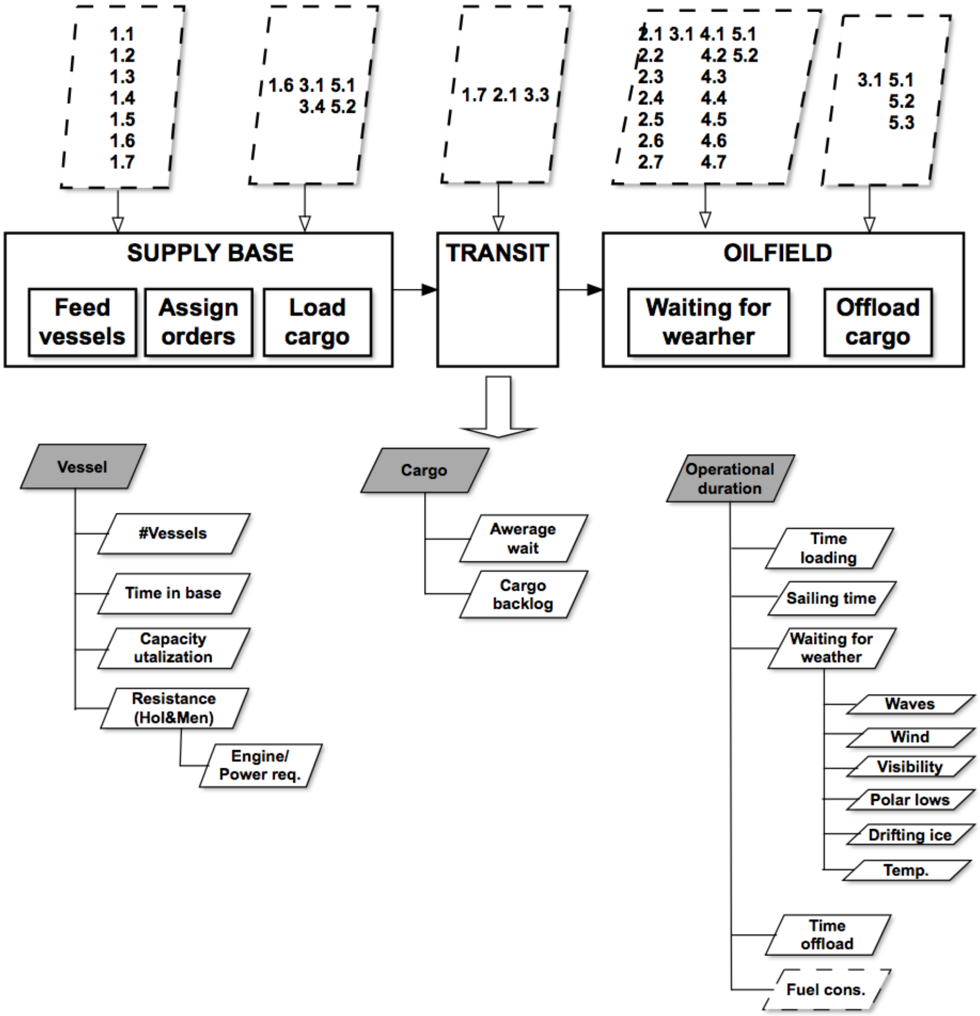


Figure 3.4: Simulation environment: Input and output

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.

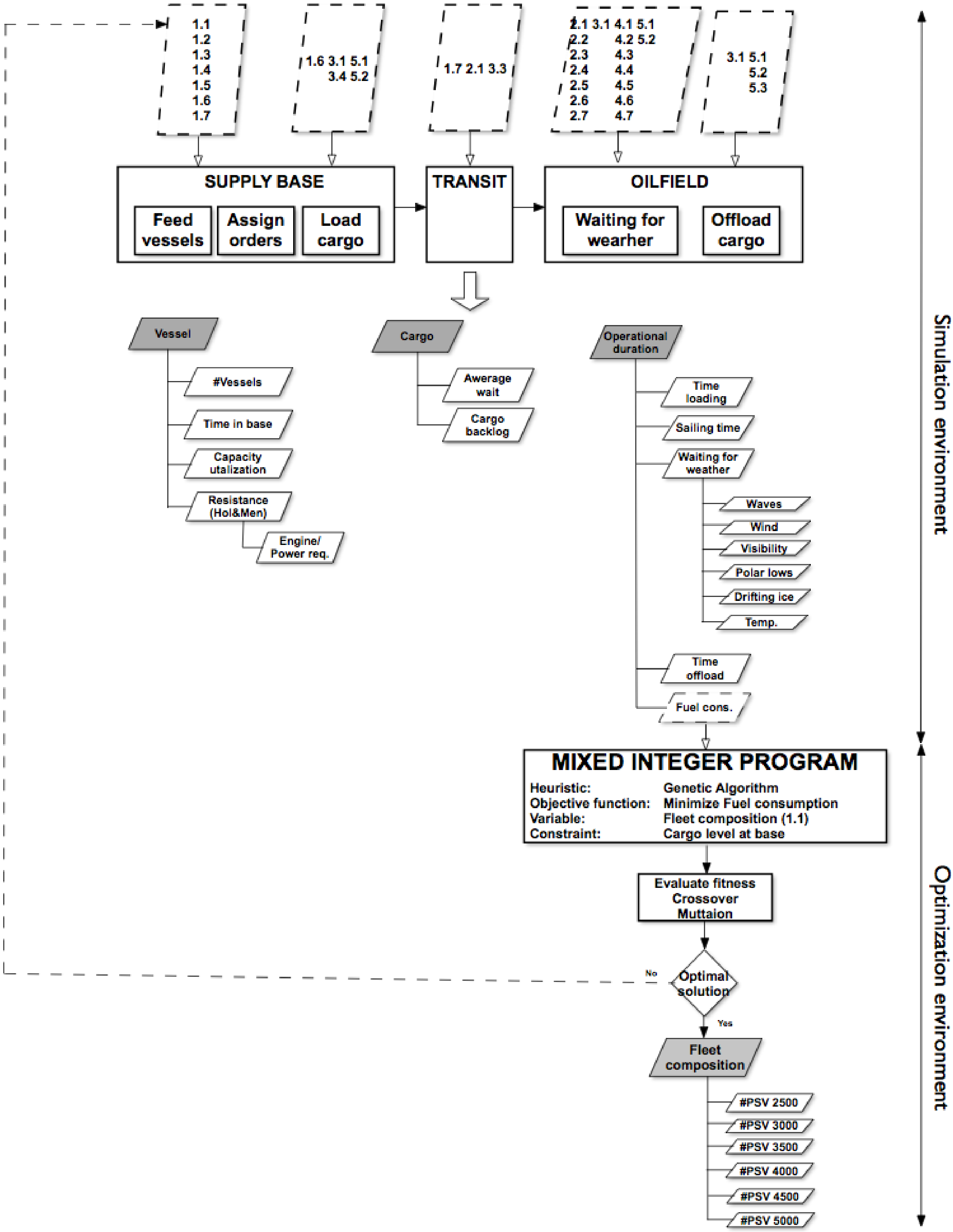


Figure 3.5: Optimization environment: Input and output

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.

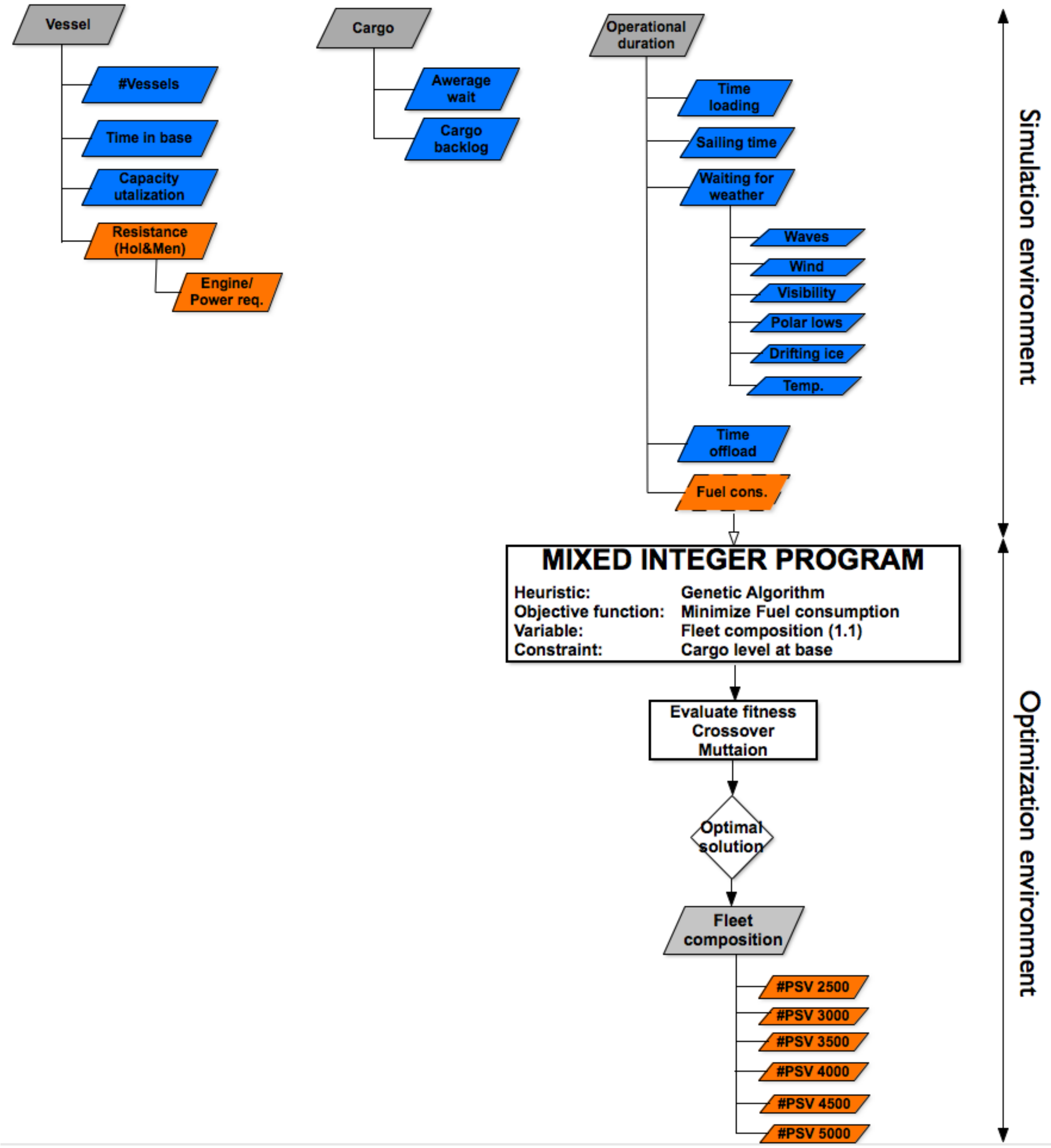


Figure 4.1: Expected outcome case study. Blue=case study I, orange=case study II

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.

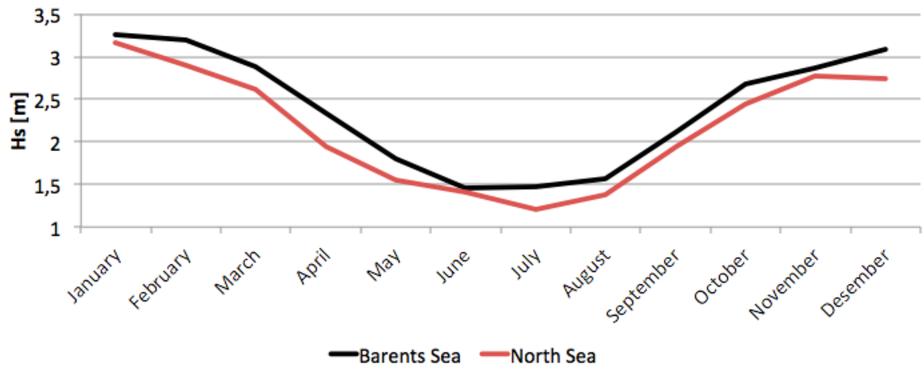


Figure 4.2: Mean Hs

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.

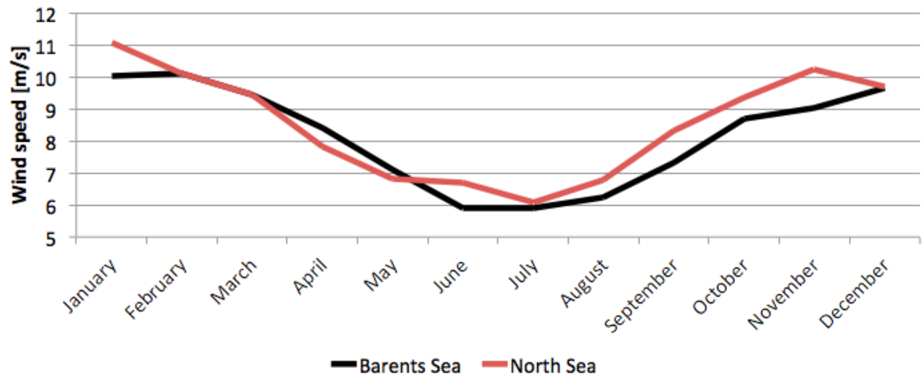


Figure 4.3: Mean wind speed 10 asl

Visibility statistics has been provided by the Norwegian Metrological Institute [11]. Fog has been set as visibility bellow 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 E illustrates the probability of fog on each location. We can see that July is the most critical month, were 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.

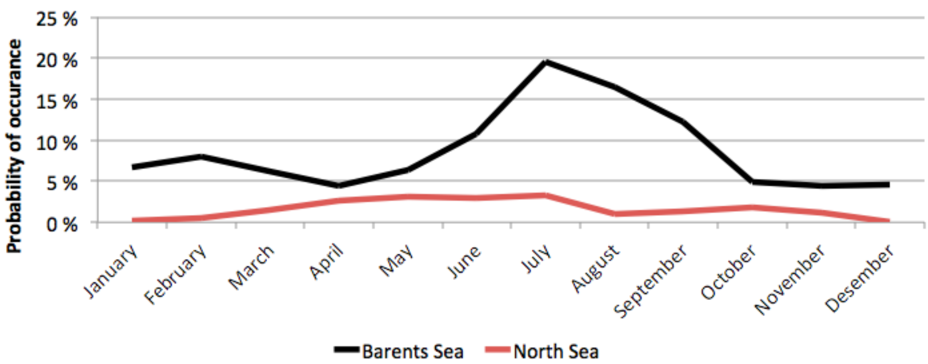


Figure 4.4: Fog

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 occurance from November to June. The results can bee seen in Figure 4.5 while data collection is given in Appendix D.

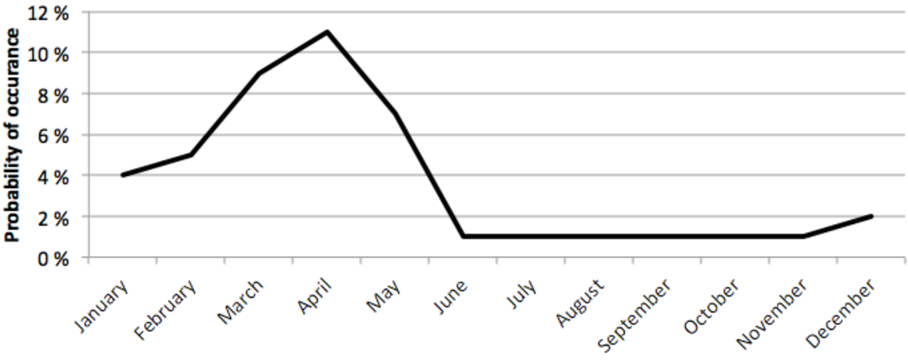


Figure 4.5: Estimated probability of drifting ice, Barents Sea

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.

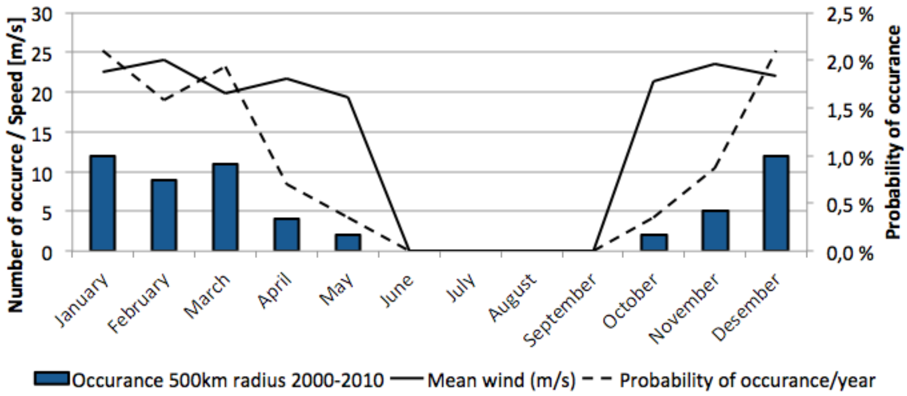
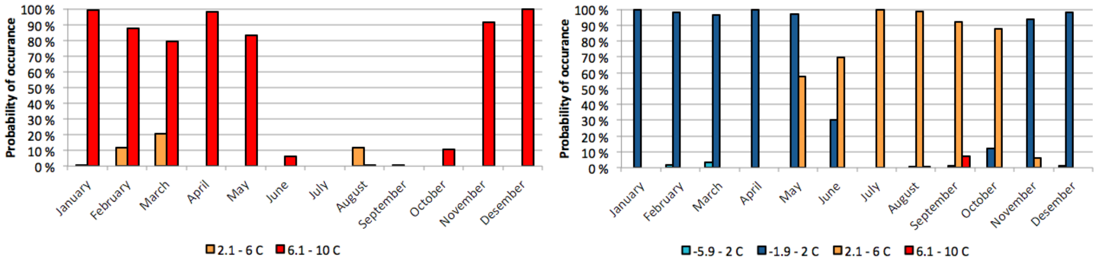


Figure 4.6: Polar low observations, mean speed and probability occurrence, Apollo.

Sea temperature in the period 2008-2013 has been provided my Norwegian Metro logical 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.



(a) North Sea (b) Barents Sea

Figure 4.7: Sea temperature

4.2 Case I: Operational duration

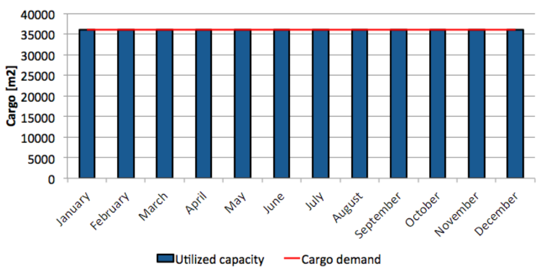
In the following case study, we investigate if the simulation model is capable of identify operational gaps between the North Sea and the Barents Sea. The comparison is based on the locations ability to meet the criteria of zero cargo waiting time, and one contingency vessel in supply base throughout 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 m2. The production platform is assumed to have a constant cargo demand of 1200$m2$ per day. The transport system is simulated over one year.

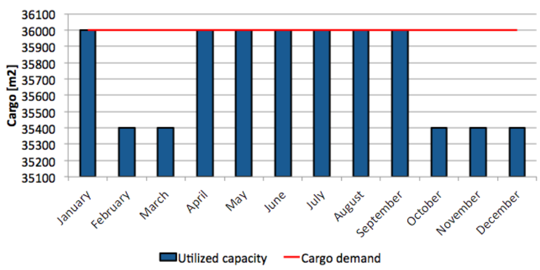
Figure 4.8: Location of the oilfield in the North Sea and Barents Sea

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



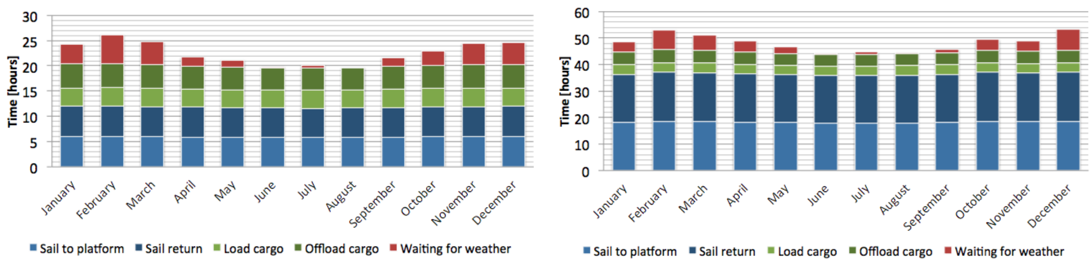
(a) North Sea



(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. Figure4.10b 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.

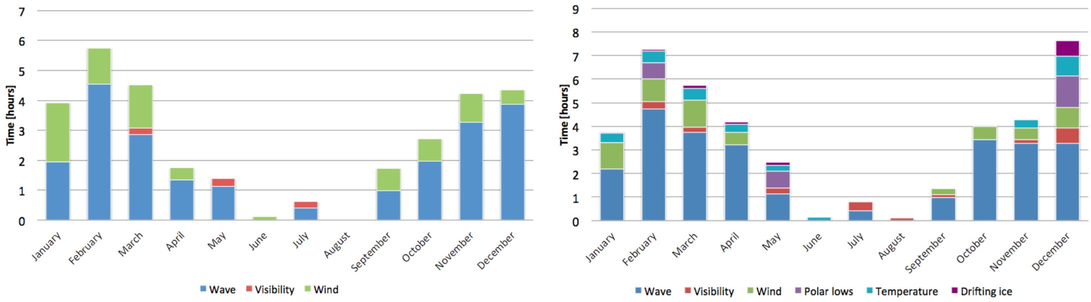


(a) North Sea

(b) Barents Sea

Figure 4.10: Decomposition of the mean operational duration

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 4.11a. 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 moths 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.



(a) North Sea (b) Barents Sea

Figure 4.11: Decomposition of environmental conditions

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.

KPI			
North Sea		**Barents Sea**	
Operational duration:	22,6 [h]	Operational duration:	48,2 [h]
Transit:	11,8 [h]	Transit:	36,5 [h]
Waiting for weather		**Waiting for weather**	
Waves:	1,9 [h]	Waves:	2.2 [h]
Wind:	0,7 [h]	Wind:	0,8 [h]
Visibility:	0,1 [h]	Visibility:	0.2 [h]
		Polar lows:	0.2 [h]
		Temperature:	0.3 [h]
		Drifting ice:	0,1 [h]

Figure 4.12: Required cargo demand

4.4 Case II: Fleet composition

In the following 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. In the previous case study, the simulation model identified that the increased distance and harsh environment will increase the operational duration of the PSV vessels. This may impact the required fleet composition.

