TMR4930 - MASTER THESIS

Optimization of transport of fresh salmon from Norway to Europe by ship and trailer

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MASTER THESIS IN MARINE TECHNOLOGY

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Topic:
Optimization on transport of fresh salmon from Norway to Europe by ship and trailer

Background
In today's practice fresh salmon that is farmed in Norway is transported to Europe mostly by trailer. With a prospect of 5 doubling the salmon production within the year 2050 other transportation alternatives need to be established in order to avoid overloading the Norwegian road network. Transporting the salmon with ships instead of trailers will both reduce the number of trailers on Norwegian roads and can contribute to reduce transportation costs.

Objective
The main objective of this thesis is to construct an optimization model on seaborne transport of salmon from Norway to Europe to gain understanding and insight of the problem.

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

a. Description of the problem.
b. Presenting relevant literature and theory.
c. Construct a mathematical problem description and simplifications made.
d. Present necessary pre-calculations of data used in the model.
e. Implement and solve the model for different scenarios is Xpress IVE.
f. Present the results and insight gained and discuss the findings.
g. Discuss strengths and improvement potential in one's approach and work – with respect to conclusions.
h. Suggestions for further work – including how the work will be extended into the Master thesis.

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

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

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

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

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

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work.
The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

Deliverable

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

Supervision:
Main supervisor: Bjørn Egil Asbjørnslett

Deadline: 09.02.2020

Preface

This Master Thesis is written for the Norwegian University of Science and Technology and concludes my education at the university. My specialization is within Marine Design Logistics at the Department of Marine Technology.

This Master Thesis is accounting for 30 credits of 30 possible credits in my 11th semester. The thesis consists of a study on transportation of fresh salmon from Norway to Europe by ship and is a continuation of my Project Thesis conducted in the fall semester of 2018.

I would like to offer my special thanks to professor Bjørn Egil Asbjørnslett, at the Department of Marine Technology for his guidance and assistance in writing this paper.
Additionally, I would like to thank Norges Sjømatråd for providing necessary data.

Abstract

In today's practice, fresh salmon that is farmed in Norway is transported to Europe mostly by trailer. With a prospect of 5 doubling the salmon production within the year 2050 other transportation alternatives need to be established in order to avoid overloading the Norwegian road network. Transporting the salmon with ships instead of trailers will both reduce the number of trailers on Norwegian roads and can contribute to reducing transportation costs.

In this thesis, the possibility of transferring some of the salmon transport from Norwegian roads to the sea is investigated by utilizing optimization. The optimization model is used to investigate if a combination of seaborne and land-based transport from a selected set of ports is economically viable under different circumstances.

The model presented is modeled as an intermodal transportation model combined with a fleet size and mix problem presented as a path flow model. The total amount of salmon produced at all considered production facilities in Norway will need to be transported to all considered customers in Europe within a certain time period, in such a way that each customer demand is satisfied. The goods can either be transported directly from a production facility in Norway to a customer in Europe by trailer or RoRo-vessels can be used to transport the goods from the production facility to a delivery port in Europe, from where the goods will need to be distributed to the customers by trailer. Fresh salmon is a perishable product with a limited shelf life, therefore the age of the salmon at delivery is important. Trailers have a relatively small capacity compared to vessels. This means that producing enough load for a vessel to be fully loaded will take considerably longer time than for trailers. Vessel usage is constrained in such a way that the delivery of the salmon at the port in Europe will need to happen without the age of the fish passing a given limit. With given constraints, the model should find the combination of land-based and seaborne transport, which gives the lowest possible cost.