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 $500m^2$.

	Order frequency [/day]		Cargo size [m2]	
	Mean	Standar dev.	Mean	Standar dev.
Platform 1	1	0.2	700	20
Platform 2	1	0.1	650	20

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 4.14. The input service speed is set at 12 knots, and consumption of 2 g/kwh

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

Table 4.2: Available pool of vessels

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

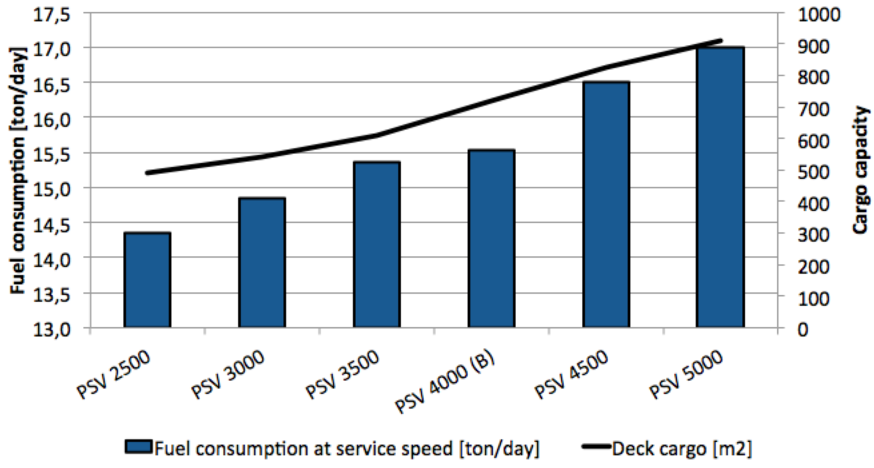
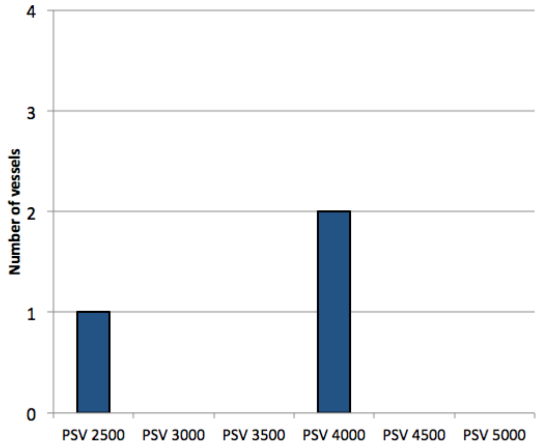


Figure 4.13: Fuel consumption ton/day at 12 knot

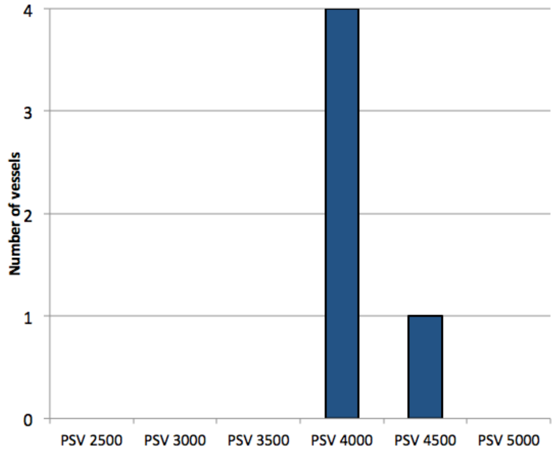
The results from the North Sea optimization process took 2019 seconds and found the optimal fleet composition of 2 PSV 4000 and 1 PSV 2500. There are 1000000 number of different compositions in the fleet, but the genetic algorithm found a suitable after trying 676 compositions.

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.



(a) North Sea



(b) Barents Sea

Figure 4.14: Optimal fleet composition

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.

	Utalization deck area [%]	Fuel consumption [tonne]	Fuel cost [$]
North Sea	75 %	82,5	49500
Barents Sea	69 %	42,3	25380

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 Almeder 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 estimating 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 decission 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.

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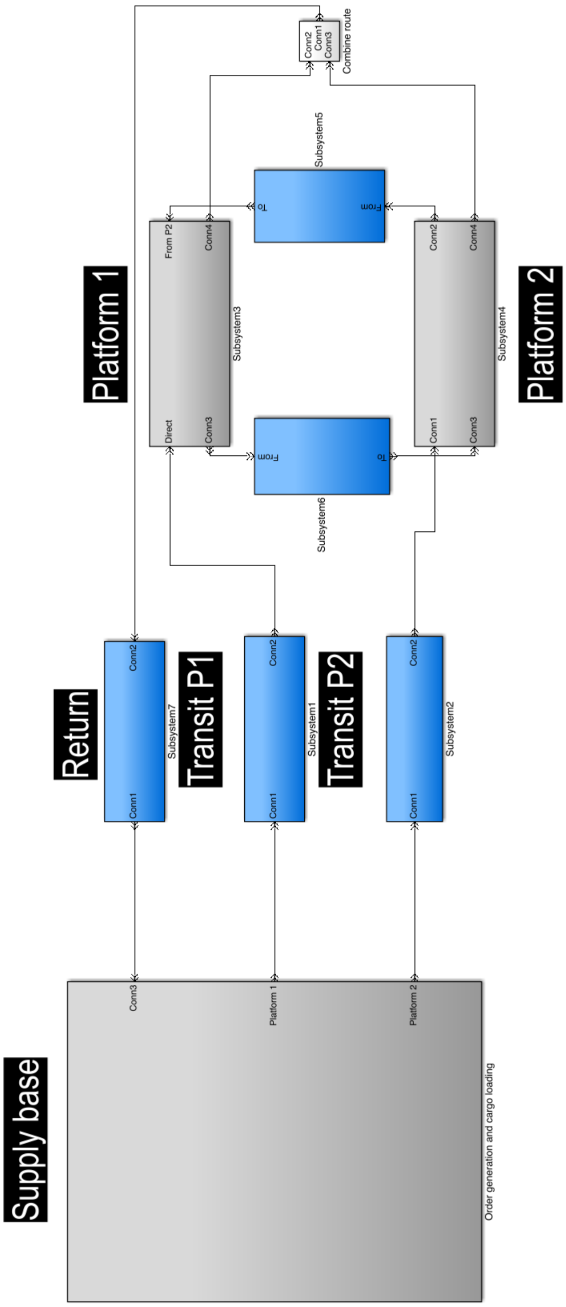
Appendix

Appendix A

Simulation model in SimEvents

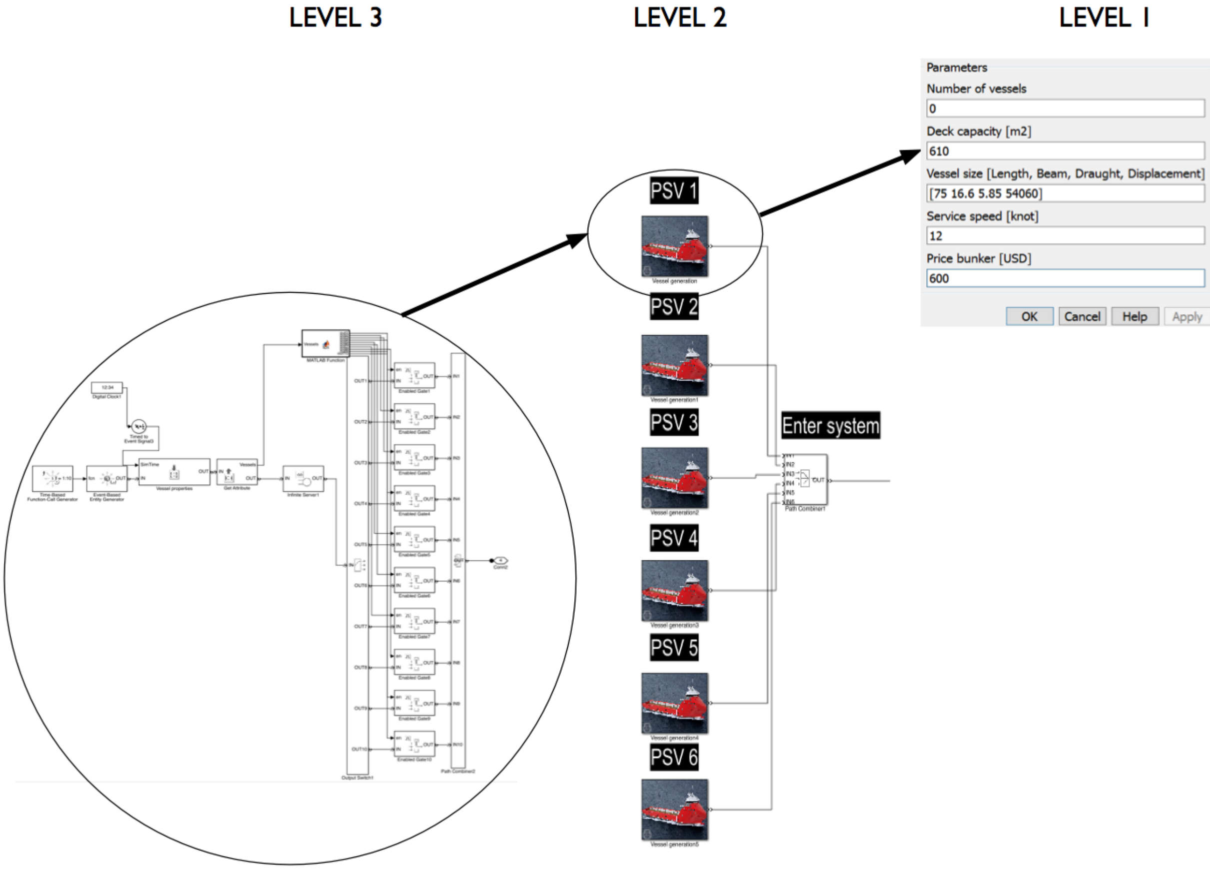
A.1 Overview of the simulation model

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.



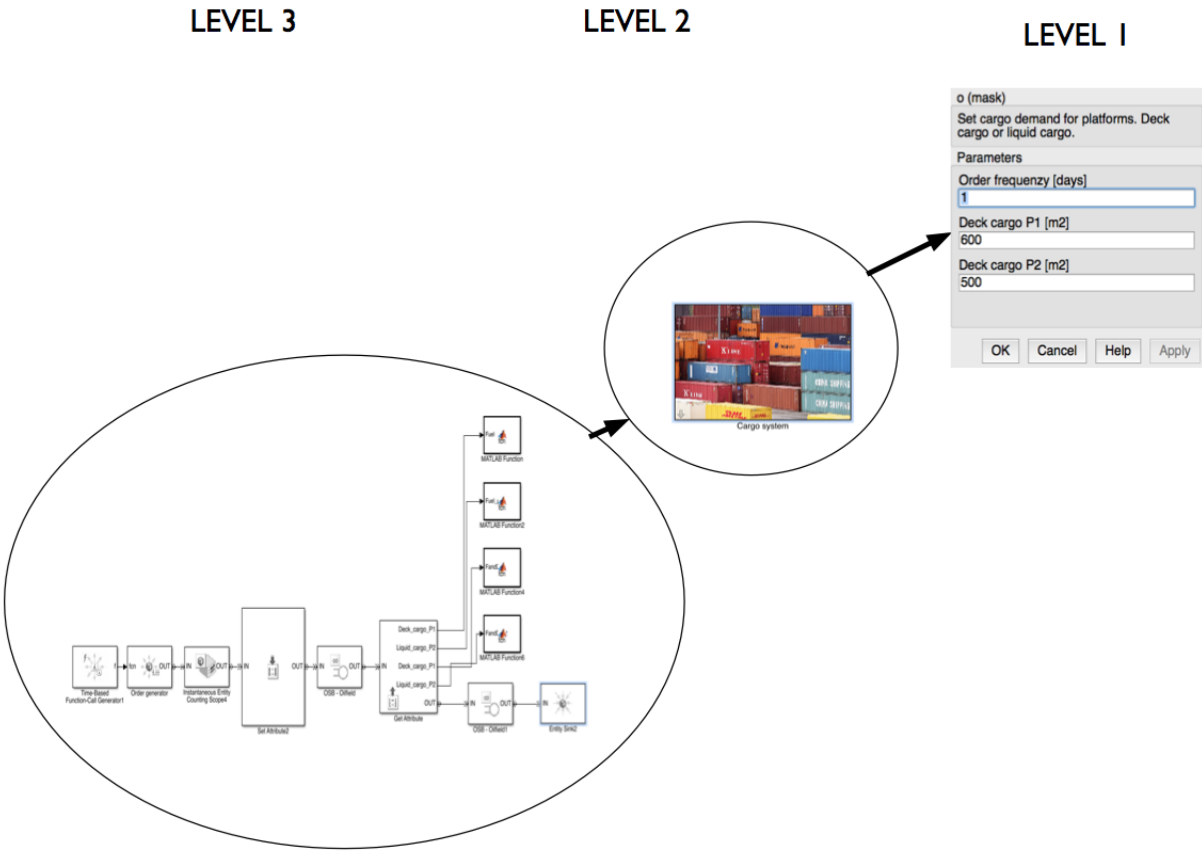
A.2 Vessel generation

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.



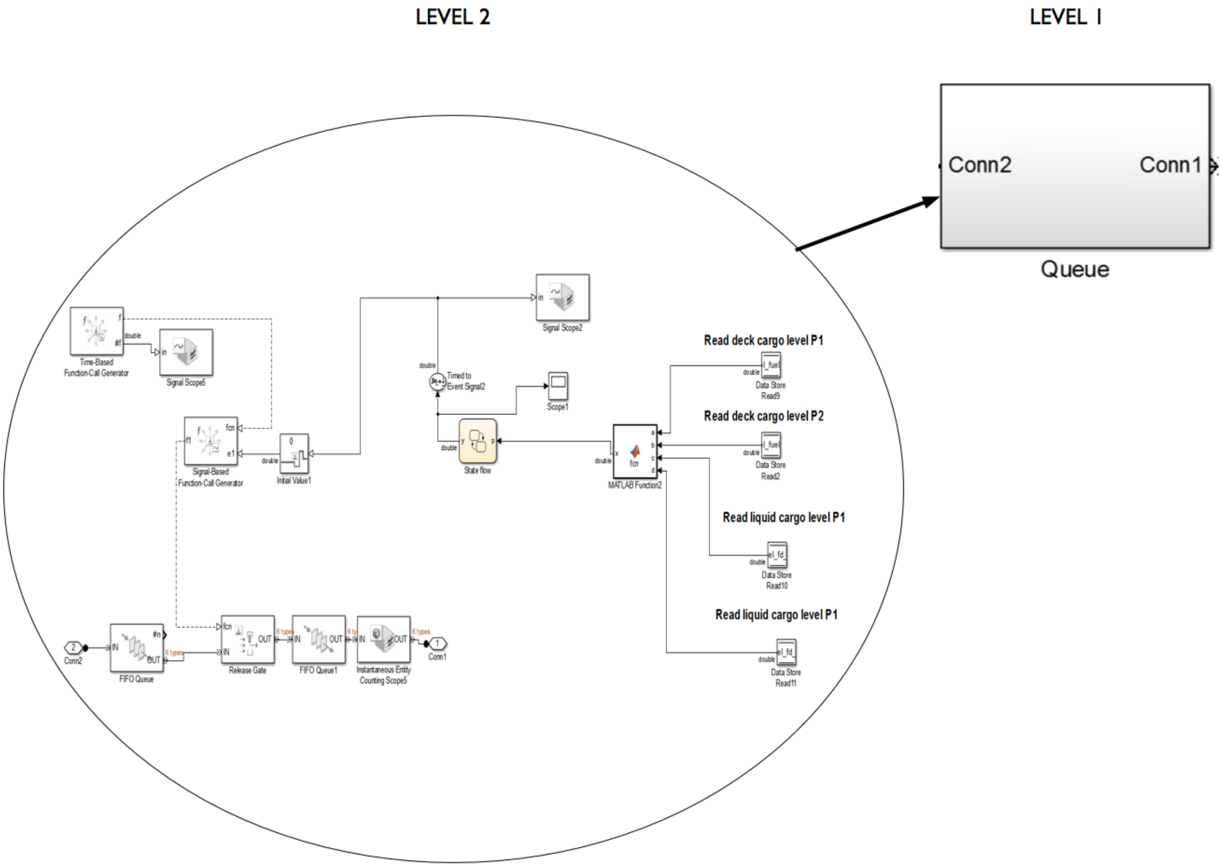
A.3 Order generation

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 an 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.



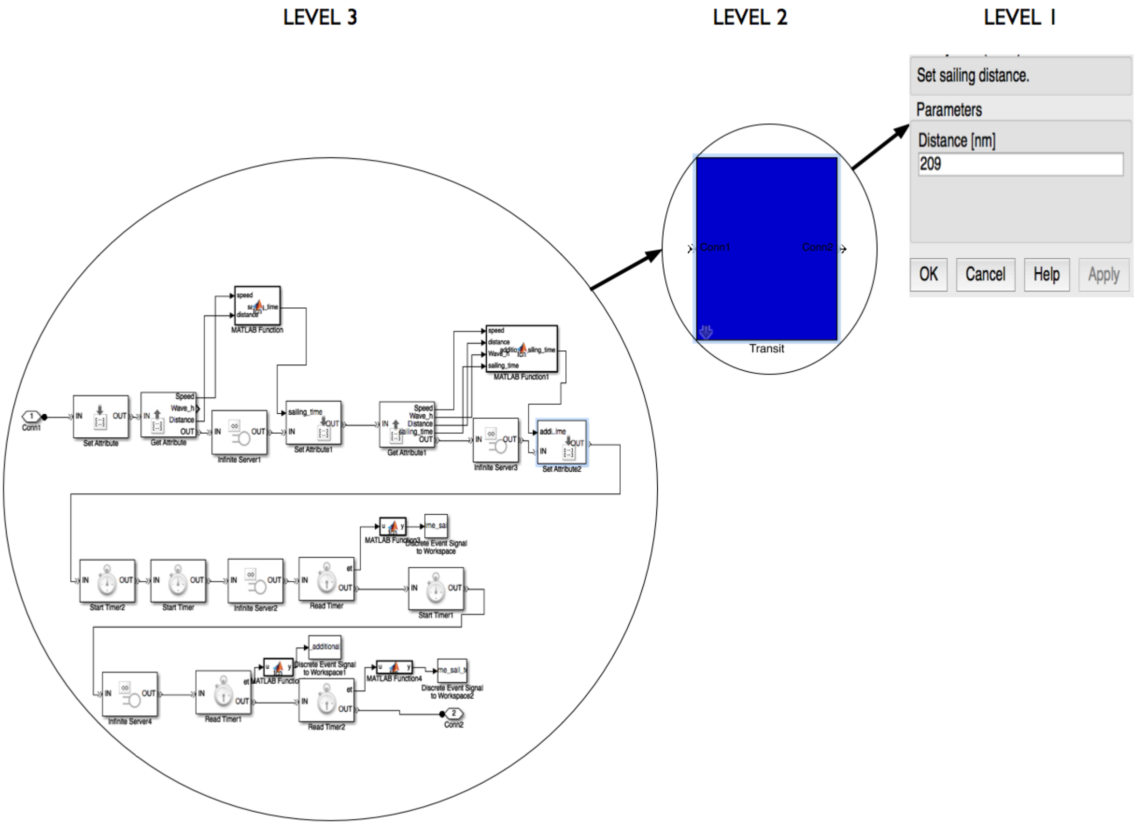
A.4 Load cargo

The vessels will wait in a queue until a 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 release 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 platform s.



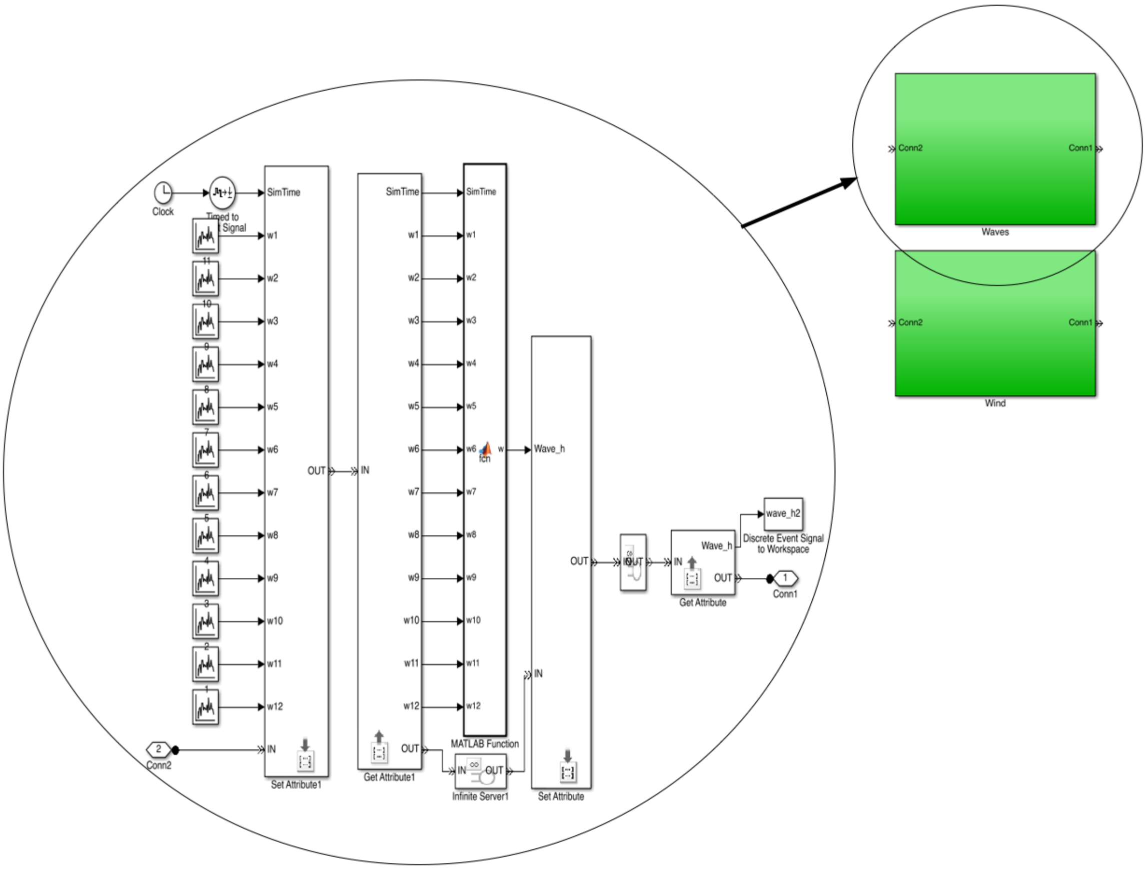
A.5 Sailing

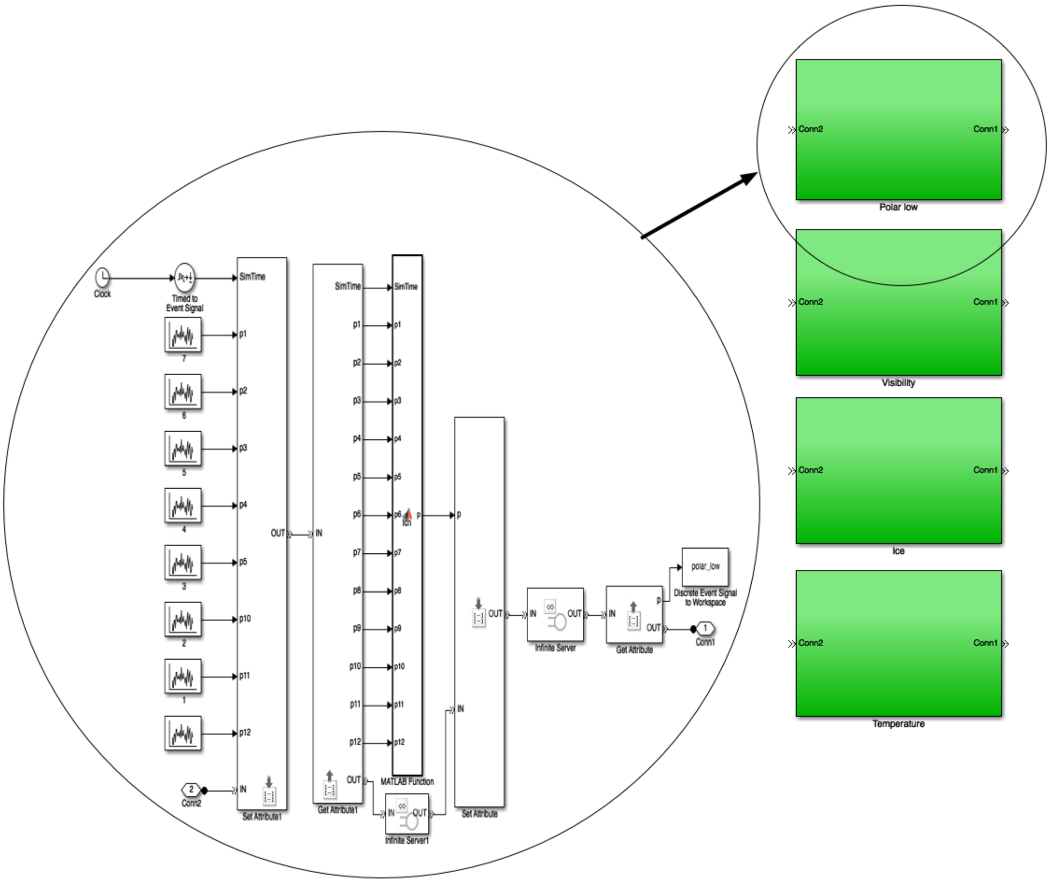
The time spent sailing is a function of speed distance and wave-height. The "sailing" block allows for setting distances to the oilfields.



A.6 Environmental input

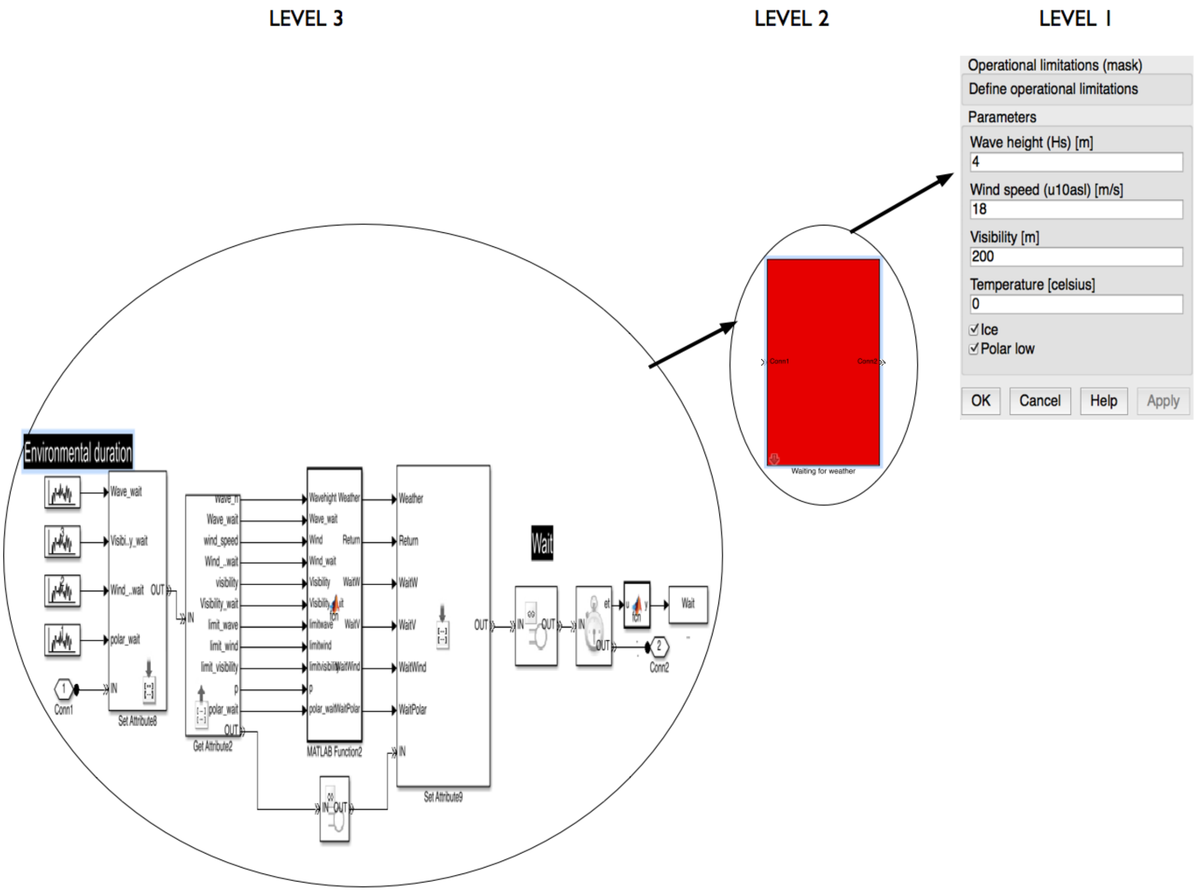
Environmental conditions are implemented in the simulation model by using a ”random number” generator. The random number is log-normal and normally distributed for wave and wind conditions. Polar low, visibility,ice and temperature is implemented by the Bernoulli equation. By using 12 ”random number” 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.




Conn2
Conn1
Polar low
Visibility
Ice
Temperature
Clock
Timed to Event Signal
7
6
5
4
3
2
1
SimTime
p1
p2
p3
p4
p5
p10
p11
p12
IN
OUT
Set Attribute1
Get Attribute1
p6
p7
p8
p9
MATLAB Function
fcn
p
Infinite Server1
Set Attribute
Infinite Server
Get Attribute
polar_low
Discrete Event Signal to Workspace

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 bellow 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. lb sets the lower bound of the optimization variables and 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. 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 gentic 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. Setparam indicates that the number of vessels will be changed in the simulation model. simOut is simulating the model and saves the value to a variable called backlogValuesCargo. 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.

```
function fleetcomposition=sim()

%%
opts=gaoptimset('PlotFcns',{@gaplotbestf; @gaplotbestindiv; @gaplot1drange},...
    '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(vecX)

%%%%
Vessel1=vecX(1);
Vessel2=vecX(2);
Vessel3=vecX(3);
Vessel4=vecX(4);
Vessel5=vecX(5);
Vessel6=vecX(6);
%%%% forandre string??? forandre mellomrom på nom, evnt en kode??
 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);

fuel=[FuelCost1 FuelCost2 FuelCost3 FuelCost4 FuelCost5 FuelCost6]*vecX'
obj=(backlogCargo*inf)+fuel
end
end
```

A.9 Order generation script

```
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
```

A.10 Load deck cargo script

```
function [Cargo_f_p1,Cargo_f_p2]   = laster(Capacity_f)
%Cargo_f_p1=Deck_cargo_loaded_p1
%Cargo_f_p1=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
%----------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
```

```
%--------Divided
elseif level_fuel_p1+level_fuel_p2<=Capacity_f
    Cargo_f_p1=level_fuel_p1
    Cargo_f_p2=level_fuel_p2
else
    Cargo_f_p1=disp('error')
    Cargo_f_p2=disp('error')
end
level_fuel_p1=level_fuel_p1-Cargo_f_p1
level_fuel_p2=level_fuel_p2-Cargo_f_p2
end
```

A.11 Liquid deck cargo script

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

%Cargo_fd_p1=Liquid cargo P1
%Cargo_fd_p1=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
```

```
%----------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

```
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_siling_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
    Cargo_f_p1=disp('error')
    Cargo_f_p2=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

```
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

```
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<=60)
    p=p2
elseif (SimTime>60) && (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

```
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
elseif  (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


elseif (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

elseif (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
```

```
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
```

```
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.