The optimization model was implemented and solved in FICO Xpress IVE. The model was tested at different production rates at different limitations on how old the salmon was allowed to be at

the delivery port in Europe. It was found that a seaborne solution was possible at today's production rate for transporting fresh salmon within 5, 6 and 10 days from when the first salmon was slaughtered until delivery at the port in Europe. The time horizon was set to 4 weeks for all cases. The cost of delivering the total amount produced at all ports of 24560 tons by using trailers and without utilizing ships came at 40,429,849 NOK. Utilizing vessels reduced the total transportation cost by 4,719,410 NOK, 8,430,515 NOK, and 11,679,916 NOK when the maximum allowed age of the salmon at the delivery port was set to 5, 6 and 10 days respectively. It should be noted that the delivery within 10 days only is allowed if the salmon is super chilled. It was found that an increase of the production resulted in even more cost-efficient transportation solutions and that delivery of the salmon by ship was possible at lower age limits of the salmon at delivery. A decreased production, on the other hand, resulted in the fish being older at delivery and was overall less cost-efficient.

Salmon prices are historically high at over 60 NOK per kg and can vary a lot in just a few months. Transferring transport from land to sea can give a reduction of less than 0.5 NOK, with a disadvantage of delivering overall older fish. Adjusting the slaughtering process to a seaborne solution, by having increased production rates before the arrival of a vessel will decrease the age of the salmon at delivery and will make a seaborne solution more robust against changes in the production. This will require organizing slaughtering shifts in another way and also an investment in new equipment. This will, however, make transport at sea more compelling to the customers and the cost reduction of utilizing vessels for transportation will possibly make the increased slaughtering cost worth it. This has however not been investigated further in this thesis.

Sammendrag

Dagens transport av fersk oppdrettslaks fra Norge til Europa skjer hovedsaklig ved hjelp av lastebiler. Det forventes en femdobling av produksjonen av laks i Norge innen år 2050. Dette gjør at alternative transportmuligheter burde evalueres, for å unngå en overbelastning av det norske veinettet. En overføring av laksetransporten fra vei til sjø vil både kunne redusere transportkostnadene og redusere belastningen på veinettet.

Denne masteroppgaven ser på muligheten for å overføre laksetransporten fra norske veier til sjøen ved hjelp av optimering. En optimeringsmodell blir brukt for å undersøke om en kombinasjon av av landbasert og sjøbasert transport er økonomisk gunstig under forskjellige forutsetninger.

Modellen brukt består av elementer fra en ”inter modal transportation model” og et ”fleet size and mix problem” med forhåndsbestemte ruter for skipene. En planleggingsperiode på fire uker er satt og all laks produsert innen denne perioden må transporteres til et utvalg med kunder i Europa, med hver sin etterspørsel av laks som må oppfylles. Laksen som blir produsert kan enten sendes direkte via lastebil fra slakteriet til en kunde eller med RoRo-skip via en havn i Europa, hvorfra laksen sendes videre til kundene. Siden laks er et bedervelig produkt med en begrenset holdbarhet, så foregår sjøtransporten på en slik måte at alderen på fisken ikke overstiger en satt grense ved leveranse i havnen i Europa. Denne begrensningen gjelder kun skipene brukt i systemet siden det er antatt at lastebilleveranse direkte fra Norge vil skje innen god tid. Under gitte betingelser har modellen som hensikt å finne den løsningen av lastebiler og skip brukt for transport som gir lavest kostnader fra slaktereiet til kunden.

Optimeringsmodellen ble implementert og løst i programvaren FICO Xpress IVE. Modellen ble testet for ulike produksjonsmengder og med ulike tidsbegrensninger på alderen på fisken ved leveranse i havn. Med dagens totale produksjon på 24560 tonn ved de valgte slakteriene, ble den totale transportkostnaden på 40.429.849 NOK. Ved bruk av skip kunne denne kostnaden reduseres med 4.719.410 NOK, 8.430.515 NOK og 11.679.916 NOK med en garantert alder på fisken ved leveranse i havn på henholdsvis 5,6 og 10 dager. En tid på 10 dager kan dog kun bli brukt, hvis fisken blir

konservert ved såkalt ”super chilling”. En økning i produksjonen førte til enda høyere besparelser ved de ulike tidsbegrensningene og det var mulig å levere fisken med en lavere alder. Det motsatte var tilfellet når produksjonen av laks ble senket. Det førte til at bruken av skip generelt sett ble mindre kostnadseffektivt og at fisken hadde en høyere alder ved leveranse.