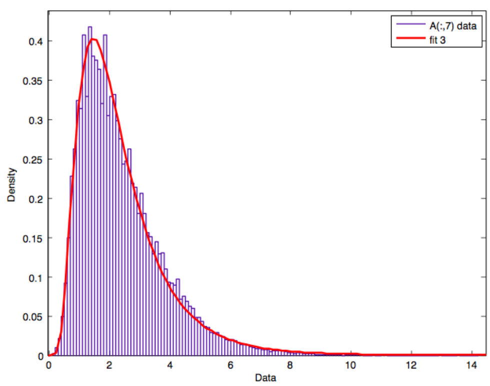


Figure B.1: January-December, Balder

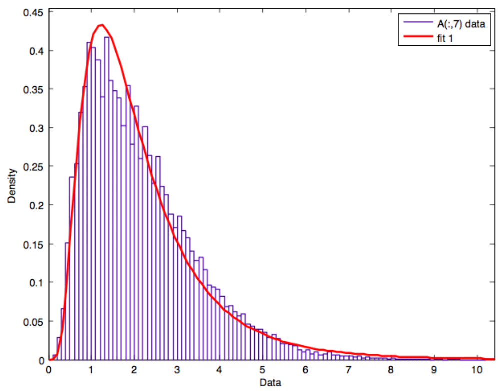


Figure B.2: January-December, Ringhorne

B.1 Barents Sea

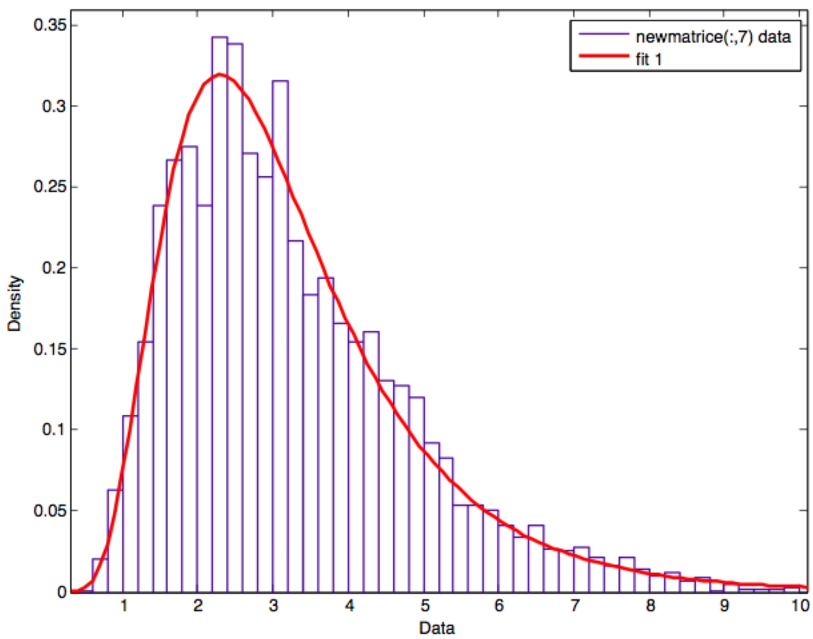


Figure B.3: January

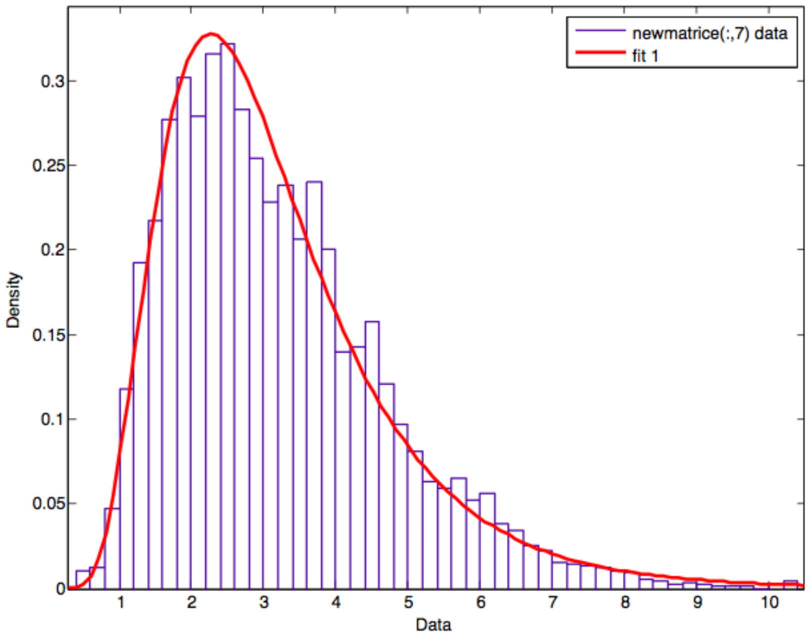


Figure B.4: February

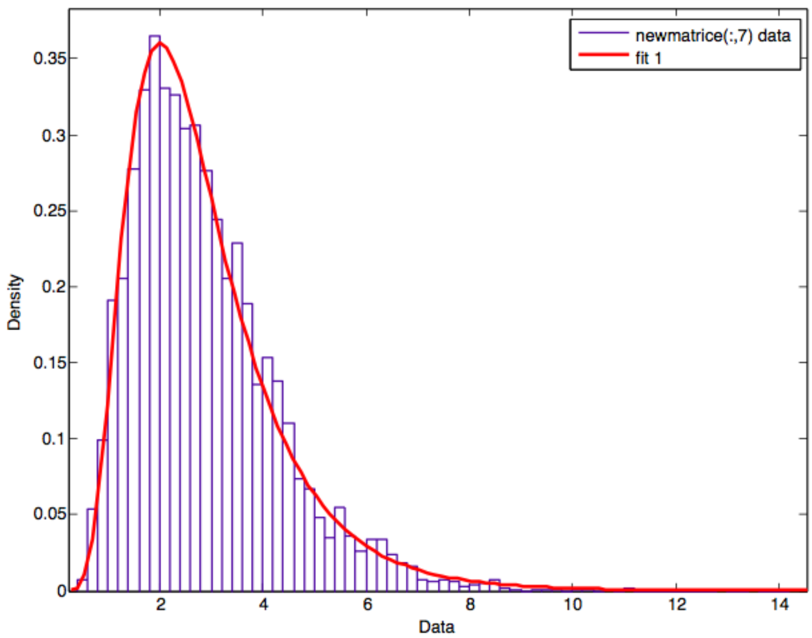


Figure B.5: March

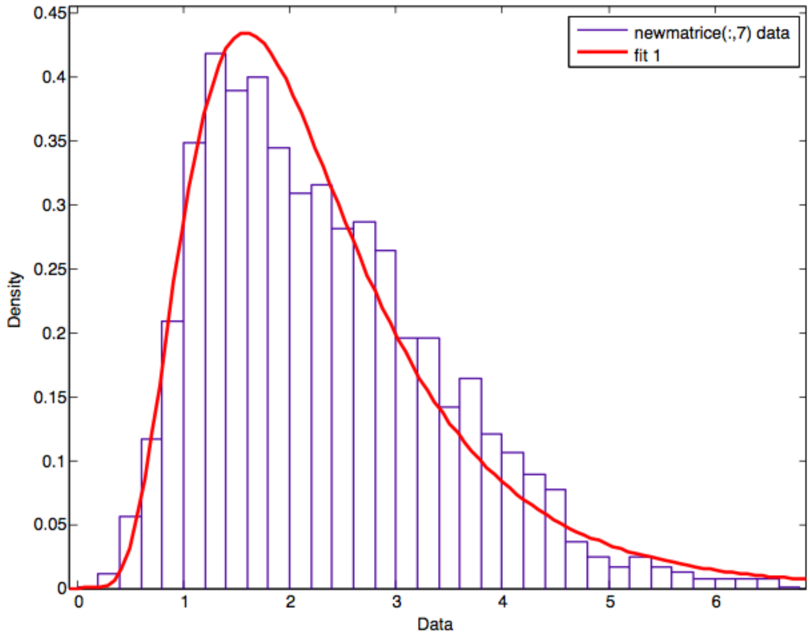


Figure B.6: April

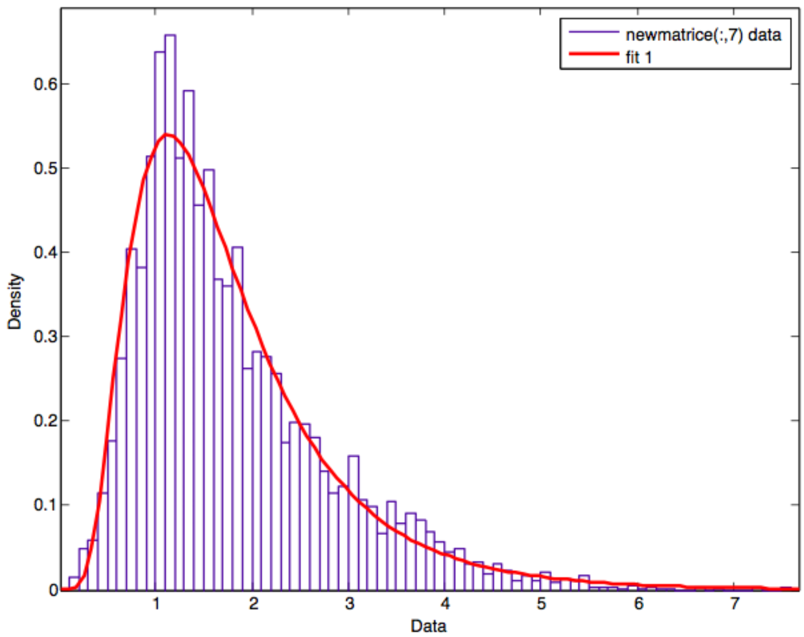


Figure B.7: May

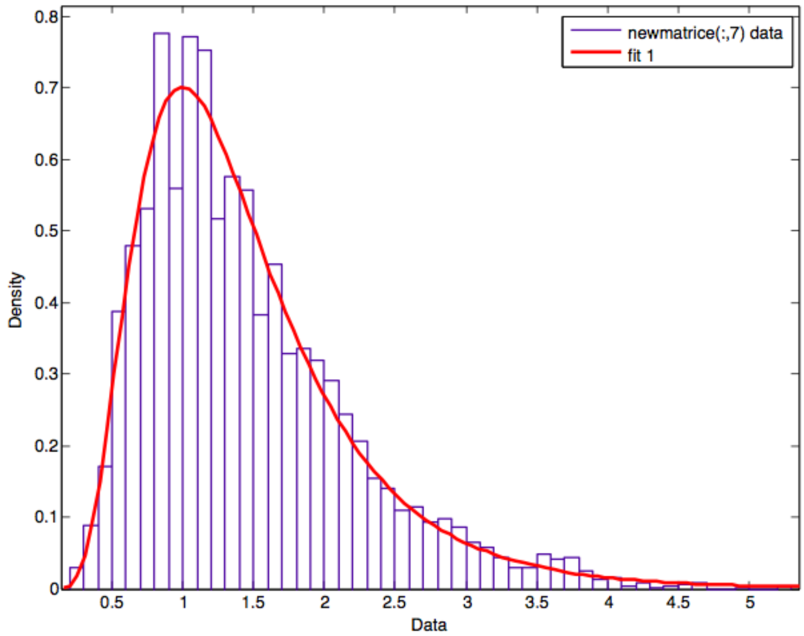


Figure B.8: June

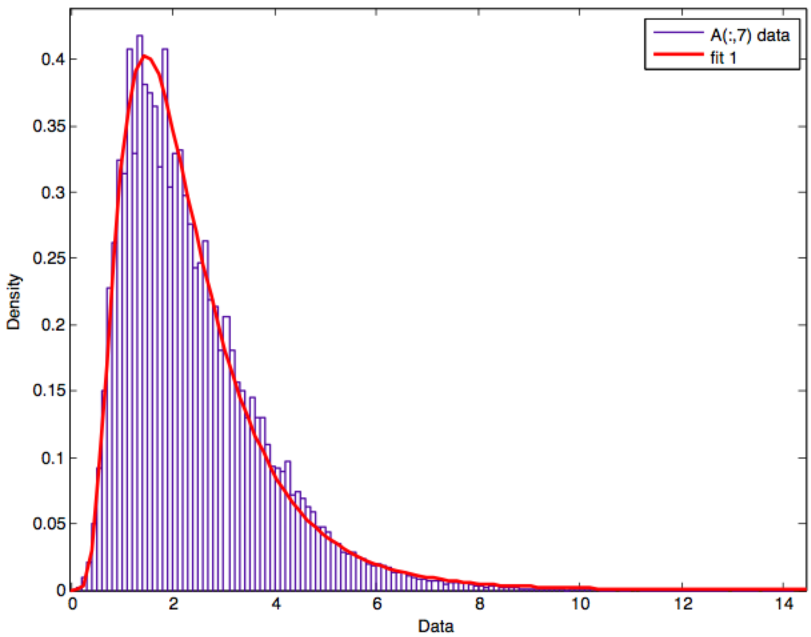


Figure B.9: July

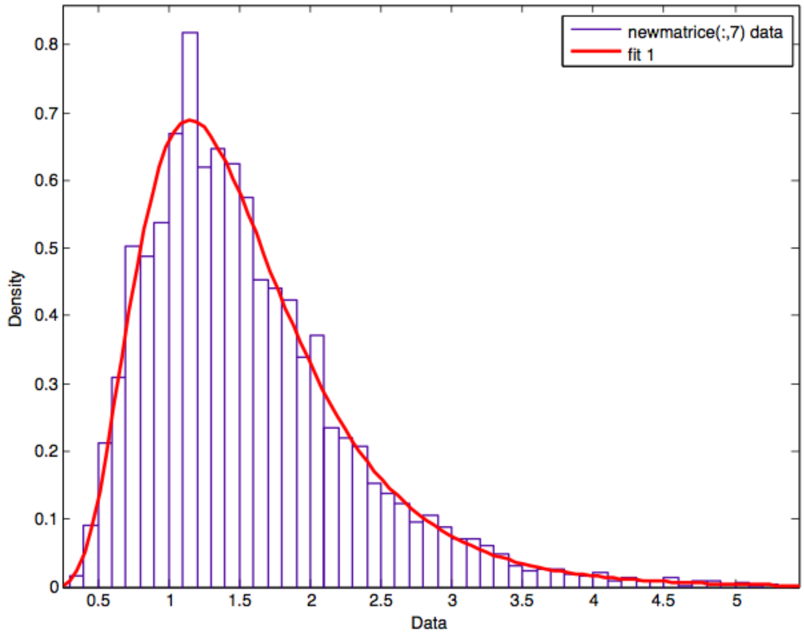


Figure B.10: August

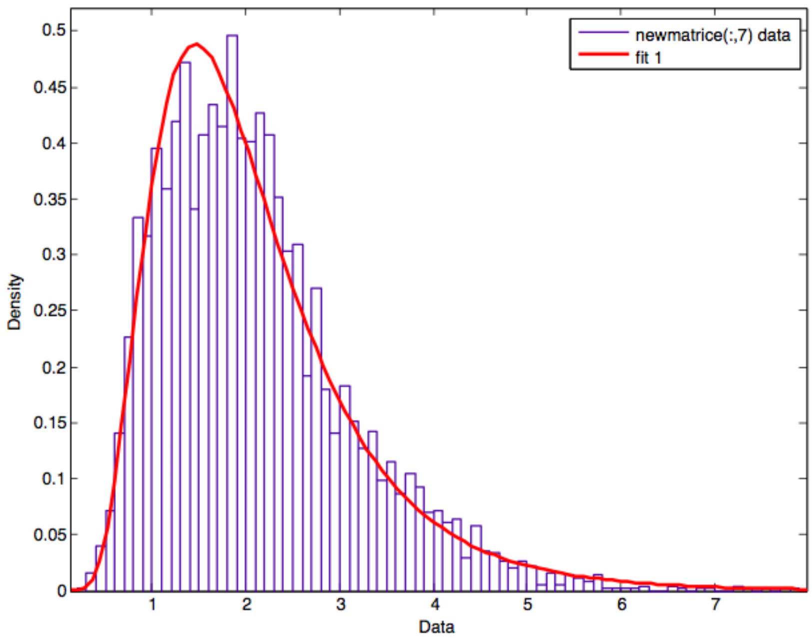


Figure B.11: September

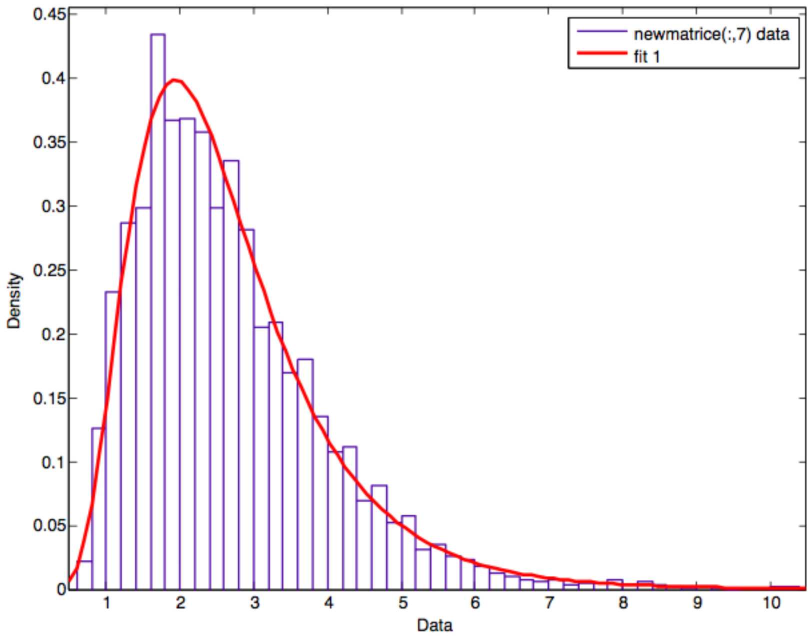


Figure B.12: October

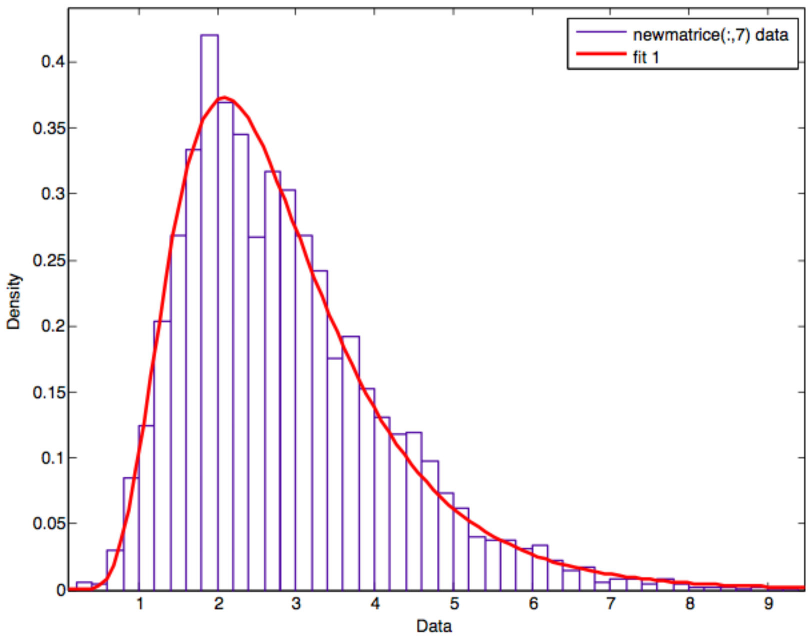


Figure B.13: November

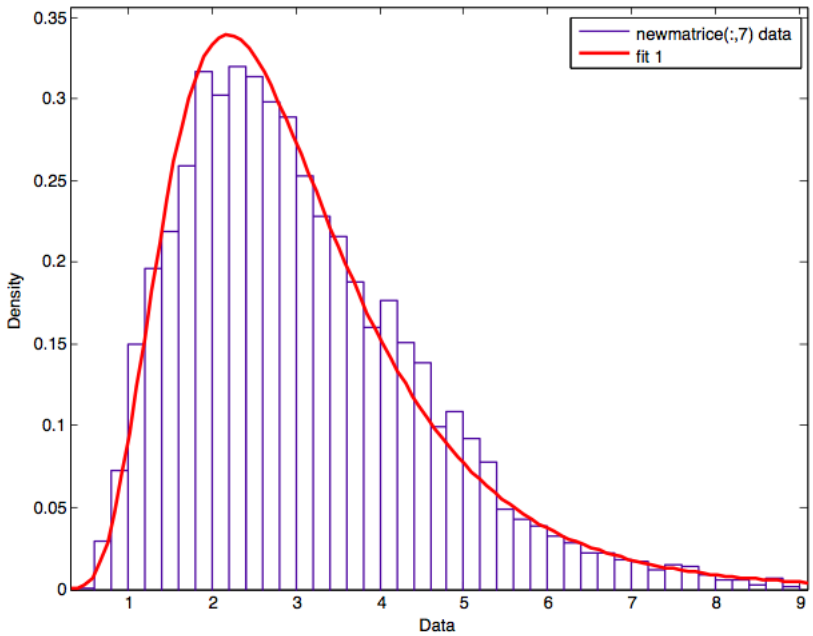


Figure B.14: December

B.2 North Sea

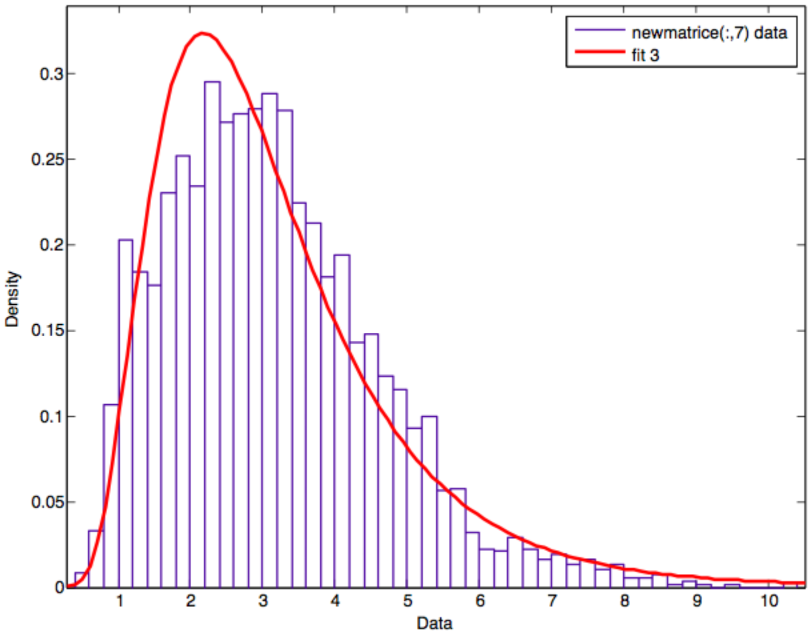


Figure B.15: December

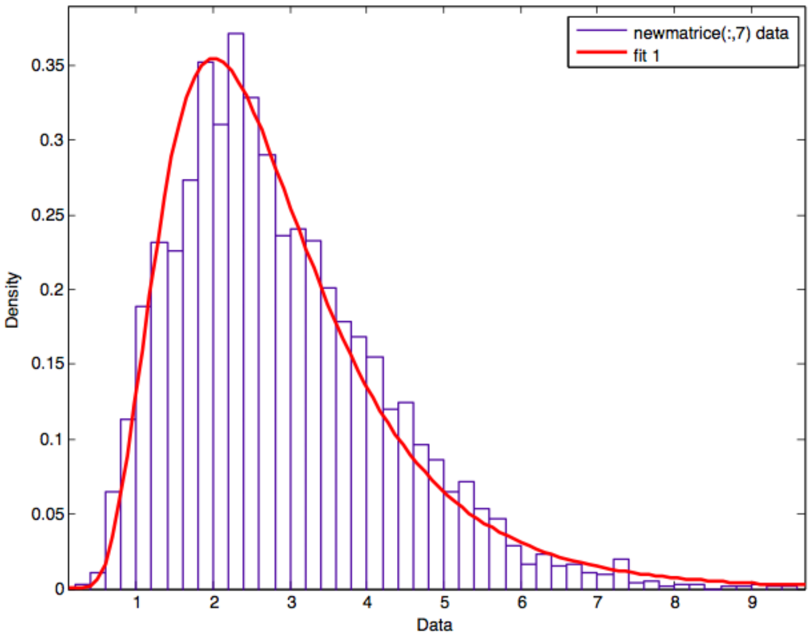


Figure B.16: February

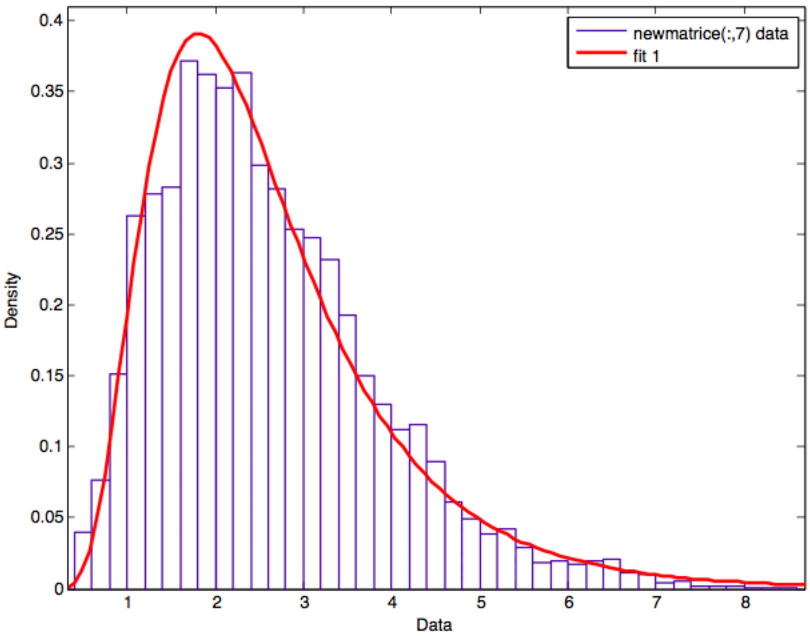


Figure B.17: March

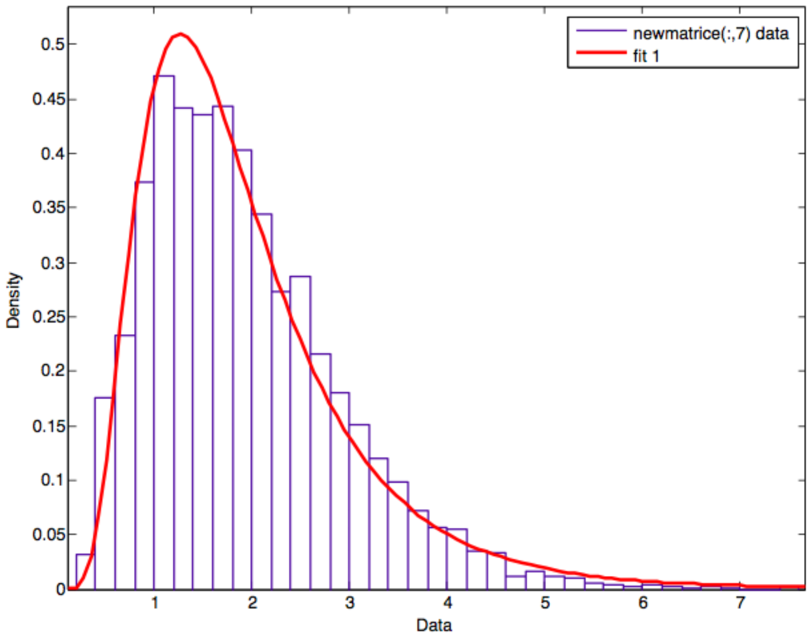


Figure B.18: April

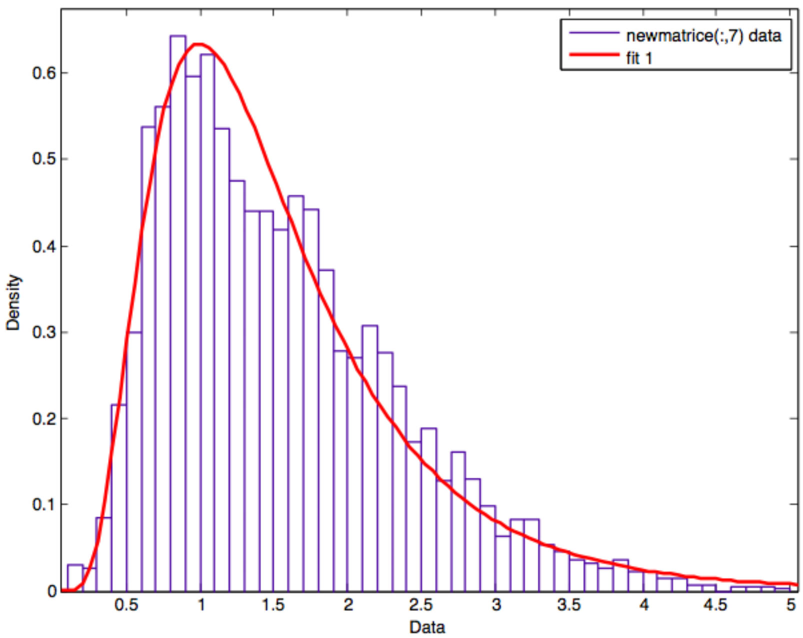


Figure B.19: May

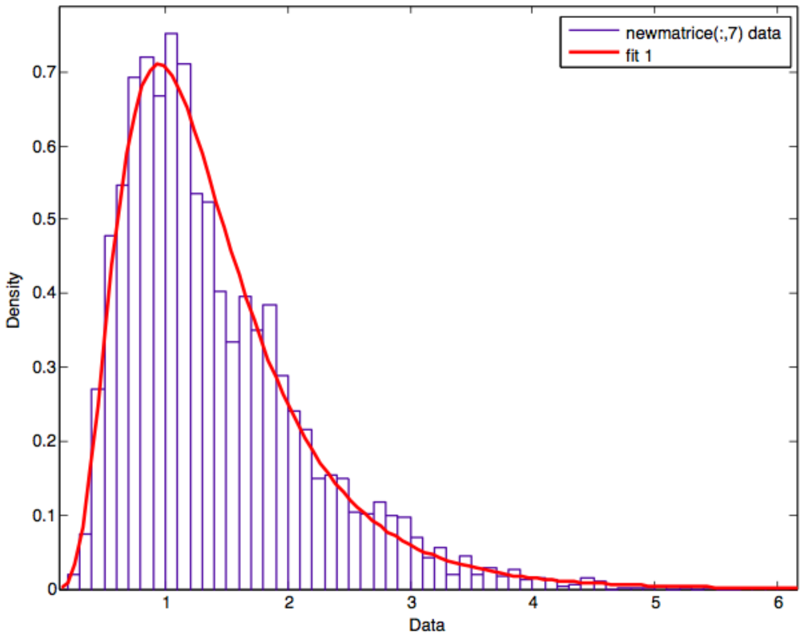


Figure B.20: June

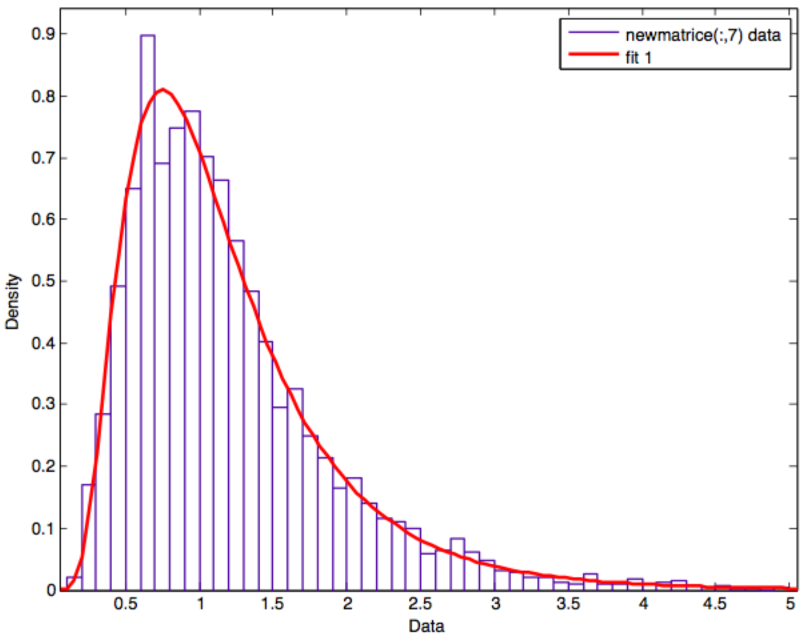


Figure B.21: July

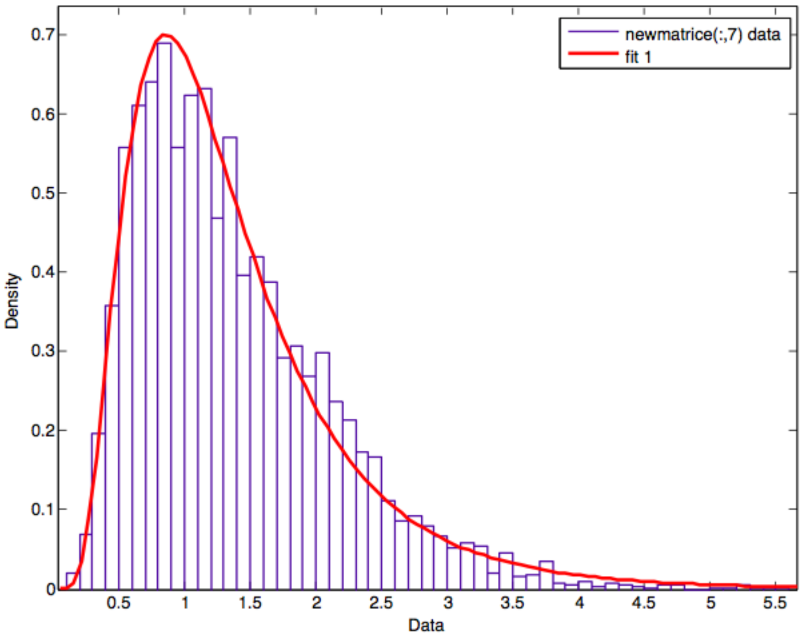


Figure B.22: August

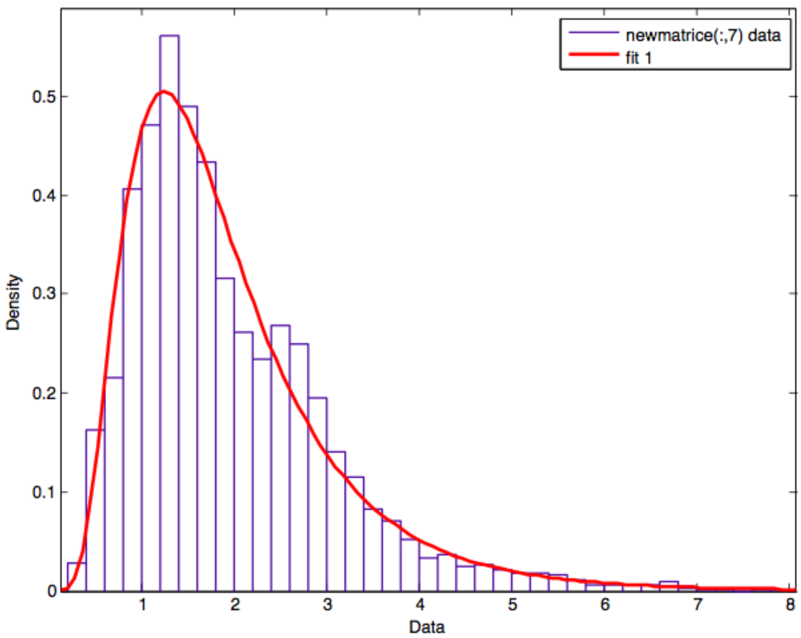


Figure B.23: September

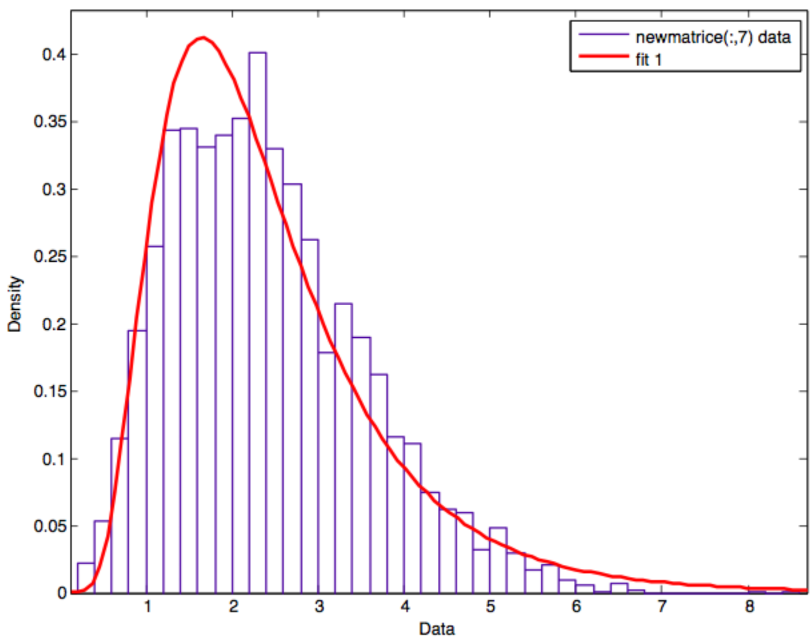


Figure B.24: October

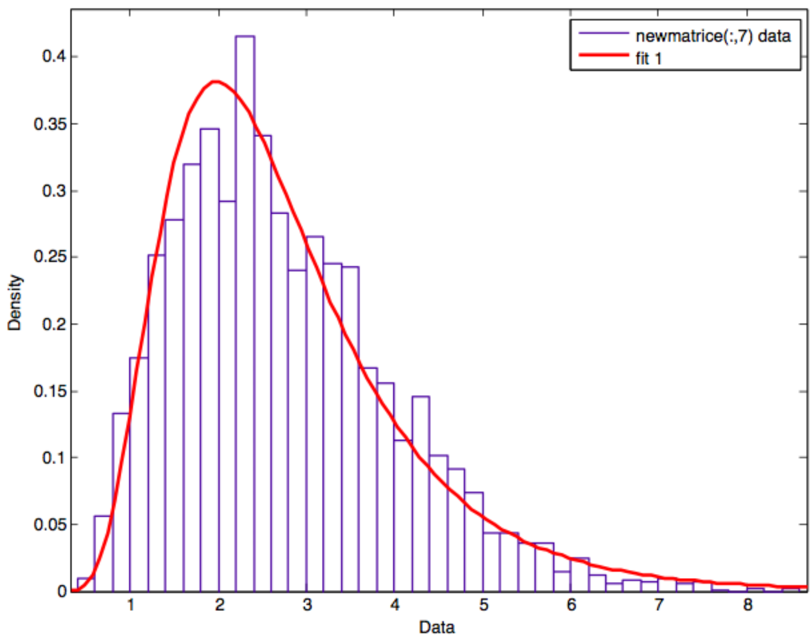


Figure B.25: November

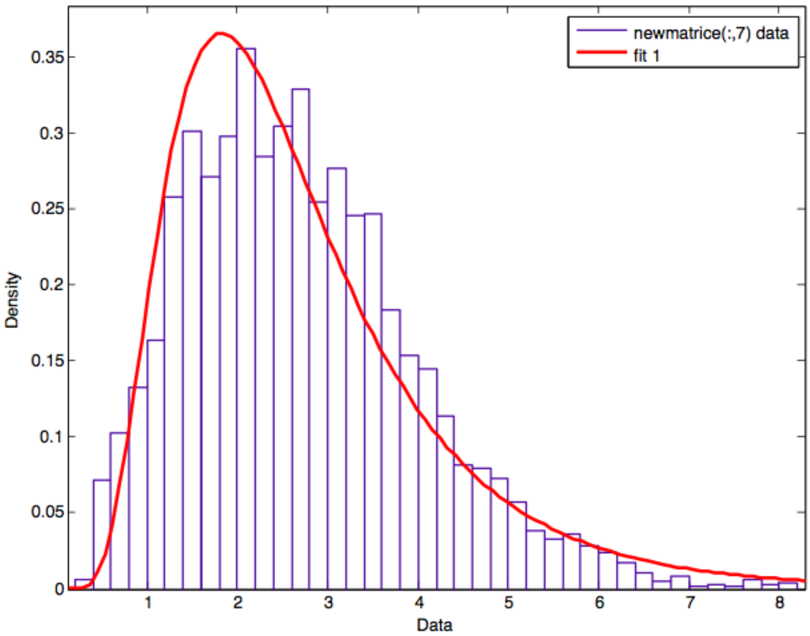


Figure B.26: December

Appendix C

Gaussian distribution of wind conditions

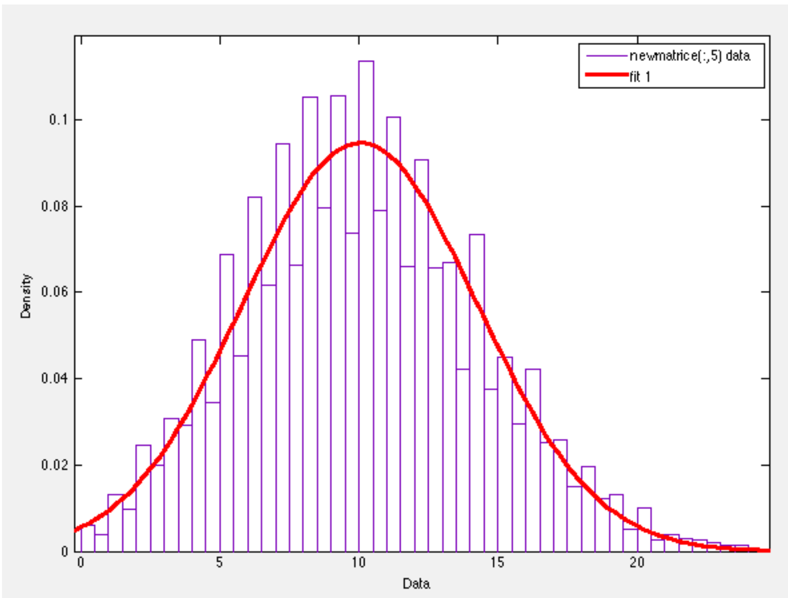


Figure C.1: January

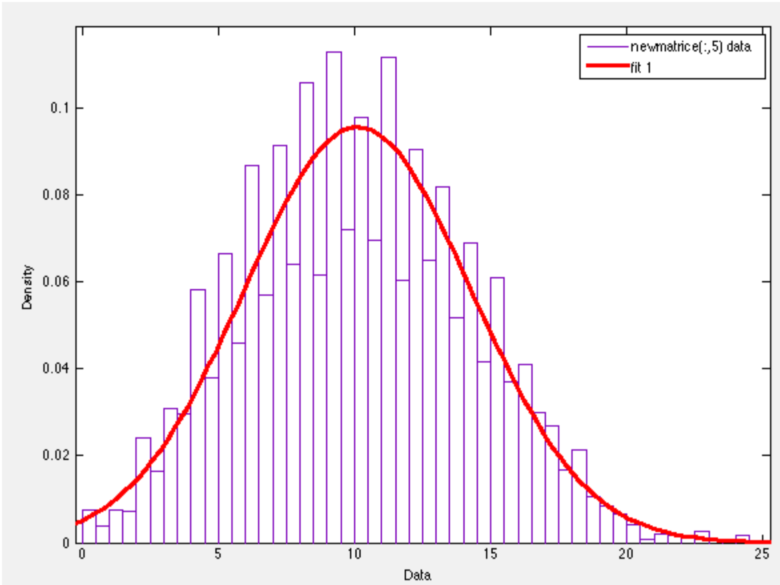


Figure C.2: February

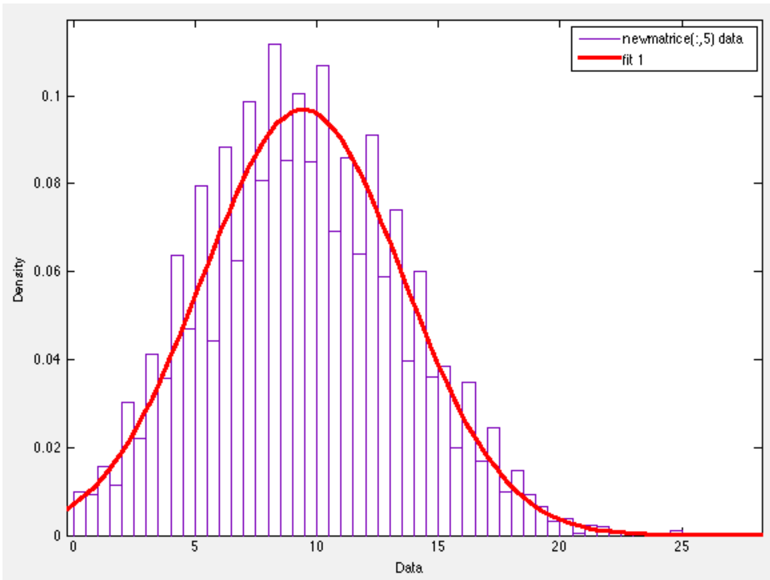


Figure C.3: March

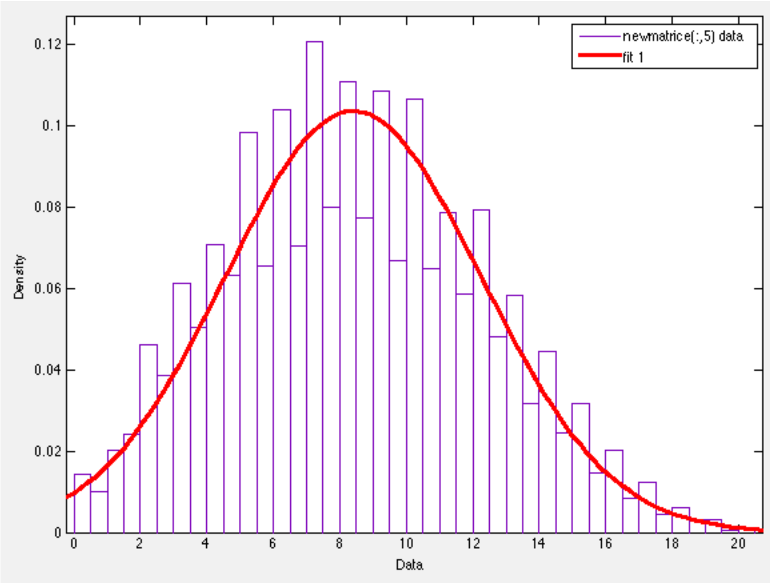


Figure C.4: April

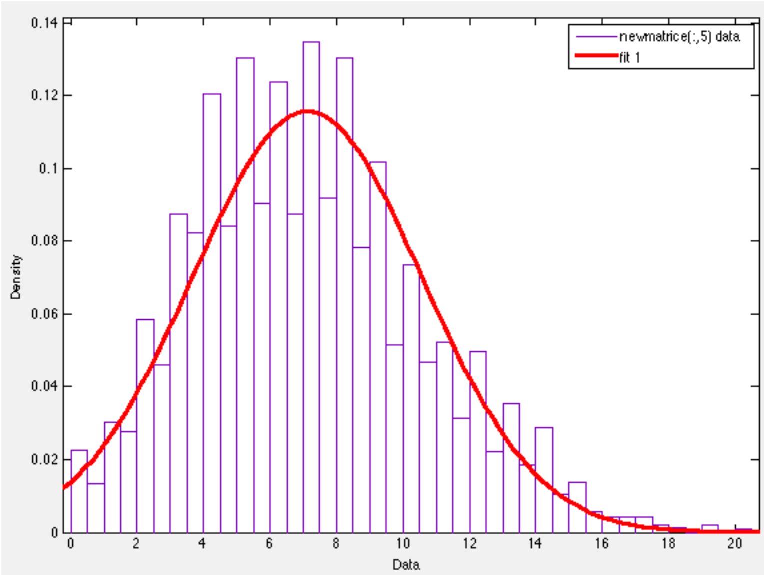


Figure C.5: May

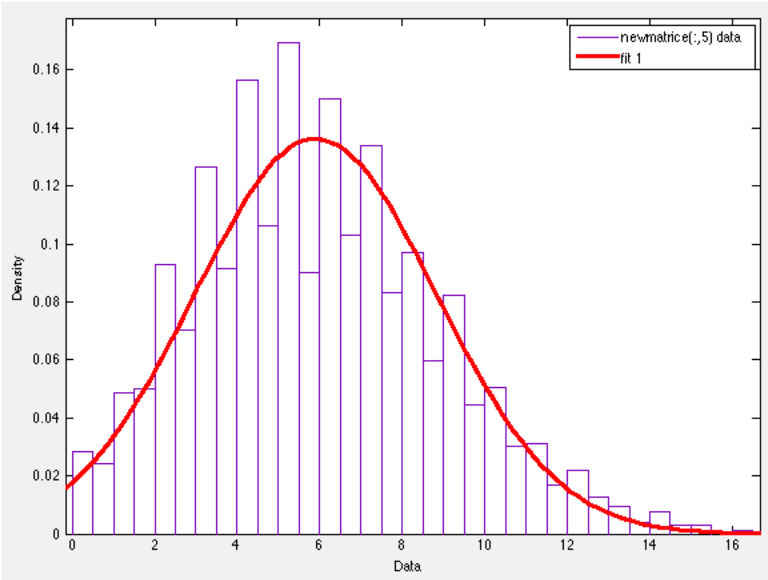


Figure C.6: June

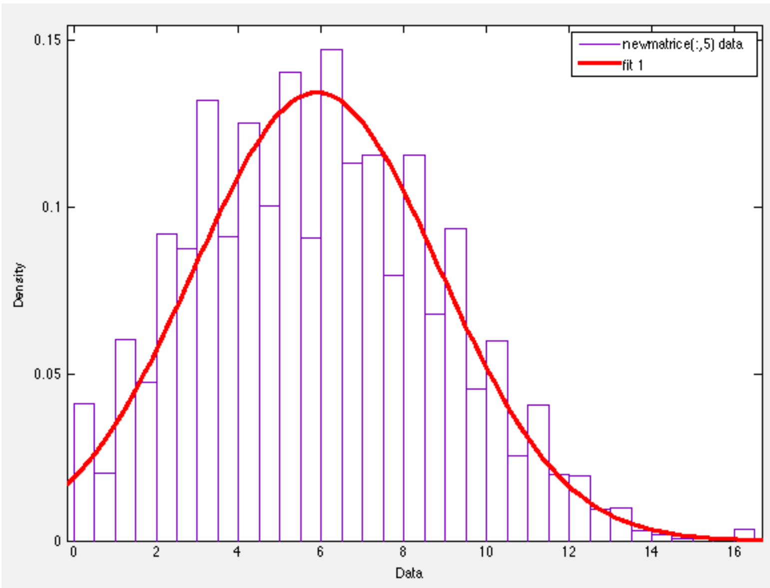


Figure C.7: July

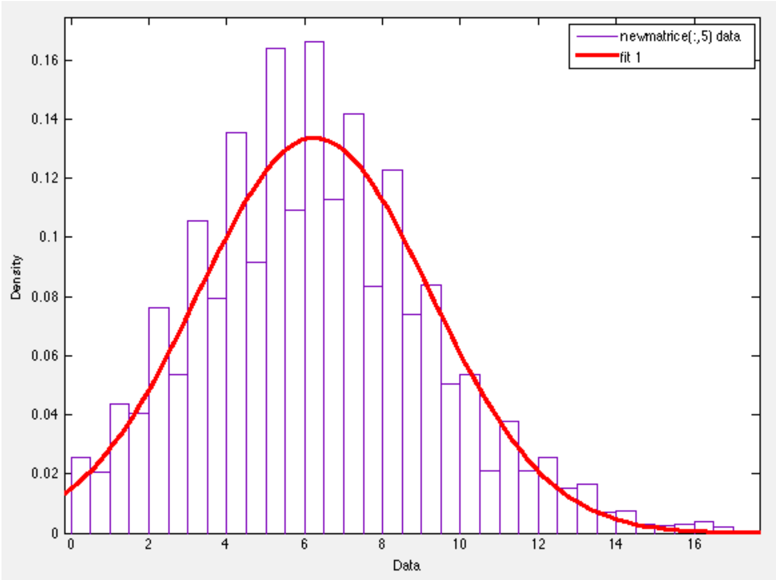


Figure C.8: August

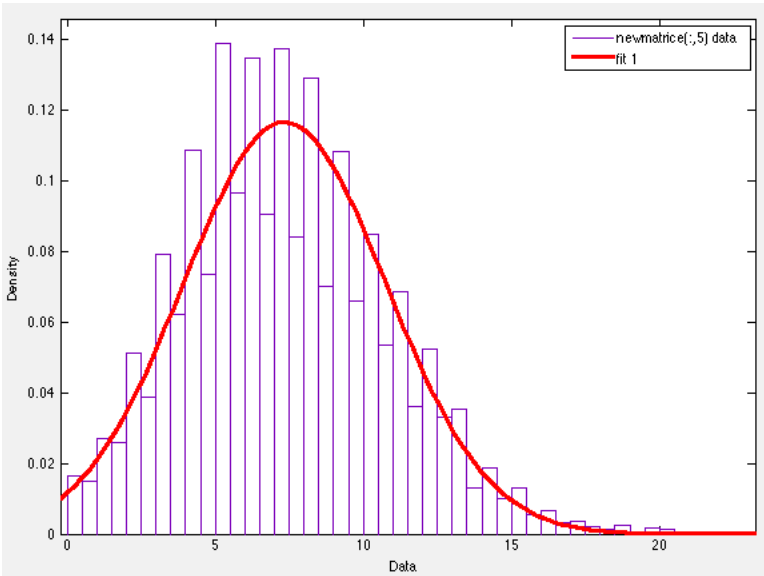


Figure C.9: September

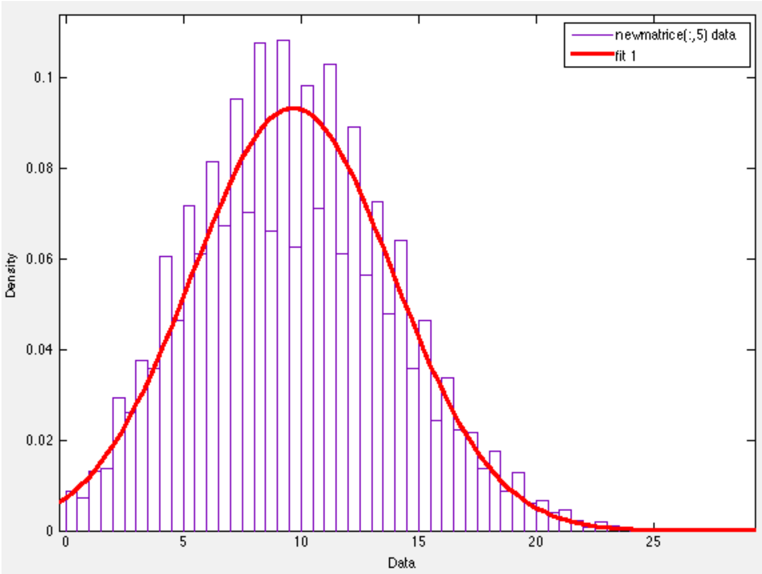


Figure C.10: October

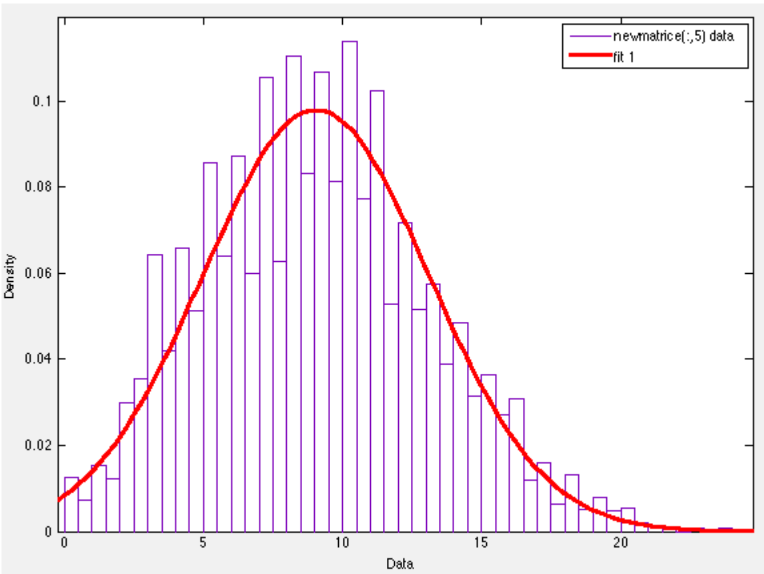


Figure C.11: November

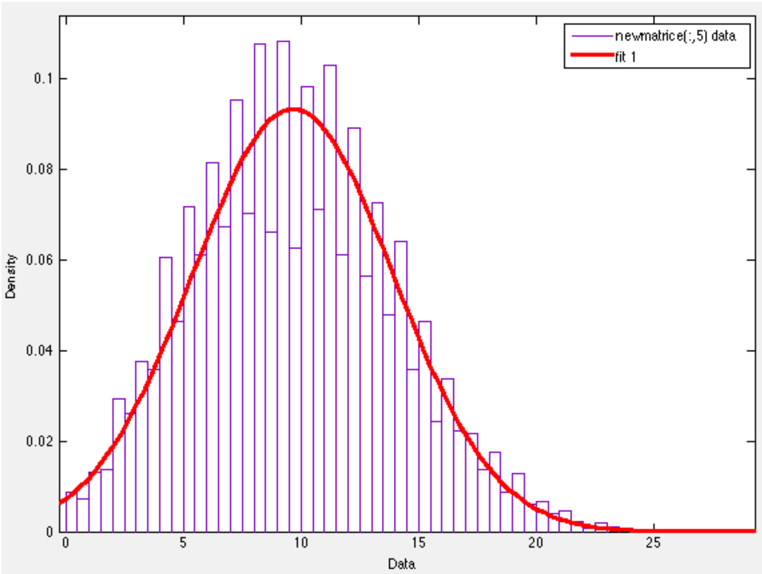


Figure C.12: December

C.1 Barents Sea

C.2 North Sea

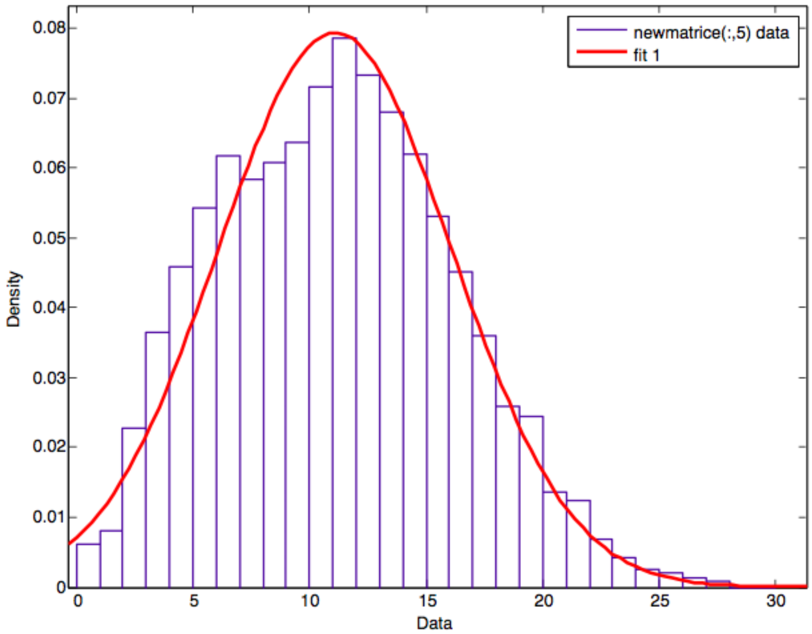


Figure C.13: January

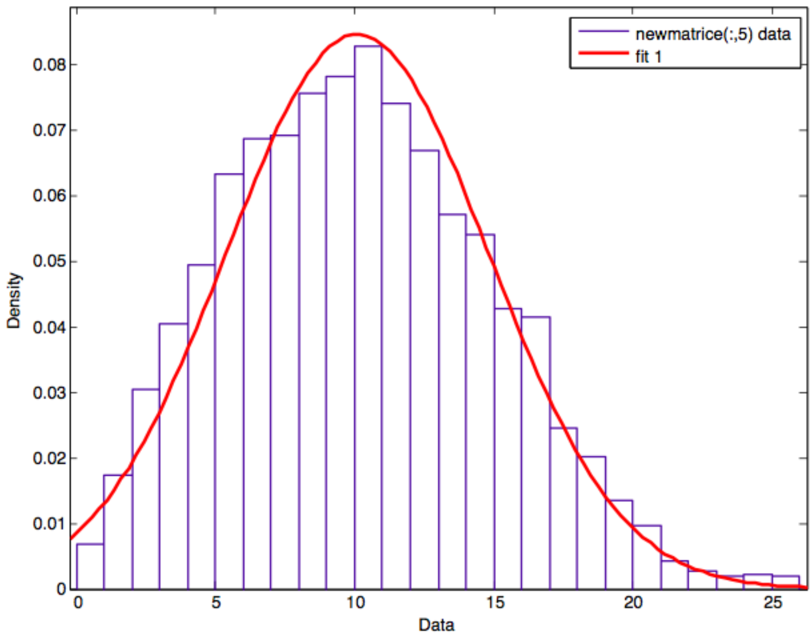


Figure C.14: February

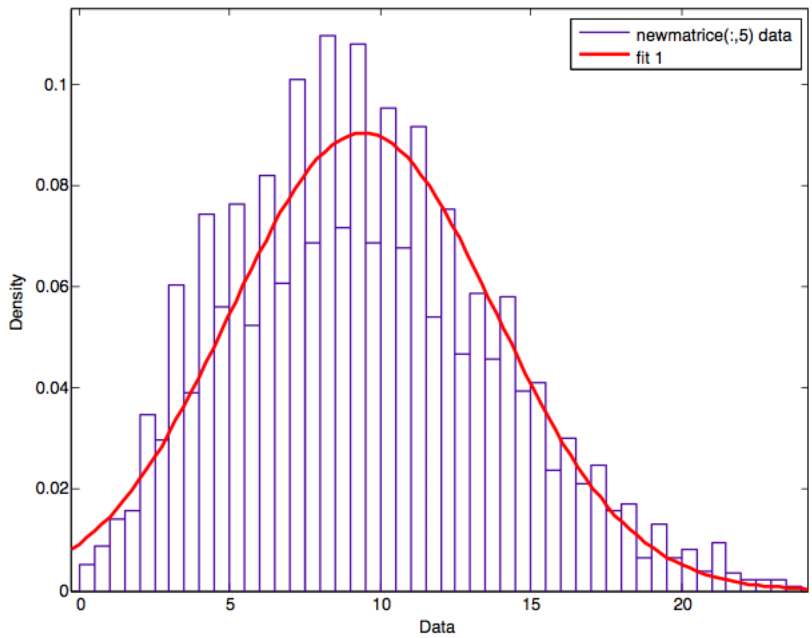


Figure C.15: March

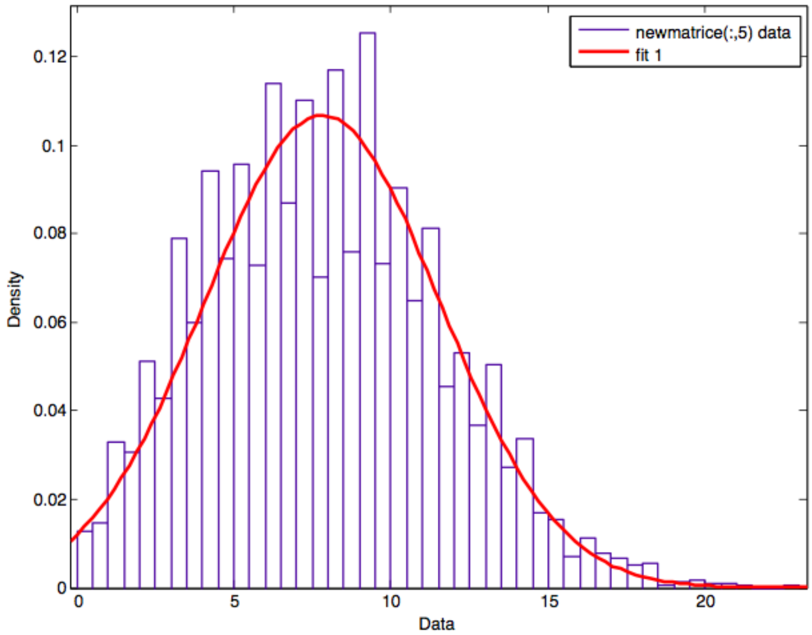


Figure C.16: April

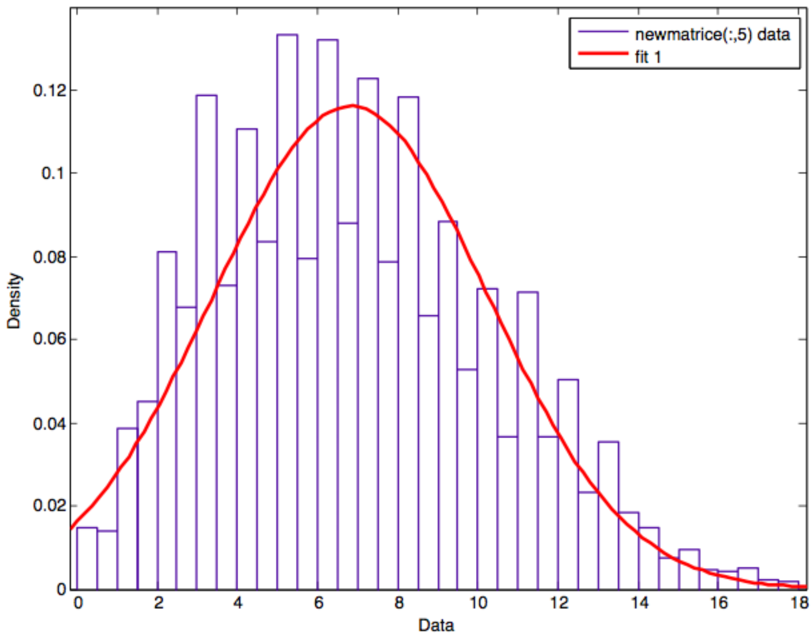


Figure C.17: May

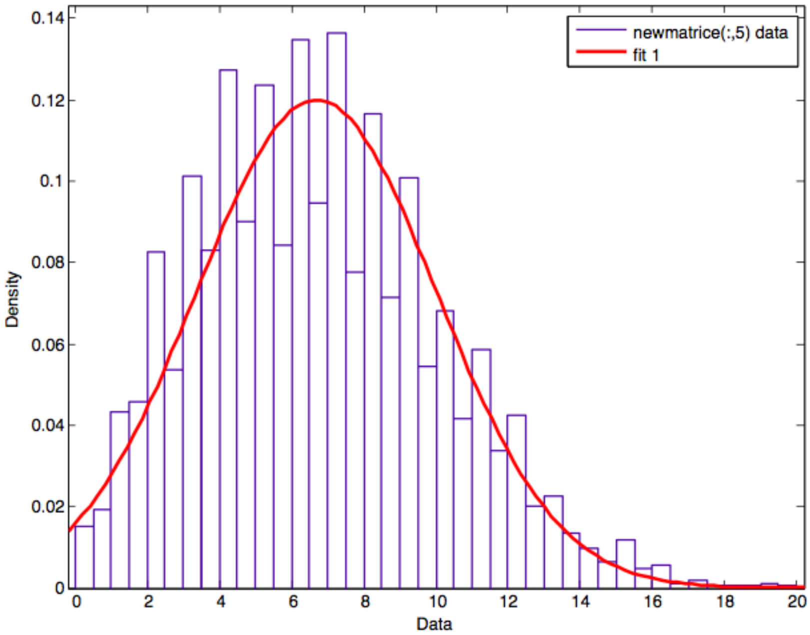


Figure C.18: June

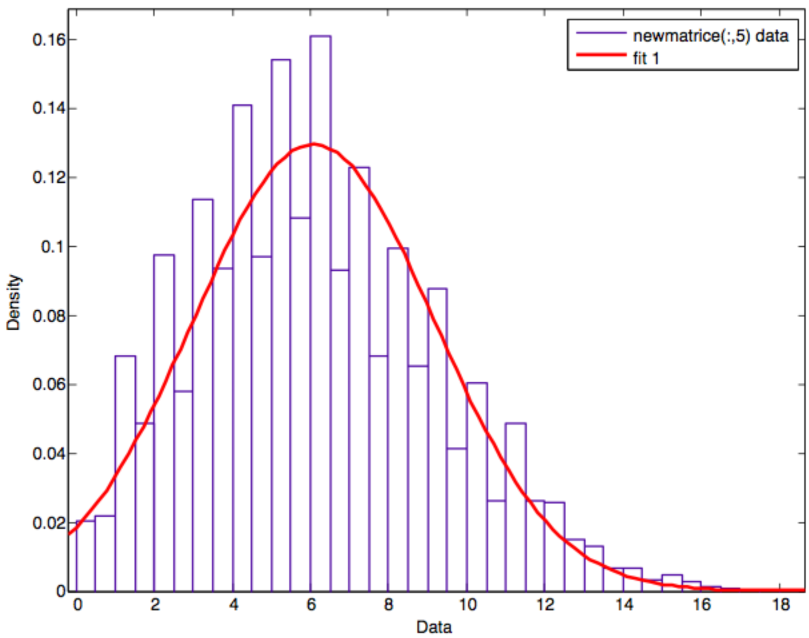


Figure C.19: July

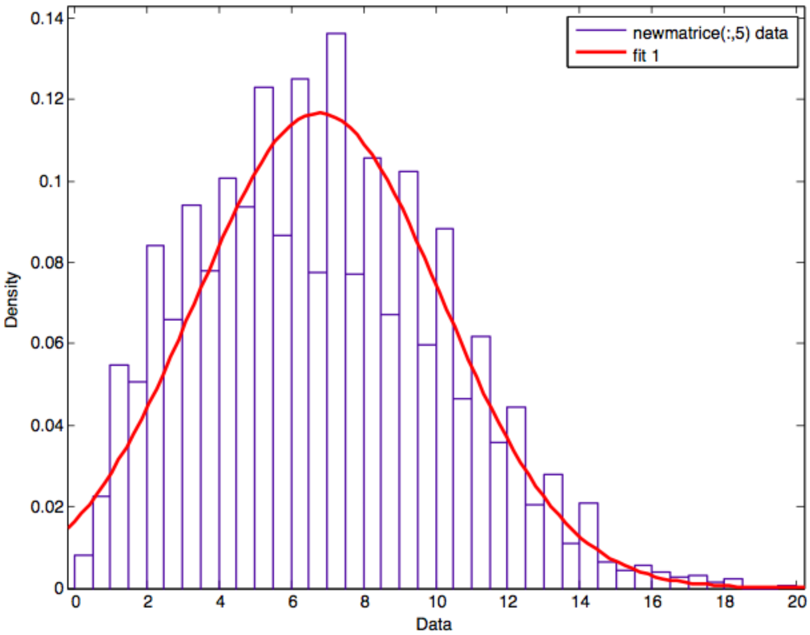


Figure C.20: August

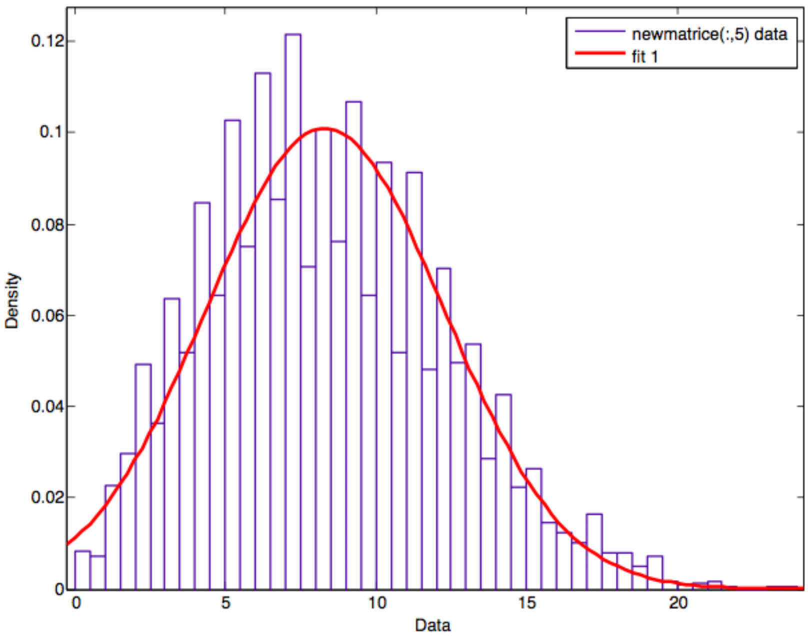


Figure C.21: September

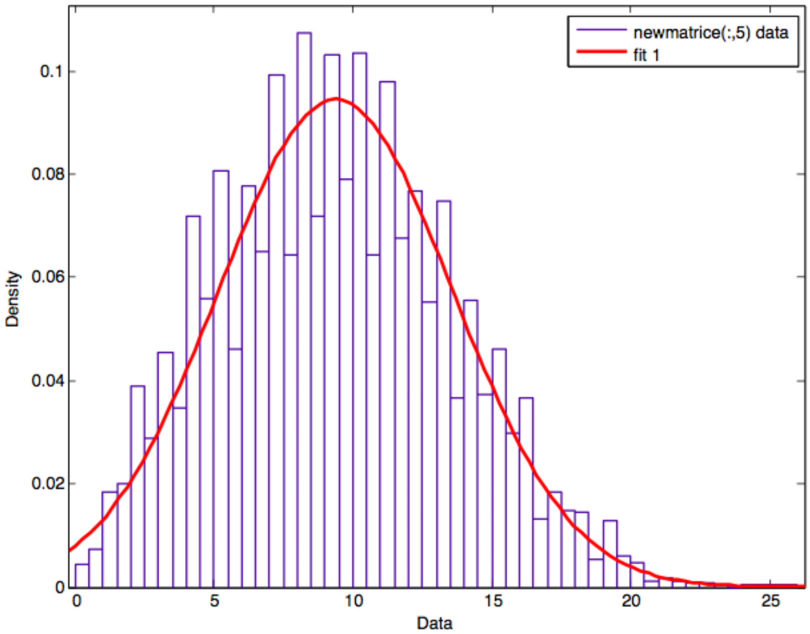


Figure C.22: October

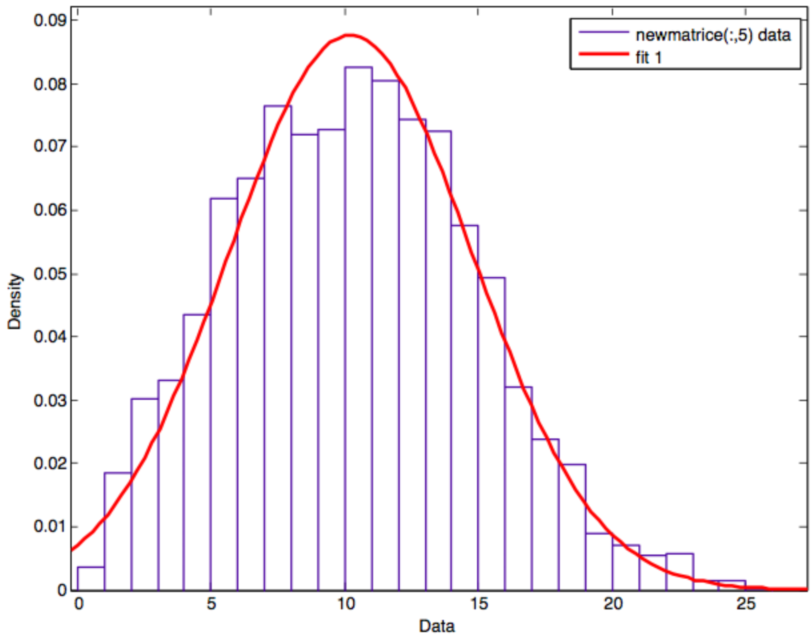


Figure C.23: November

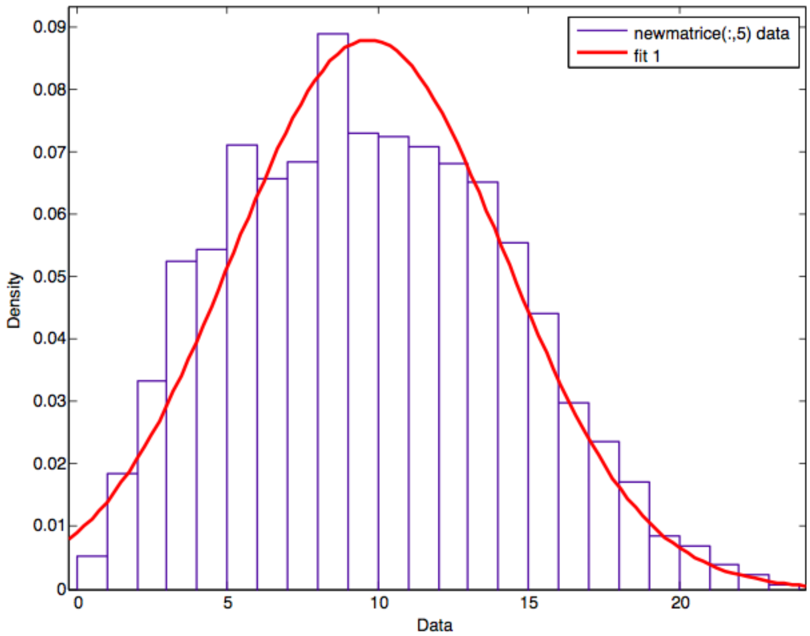


Figure C.24: December

Appendix D

Ice occurrence

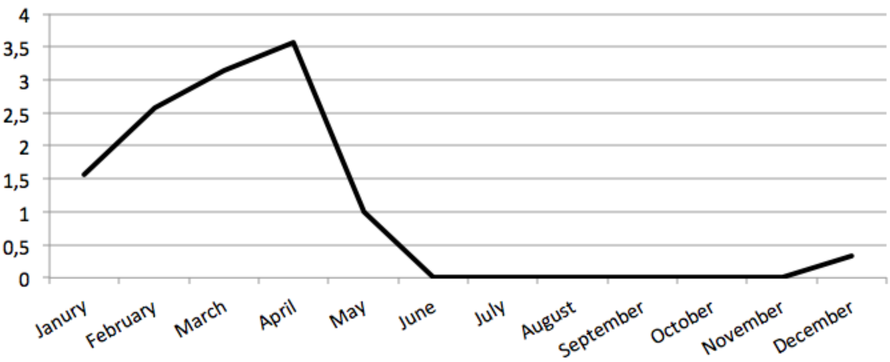


Figure D.1: Ice occurance 76 degrees North

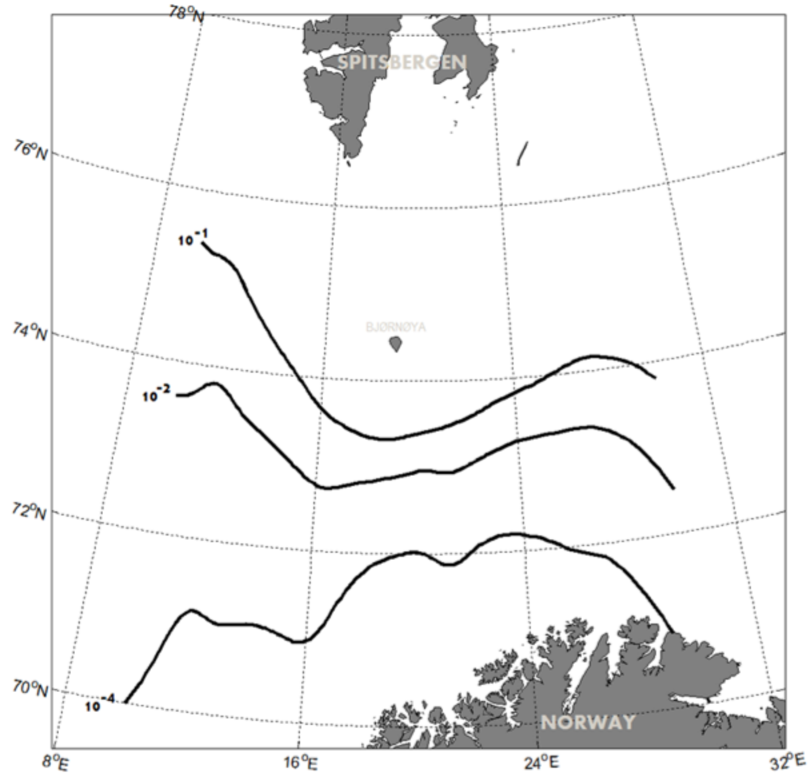
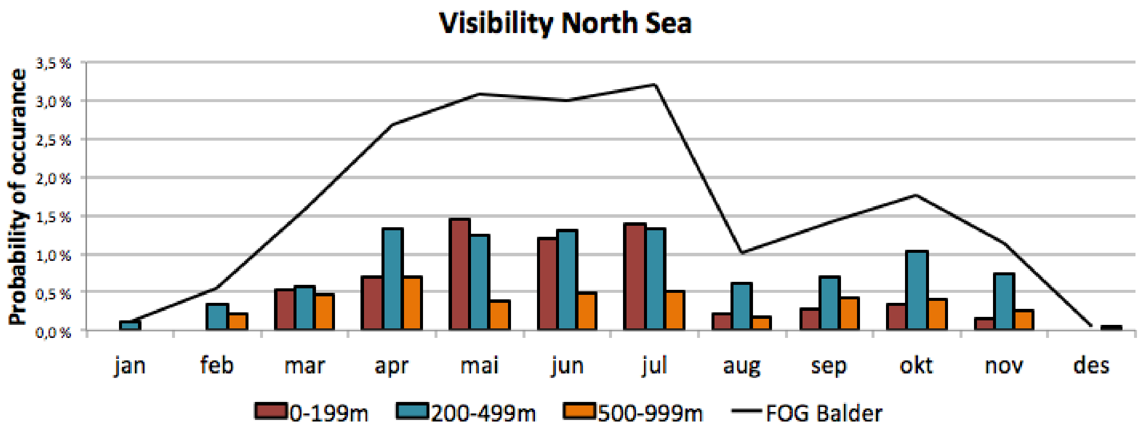
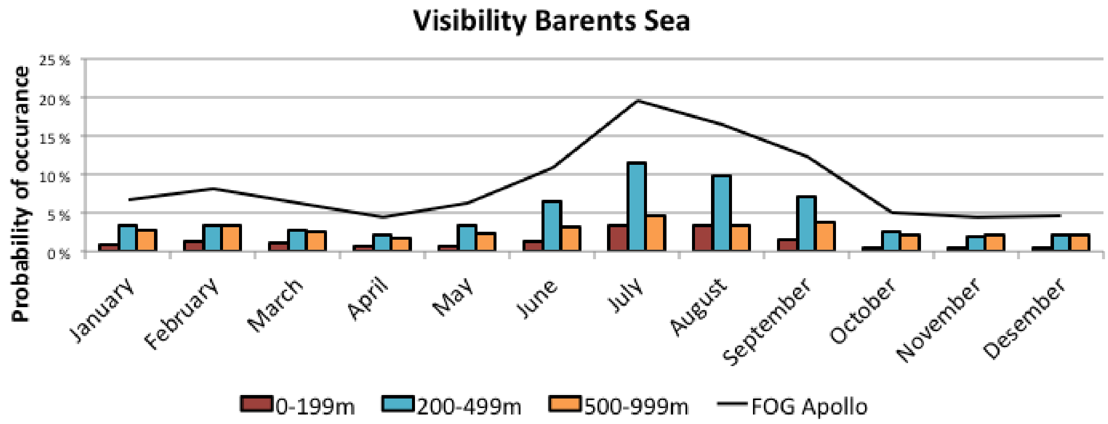


Figure D.2: Limits of sea ice with an annual probability of exceedance

Appendix E

Visibility





Appendix F

Polar lows

Date	Time (utc)	Lat.	Long.	Remark	Min.SLP (hPa)	Max wind (kt)
19.12.99	1340	72N	18E		989	45
22.01.00	0250	72,5N	29E	Old Erik	990	42
31.01.00	0610	65N	04E	Cirrus on top	978	50
08.03.00	1900	69N	4E		992	35
24.03.00	1230	72N	21E	Most beautiful	997	35-40
01.01.01	1500	75N	22E	**		
04.02.01	1540	62,5N	03W	Pre Mike		
05.02.01	1600	65N	01E	The Mike Low	998	35
02.03.01	0600	75N	41E	**		
19.03.01	1400	75N	08E	**		
24.03.01	0730	74,5N	09E	Marginal	1020	40
10.04.01	0650	71N	02E	Baroclinic	1000	58
27.10.01	1700	74N	09W	**		
01.11.01	0200	71N	19E	The Torsvåg case, Cirrus outflow	992	50
04.11.01	1900	67N	02E	**		
09.11.01	1700	74N	25E	**		
12.11.01	0700	67,5N	07E		990	45
31.12.01	0400	73N	38E	Dual **		
12.01.02	1200	73N	21E		979	35
19.01.02	0400	70N	47E		989	35
22.01.02	1100	75N	28E	Dual systems	985	50
23.01.02	1200	71N	17E	Multiple	978	35
26.01.02	0600	72N	12E	Most beautiful		
19.02.02	1300	74N	34E	Most beautiful	968	55
22.02.02	0000	74N	33E	Dual **		
23.02.02	1140	67,5N	07E		958	45
01.03.02	1200	68N	10E	The polar storm **		50
09.03.02	1100	70N	05W	**		
20.05.02	1436	7320N	1530E	Dual systems	1010	35
19.12.02	1200	74N	47E	Ivans low **		
20.12.02	1200	6820N	1100E		999	30
31.12.02	1100	73N	38E	Multiple **		
16.01.03	1400	72N	0730E			
17.01.03	0000	73,5N	25,5E	Slow moving	985	35
23.01.03	1500	73N	10E	Multiple **	995	53
29.01.03	0700	73,5N	0,5E	Reversed shear	997	50
30.01.03	0700	64N	05E	**		35
11.03.03	0000	72N	16,5E		979	45