Prisen på laks ligger i dag veldig høyt på over 60 NOK per kg og kan variere veldig i løpet av noen måneder. Bruken av skip vil kunne gi en reduksjon på under 0,5 NOK per kg, og alderen på fisken vil være høyere enn ved lastebiltransport. For kundene er derfor prisreduksjonen minimal med hensyn på total kostnaden. Det som hovedsaklig gjør alderen på fisken så høy ved leveranse med skip er den lange slaktetiden som er nødvendig for å produsere nok last. Ved å tilpasse slakteprosessen til sjøtransporten kan alderen på fisken reduseres betraktelig ved leveranse, som igjen gjør den mer konkurransedyktig mot laks som er transportert med lastebil. Skipstransporten vil dermed også bli påvirket i mindre grad av endringer i mengden produsert. For å få til dette må slakteriene slakte fisk i et høyt tempo før det forventes at et skip kommer og dette vil kreve endringer i skift og også investering i flere slaktemaskiner. Den resurte transportkostnaden kan i så fall potensielt sett dekke disse ekstra utgiftene til slakteriene. Undersøkelse på hvor mye det koster å oppgradere slakterier har ikke blitt sett på nærmere i denne oppgaven.

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Chapter 1

Introduction

Norway exported in 2017 about one million tonnes of salmon for a total value of 64,58 billion Norwegian kroner[38]. The amount of salmon exported has in the last 18 years tripled and it is expected that the Norwegian seafood production in 2050 can be 5 times as high as today's production [29]. Around 81% of all salmon produced in Norway is transported by trailer [14]. To avoid increasing the load on the road network, alternative transportation methods, that are competitive with today's transportation method are desirable. The transport of fresh salmon is done under strict regulations as it is considered a perishable product. The price, delivery frequency and age of the fish at delivery is important for the customer. An alternative transportation method will, therefore, need to maintain the strict regulations given and also be competitive in regard to the customer needs.

Multiple previous studies have been made on this problem. I was self part of a study in 2017 concerning this problem in the course TMR4254 "Prosjektering av marine systemer", where a RoRo-vessel was designed with the goal of transporting fresh salmon from Norway to Europe. In the master thesis by *M.T. Kamphus* an inventory routing optimization model was developed to model the performance of seaborne transport of salmon [20]. *DNV-GL* conducted a study directly comparing the economics of seaborne salmon transport to land-based salmon transport [23] A study was done concerning the transportation flow of fresh salmon and trout from Norway by Hansen [14]. Havline is a company trying to use slaughtering vessels, which slaughter the fish onboard the vessel and transport it directly to a port in Europe [7].

The main objective of this paper is to look at the possibilities of transporting salmon from Norway to Europe using a seaborne alternative with the help of an optimization model. A two-stage transportation problem combined with a fleet size and mix formulation. The model will be used to get more insight on how vessels can be utilized to aid the current transportation chain.

In Chapter 2 background information is presented with information about the salmon industry and different transportation systems. The problem description is presented in Chapter 4. Chapter 3 presents relevant literature on the problem and how the methodologies described are used to formulate the mathematical model described in Chapter 5. In Chapter 6 pre-calculations necessary for the model are presented. The mathematical model was implemented in FICO Xpress, where the model was tested for different scenarios. The results of these scenarios where then presented in Chapter 7. Chapter 8 presents a discussion on the model itself and the results obtained. Lastly Chapter 9 and Chapter 10 present the conclusion and recommendations for further work respectively.

Chapter 2

Background

In this section, background information that is considered relevant for this master thesis will be presented. The background information is based on the work done in the project thesis. Much of the data presented is based on data received by *Sjømatrådet* which is attached in the excel file called "Seasoncountry2.xls".

2.1 Market

2.1.1 Production

Norway produced on average 1258473 tonnes of salmon per year in the period between 2015 and 2017. Table 2.1 shows how much salmon annually was produced in the different counties in Norway in this three year period. Nordland is the biggest producer, followed by Troms and Hordaland.