23.03.03	0300	68,5N	12,5E	Comma in SW		45

24.10.03	0600	71,5N	18E	Reversed shear	990	45
05.12.03	1320	72N	14E	Reversed shear	990	40
08.12.03	1320	71N	31E	Reversed, secondary	985	44
17.12.03	1300	72N	38E		988	45
27.12.03	1200	73N	18E			38
29.12.03	1200	69N	13E	**		54
27.01.04	0900	71N	12E	Widespr. conv., -50@500hpa	988	45
30.01.04	0700	70N	08W	Short lived	**	
06.02.04	1300	71N	12E	**		
21.02.04	1000	68,5N	03E	Neutral (no) shear	990	55
01.03.04	1200	70N	06,5E	Direct shear, fast moving, dual	999	44
27.03.04	1200	65N	05E	**		53
30.03.04	1800	69N	09E	**		
15.11.04	1400	70N	00E	Dual, neutral, secondary	1002	42
16.11.04	0120	69N	15E	Reversed, secondary	982	44G72
16.11.04	1600	69N	37E	Reversed	987	40
18.11.04	0400	74N	45E	Dual **		
23.11.04	1200	72,5N	46E	Small **		
10.12.04	1700	63N	04W	Secondary, direct shear	1003	50
18.12.04	0700	70N	06E	Secondary, reversed, Radar, Soundings	981	52
13.01.05	1640	68N	07E	Primary, neutral, poor models	1002	55
18.01.05	1800	72N	03W	Large system **		
23.01.05	1320	67N	13E		1003	43
27.02.05	0500	69N	37E	**		
01.03.05	1500	76N	35E	**		
07.03.05	0700	72N	18E	The Brümmer case		35
15.03.05	0900	64N	04E	Direct, primary	999	48
17.03.05	0140	72N	48E	Direct/neutral		
02.04.05	0900	75N	2430E	Secondary, strong reversed.	994	70
26.04.05	1700	74N	25E	Cirrus shield **		
12.10.05		76N	00E	**		50
23.11.05	1500	74N	18E	Double-system/Comma in SW		44
29.11.05	1700	66N	04E	Sounding LDWR, Radar		50
19.12.05	03-06	Vest-	Finnmark	Small (130km)		36
29.01.06	15-21	Hopen		Shear vorticity (Bear Island-Spitsbergen)		35
06.03.06	18-24	Lofoten -	Vesterålen	From a CB-cluster		30G48
20-22.03 .06		67N	00E	Multiple, widespread conv. JM sound.1005		40
29.10.06	1200	72N	16E	Primary, good models	992	38G54
08.11.06	1800	63N	07W		998	45
22.12.06	12-18	7150N	17E	Secondary, baroclinic, poor mod.	979	48G61
26.12.06	03-18	7230N	18-22E	Secondary, inst. Occ., reversed	977	49G63

21.01.07	0600	73N	41E	Primary, Stockman, widespread	993	50
22.01.07	1500	76N	04E	Primary, direct, widespread		
26.01.07	04-12	7030N	1430E	Primary, cold, cirrus shield, case	974	51
27.01.07	0000	Vest-	Finnmark	Primary, cold, cirrus shield	982	51
05.02.07	00-06	6430N	09E	2 small polar lows	994	41
13.02.07	0600	7130N	23E	Small PL	1004	40
06.04.07	00-24	7330N	11E	Strong PL, long life time, baroclinic	986	53
29.04.07	01-05	Berlevåg-	Vadsø	Baroclinic PL	1001	51
03.09.07	0500	64N	07E	Season start !	993	40
11.12.07	1930	71N	31E			35
25.01.08	1700	6730N	08E	Comma		35
31.01.08	04-24	74N	11E	Primary		40
14.02.08	2330	69N	38E	Primary, Reversed ?	1012	45
29.02.08	1030	74N	24 E	Dual	950	40