County	average produced 2015-2017[tonnes]	Fraction of total production[%]
Rogaland	79146	6,29
Hordaland	165970	13,20
Sogn og Fjordane	99553	7,92
Møre og Romsdal	141136	11,22
Nord-Trøndelag	136656	10,9
Sør-Trøndelag	97936	7,88
Nordland	255894	20,34
Troms	173144	13,77
Finnmark	92923	7,38
Other counties	16115	1,28

Table 2.1: average Salmon produced in different counties from 2015 to 2017[34]

Figure 2.1 shows that the amount of salmon exported has tripled from the year 2000 to 2016, which shows the scaling potential of this sector. However, the export amount has stagnated since the year of 2013 and the amount of salmon exported has stabilized around 900000 tonnes a year.

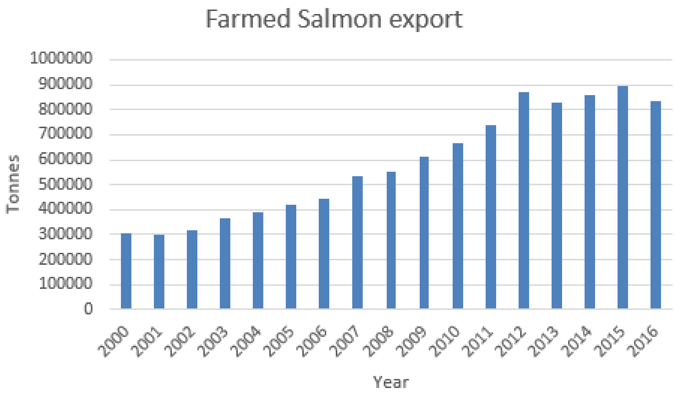


Figure 2.1: Farmed Salmon export [35]

Looking at how the prices have evolved over the same period as depicted in Figure 2.2 one can see that prices for fresh salmon more than doubled after export rates stagnated. This indicates that production has stagnated and not demand. This again indicates that fish farms have production issues. Part of the reason salmon prices have increased can also be explained by a historically weak Norwegian kroner in the later years, but this can not account for the entire price increase of the salmon.

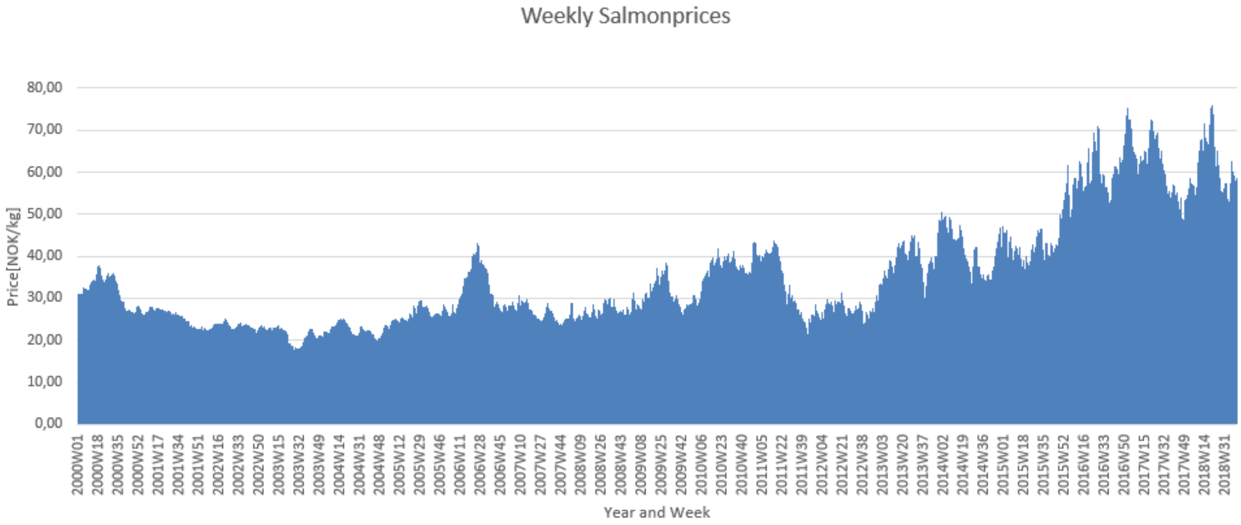


Figure 2.2: Historical salmon prices

2.1.2 Export to Europe

The European Union stood in 2017 for importing 73% of the fresh salmon exported from Norway [38]. In Figure 2.3 one can see how much salmon was imported by the different countries in Europe. Poland is the biggest importer followed by France and Denmark. Those three countries alone stand for 44% of the total export to the EU. In Poland and Denmark, the salmon is mostly refined into smoked salmon, which after refinery is exported to other countries [3] [27] [22]. In France, on the other hand, the fish is mostly sold directly to the consumer at supermarkets and fish markets[26].

Figure 2.3: Percent salmon imported by country in 2017 [38]

2.1.3 Seasonal variations

The export of fresh salmon is not continuous throughout the year. There will be variations throughout the year. When looking at weekly export numbers from the year 2000 until 2017 as shown in Figure 2.1 one can see that the export is on average lower the first half of the year than the second half of the year. Additionally, spikes are seen between weeks 9 and 15 and between weeks 49 to week 2. These spikes have in common that the export rates first increases and then drops. The spikes between weeks 9 to 16 are caused by the Easter holidays each year. One can see that the export rate increases the week before Easter and then drops in the week Easter is held. This is because most stores are closed in the holidays and will therefore not take in or sell any fish during these days. The spikes are spread throughout this period of weeks because Easter is held a different week each year. Christmas, on the other hand, is on the same date each year and export numbers, therefor start increasing at around week 48 and start dropping in week 50.

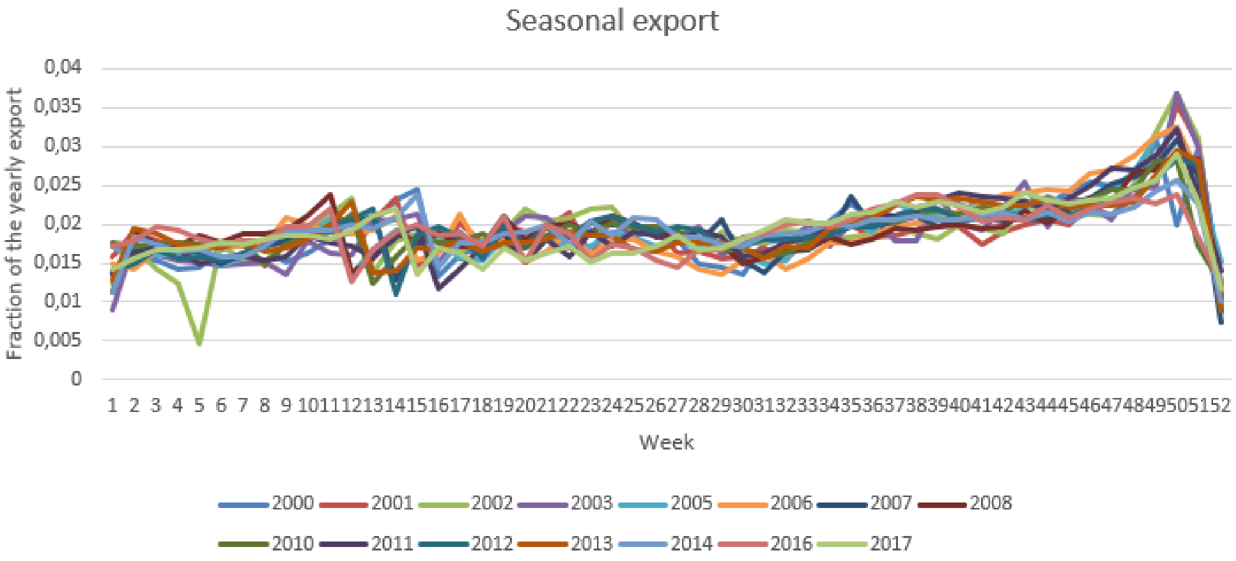


Figure 2.4: Weekly export rates plotted for different years[35]

Figure 2.5 shows the median export, based on the export rates of the different years. This way abnormal export rates like the drop in week 5 in 2002 can be filtered out to give a better estimate of how salmon will be exported in a given week in the future.