02.03.08	2100	75/69N	09/10E	Dual, small		35
04.03.08	0130	71N	03E	The Thorpex Low	990	45
16.03.08	0830	7140N	12E	Baroclinic		35
18.03.08	1500	7330N	2830E	Dual, reversed		35
20.03.08	0700	72N	43 E			35
04.04.08	0100	72N	01E	Primary, reversed		45
24.04.08	1200	71N	41E			40
27.10.08	2300	6540N	04E	Secondary, reversed, NE of Scotland		50
17.11.08	0700	75N	25E		990	35
18.11.08	0200	75N	02E		980	40
18.11.08	2030	71N	14E	Baroclinic,	971	55
20.11.08	0600	69N	08E	Secondary, reversed, good models	967	65
28.11.08	0900	70N	00E	Secondary, reversed, dual	988	40
29.11.08	1900	73N	01W	Convergence, baroclinic	1004	35
30.12.08	1200	72N	34E	Marginal	995	40
07.01.09	0300	72N	28E	Multiple		50
15.01.09	0100	76N	53E	*		
16.01.09	1200	71N	57E	Baroclinic, Kara Sea	990	40
05.02.09	0300	72N	03W		1008	33
05.02.09	1800	69N	40E	Small, dual	1010	30
07.02.09	1800	72N	43E	Dual	1005	
25.02.09	2100	7130N	22E	*		
26.02.09	1800	70N	13E	Dual, reversed, Baroclinoc	985	40
27.02.09	1800	7230N	3230E	Neutral, baroclinic	1000	30
27.03.09	2300	69N	07W		995	35
02.04.09	0900	73N	3530E	Baroclinic, reversed	1008	35
05.04.09	0000	72N	43E	Baroclinic, reversed	990	40
05.04.09	0700	73N	25E	Cirrus waves on top !	1008	30

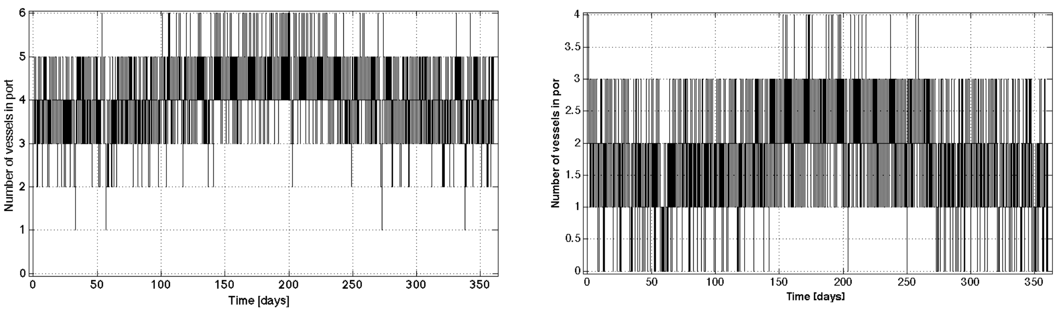
08.01.10	1200	8030N	1630E	Small, N of Spitsbergen, conv.		30
29.01.10	1800	68N	08E	In SE off Scandinavian mainland		45
30.01.10	1800	62N	04E		977	36
02.02.10	1600	61N	02E	Convective, marginal	990	35
16.02.10	0900	71N	04E	No observations		
23.02.10	1800	67N	17W		1011	55
02.03.10	0800	6330N	04E	Small, dual, U~20, B, Neutral, Florø	1005	39
04.03.10	1800	73N	42E	Small	1000	40
10.03.10	1600	76N	41E		985	35
12.03.10	1200	72N	19E	Multiple	991	35
14.03.10	1200	73N	16E	No observations	996	
19.03.10	1200	7430N	18E	Dual	994	35
21.03.10	0300	67N	12E	Short lifespan, Neutral, U~20	995	39
24.03.10	1800	72N	18E	Comma, later PL	1012	
27.03.10	0100	7230N	1930E	Baroclinic, reversed, U~20	1005	35
23.04.10	0900	71N	02E	Baroclinic, reversed	1005	35
31.05.10	1800	7030N	1930E	One fatality, baroclinic, neutral	1008	40

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).

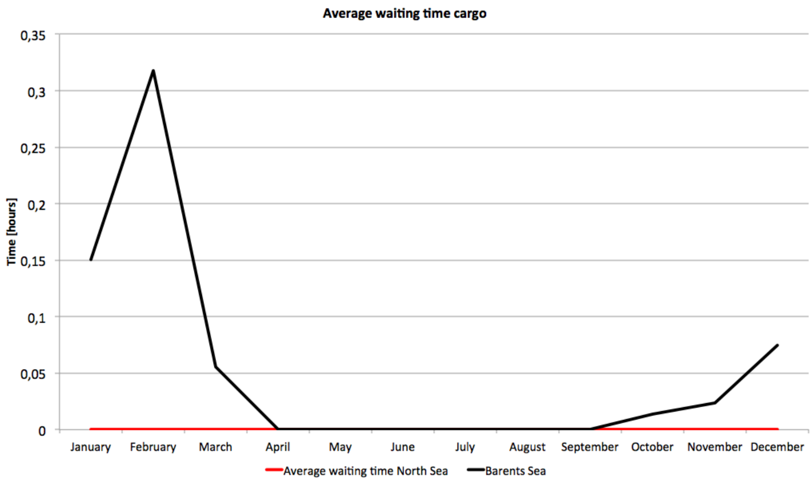


(a) North Sea

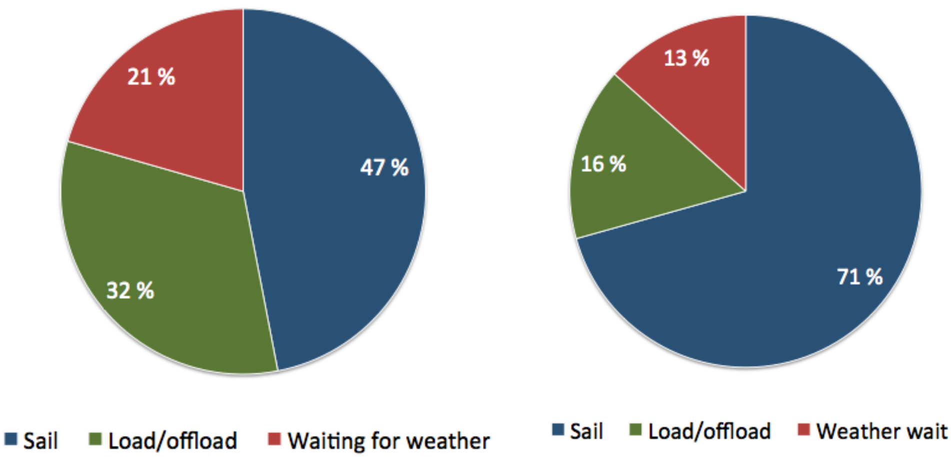
(b) Barents Sea

Figure G.1: Number of vessels in Supply base

Average cargo wait in North Sea and Barents sea.



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.

Vessel type	Power at service speed [kW]	Consumption in service speed [ton/day]
PSV 2500	2988	14,3
PSV 3000	3094	14,9
PSV 3500	3199	15,4
PSV 4000	3235	15,5
PSV 4500	3438	16,5
PSV 5000	3543	17,0