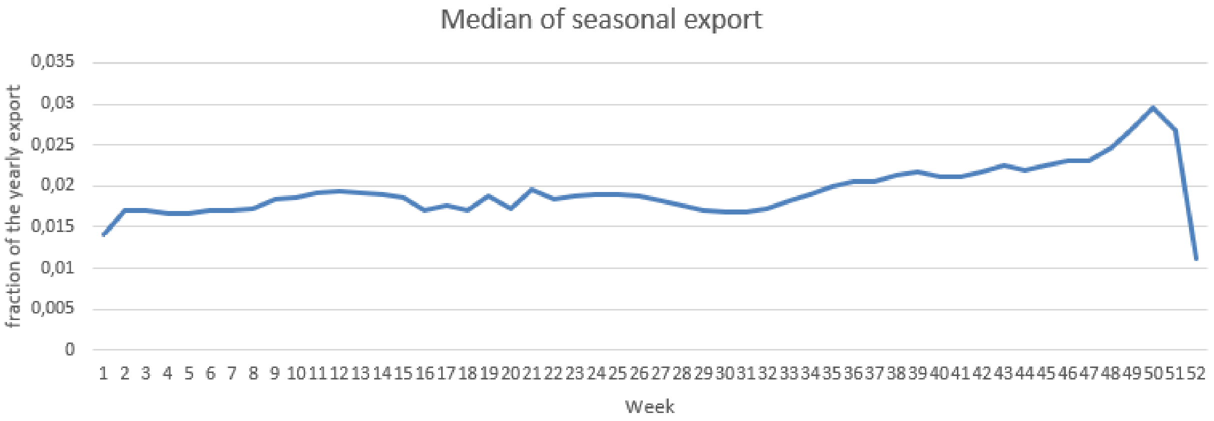


Figure 2.5: Median of weekly fractional export

To give further insight Figure 2.6 shows the seasonal import of fresh salmon of the 9 countries in Europe that stand for the greatest import numbers of fresh salmon from Norway. The figure is based on data provided by ”Sjømatrådet”. This was mainly done to see if some countries had another distribution of import through the year than the total export of salmon, which would make a solution that involved shipping salmon to different ports through the season an interesting option. One can see that the structure of the graph for the seasonal import of each country are mainly the same as the seasonal variations for the total amount of exported salmon. Lithuania’s seasonal import numbers are those that vary the greatest from the total seasonal export to Europe, and this is mainly caused because volumes exported to this country are relatively small and not existing for some weeks.

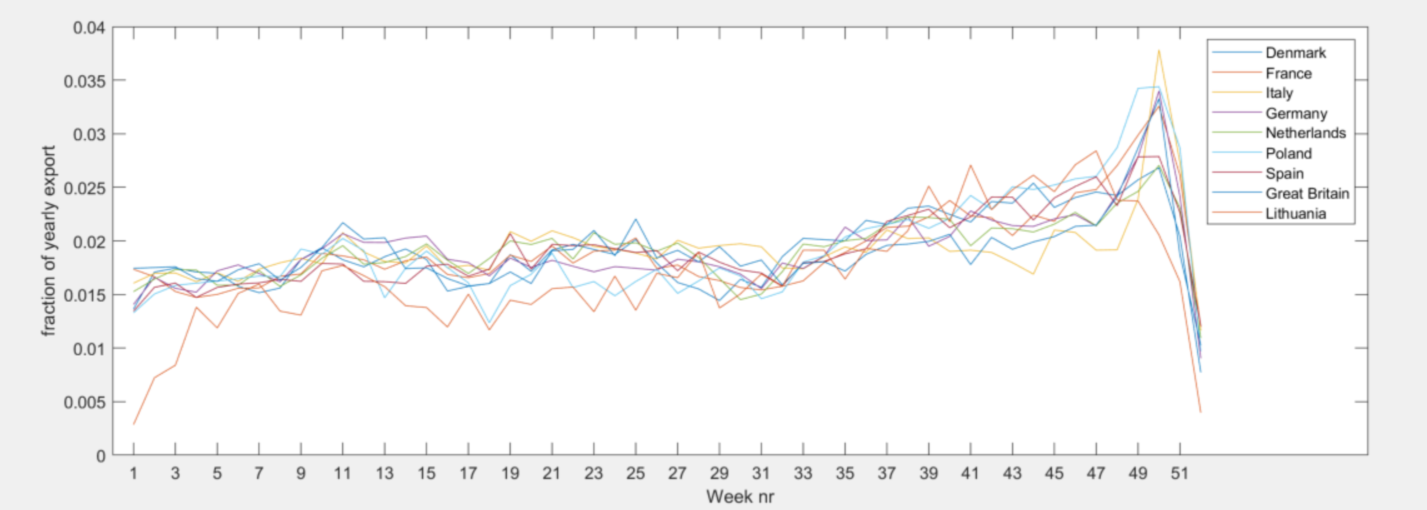


Figure 2.6: Median of weekly fractional import sorted by country

2.1.4 Future

The amount of salmon which will be produced in Norway and exported to other European countries will depend on many factors. The two main forces affecting this is demand and production. The production can be influenced by factors such as increased competition from other countries.
The production volume in Norway is dependent on how much people are willing to buy. Competition from other countries could take marked shares from Norwegian fish farms. The unique conditions in Norway are the main reason why Norway is the biggest producer of fresh salmon in Europe. New technology such as land-based fish farming could lead to competition from other countries, as they could be able to produce salmon for lower prices than Norway. Already established fish farmers in other parts of the world could also lead to higher competition in the European market, if the technology is developed, that can increase shelf life of fresh salmon or transport alternatives, that can go long distances in a short amount of time. These new technologies will also lead to Norway being able to compete at a higher degree in other markets.

One can see that the prices of fresh salmon have almost doubled in the last years, where the export volume has stagnated. This may indicate that export numbers have stagnated not because the demand increase has stopped up, but rather because of issues related to production increase. Rules and regulations enforced by the Norwegian government as well as issues with lice can be the issues that have led to stagnation in further expansion of the fish farming industry in Norway. New technologies such as offshore fish farming, closed fish pens are under development and partially already established and can potentially lead to a further expansion of the Norwegian production of salmon [31] [21].