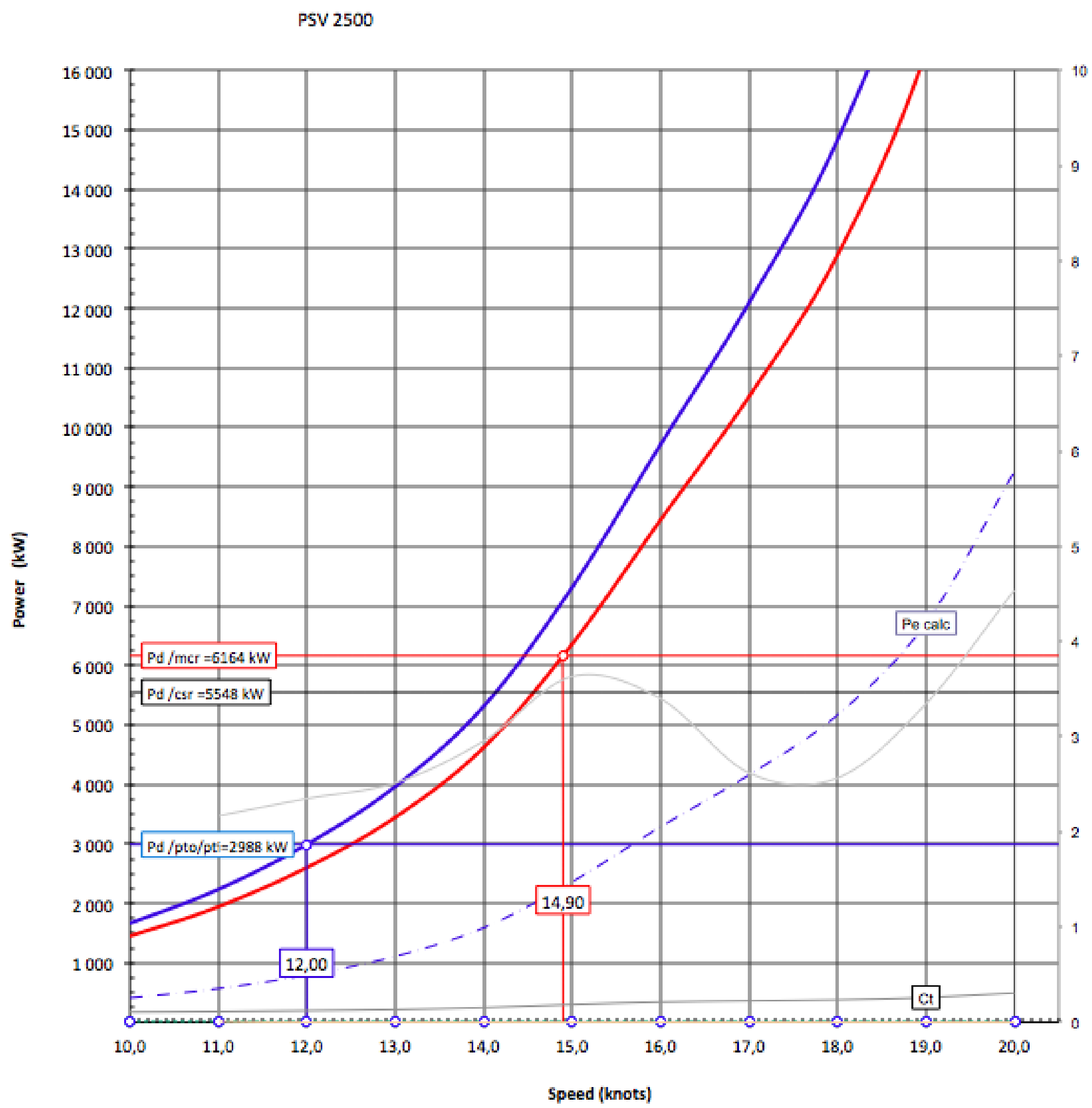


Figure G.3: PSV2500

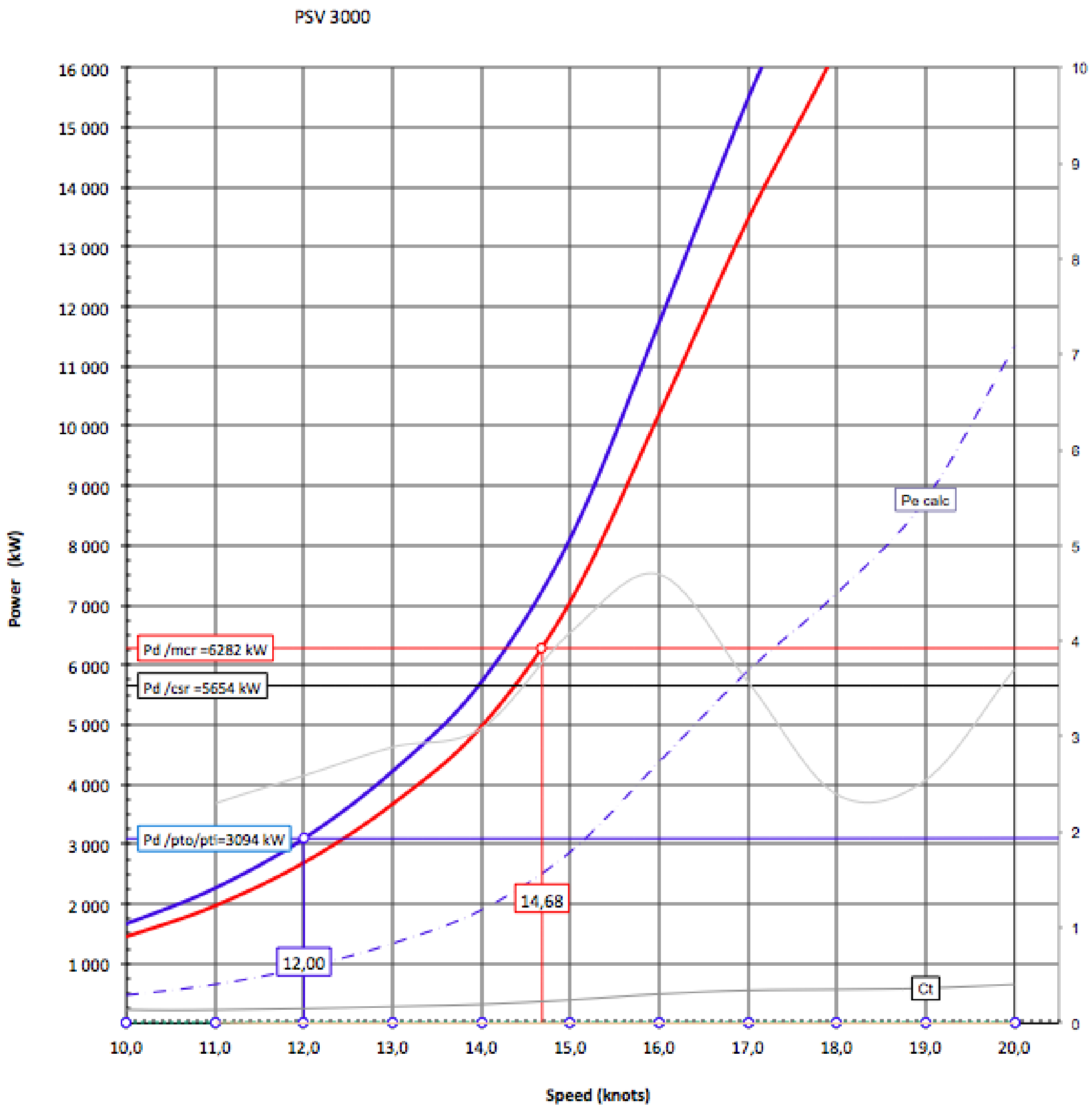


Figure G.4: PSV3000

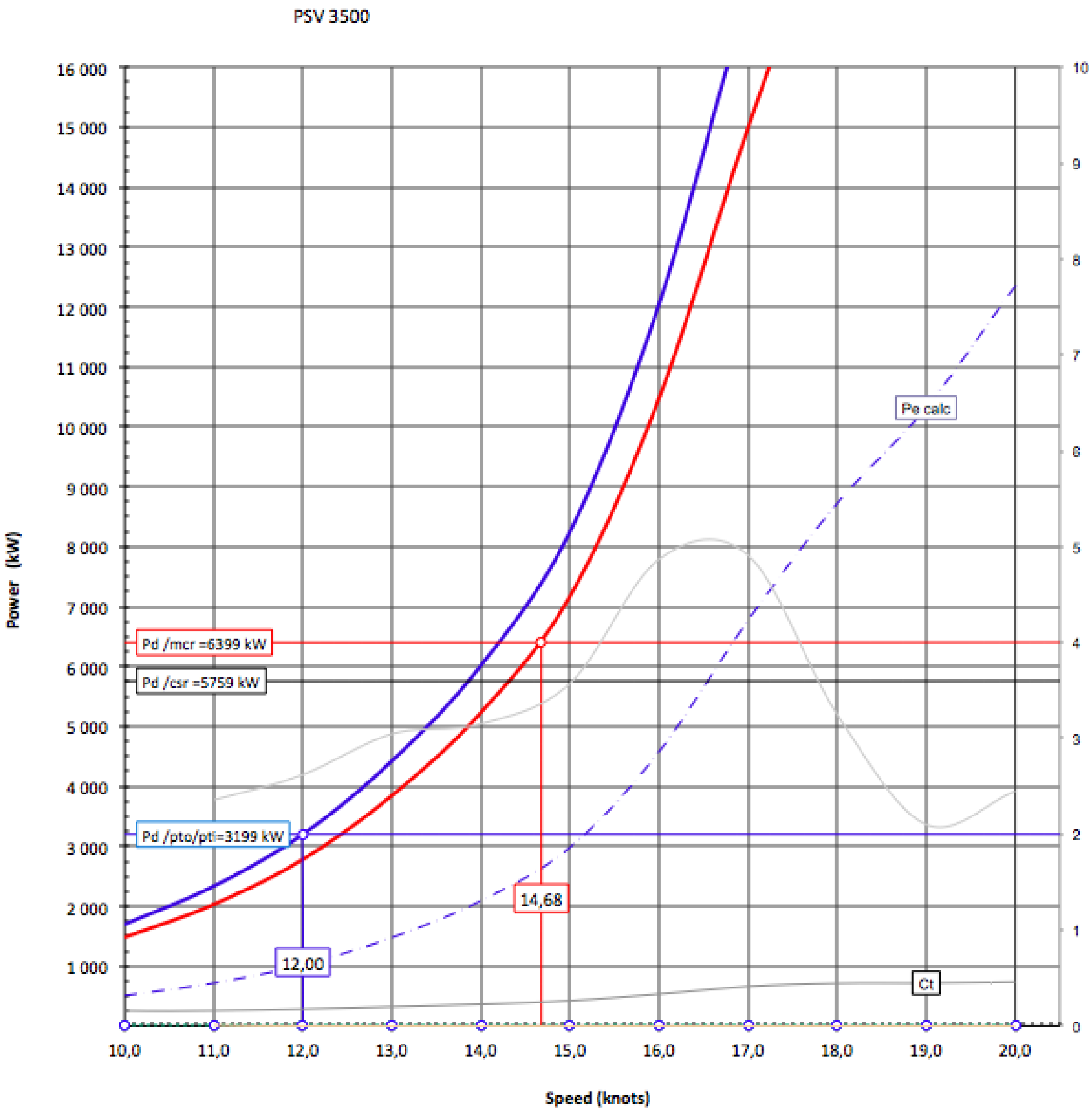


Figure G.5: PSV3500

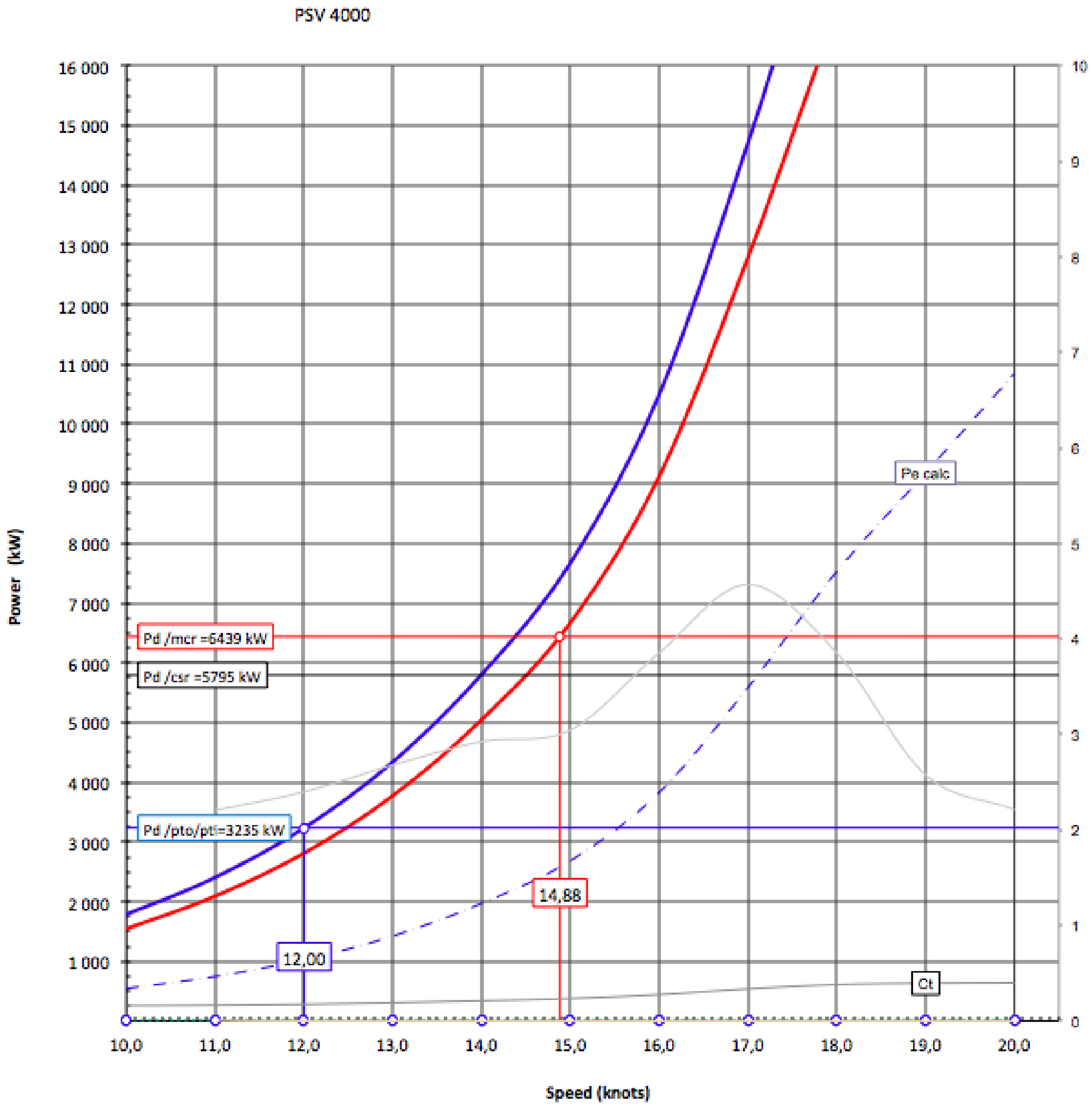


Figure G.6: PSV4000

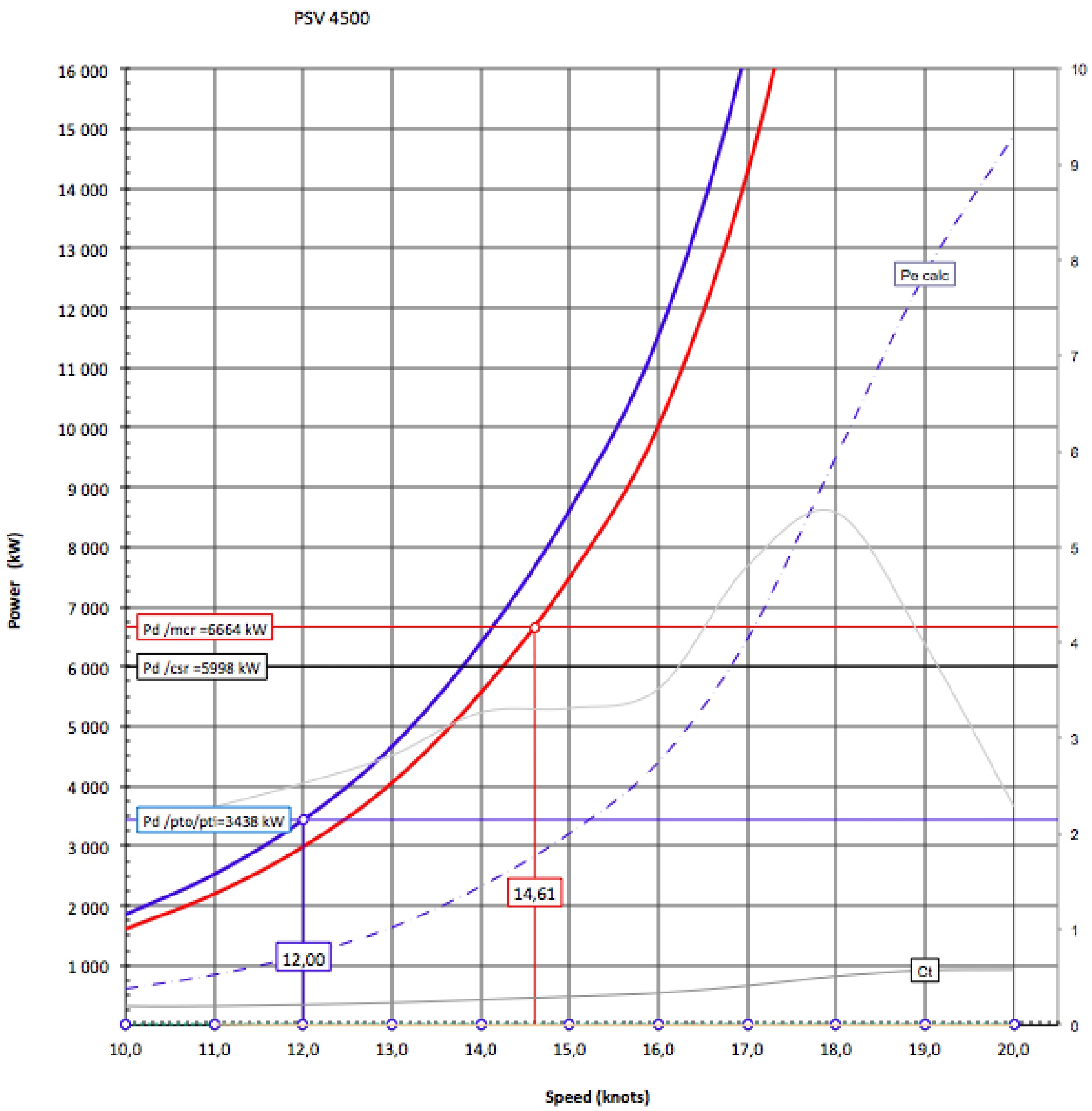


Figure G.7: PSV4500

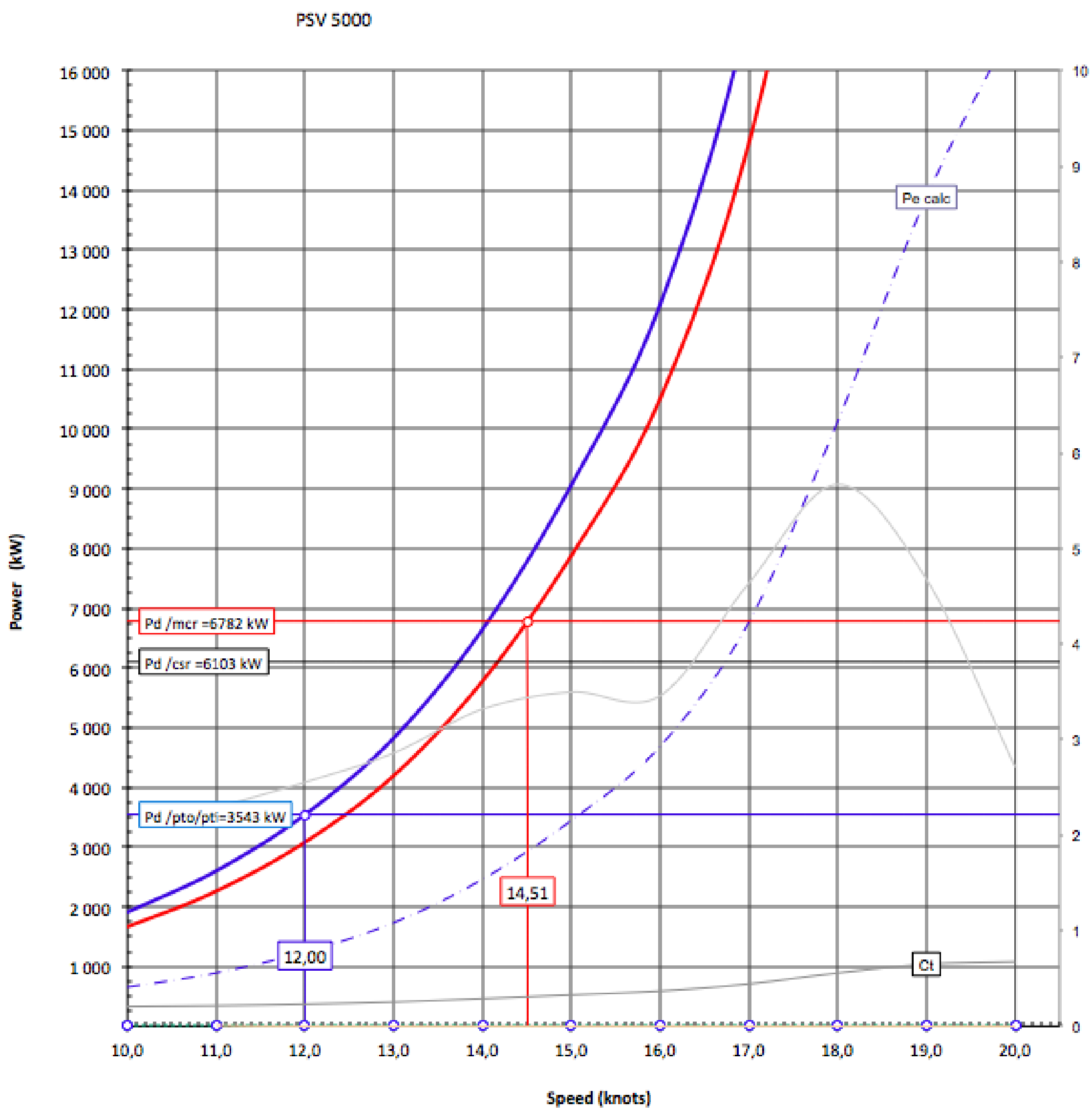


Figure G.8: PSV5000

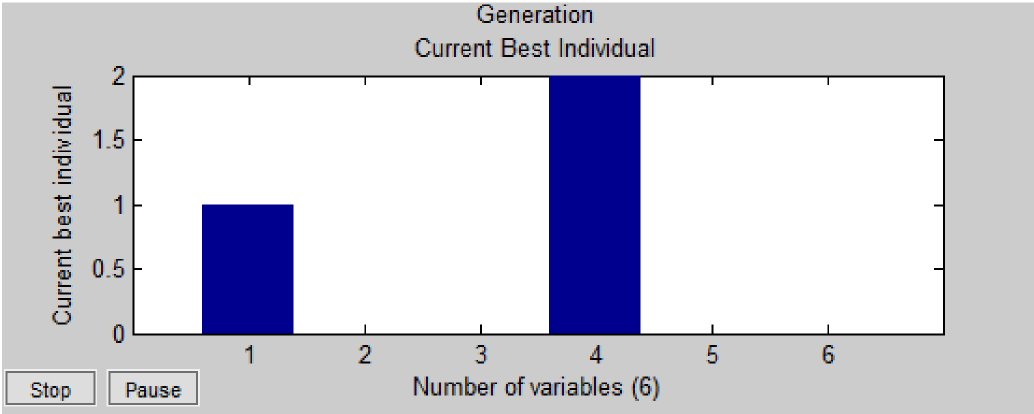


Figure G.9: Optimal fleet composition North Sea

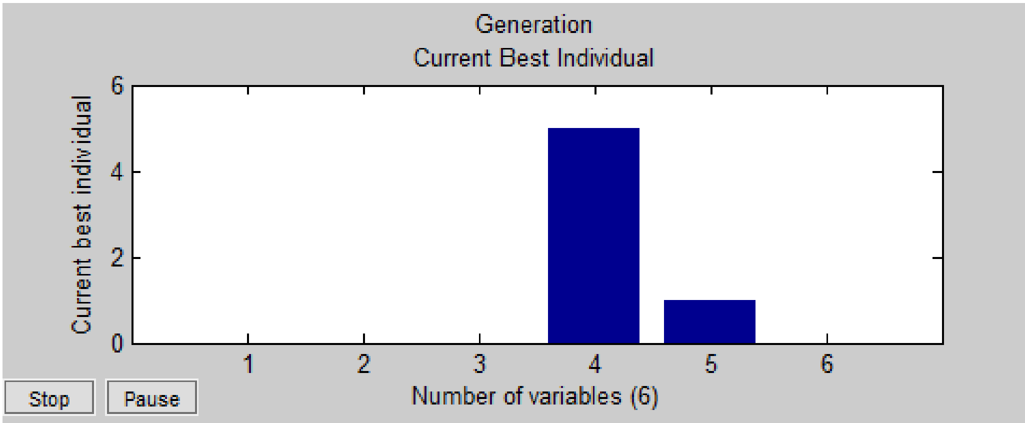


Figure G.10: Optimal fleet composition North Sea