2.2 System

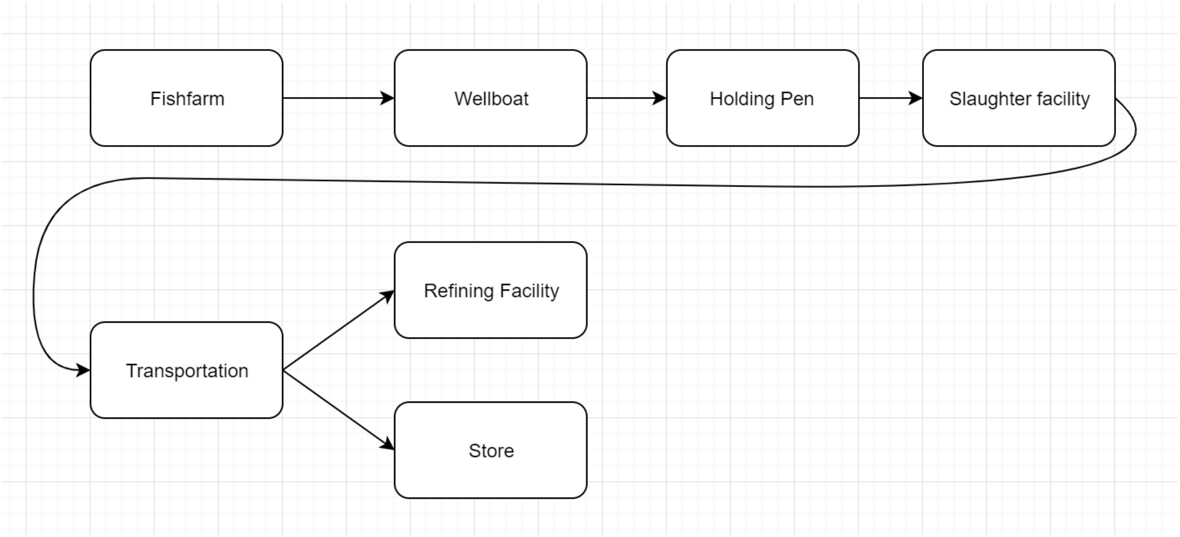


Figure 2.7: Process from fish farm to market

When the fish is fully grown, it is ready to be sold to the market.
A well-boat will be used to pump fish aboard the vessel. The well-boat will then transport the living fish directly to the slaughtering facility or to a waiting pen. At the slaughtering facility, the fish is slaughtered and packed into crates with ice. Those crates are then picked up by a refrigerated truck and transported directly to a store or to a refinery [19].

2.2.1 Requirements

Time and Frequency

Fresh salmon has a shelf-life of 10 days [39]. This means that the fish must be bought by a customer within 10 days after it has been slaughtered. If this is not the case the fish is considered waste.

In Figure 2.8 one can see how the time after the fish has been slaughtered can be distributed. One has a total time of 10 days until the product gets spoiled. The minimum time needed to deliver the fish will vary depending on how far away the store is located from the slaughtering facility and the slaughtering rate. The store will also require a minimum time to be able to sell the fish before it gets spoiled. It is assumed that this time limit is one day. Between those boundaries, the time of delivery can vary, this, however, has its positive and negative effects. When increasing the time spent to deliver the product the costs for slaughtering and transportation will get lowered, but this will lead to the store having less time to sell the product.

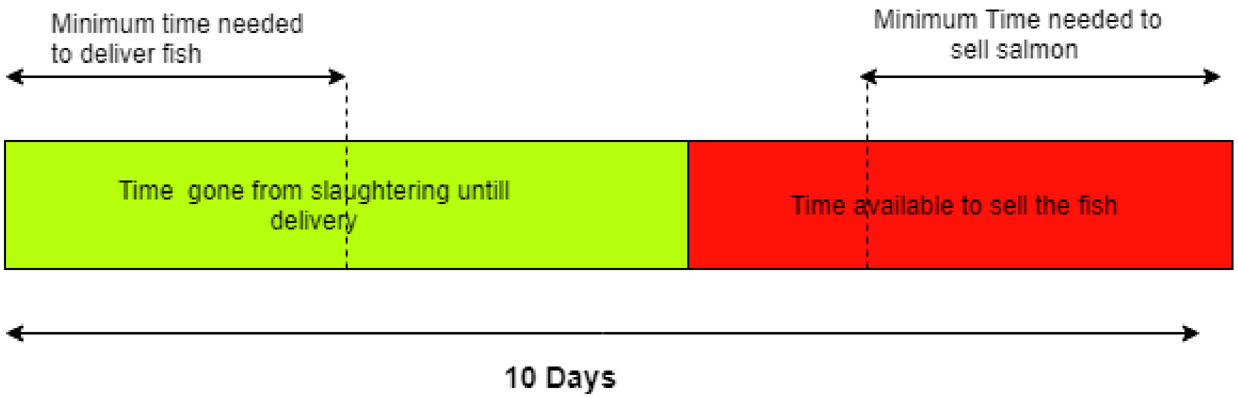


Figure 2.8: Time window for fresh salmon

Temperature

Because fresh salmon is considered a perishable product, strict rules and regulations are set on how the product should be handled safely. The temperature of the salmon must be kept between $0°C$-$2°C$ [25]. Today fresh salmon is therefor transported in crates filled with ice which again are within a reefer container that ensures that the ice does not melt. Such a reefer container has the capacity of about 19 tonnes of salmon [23].

2.2.2 Super chilling

Salmon is today mostly stored in boxes with ice, this way the salmon keeps the temperature at around $0°C$-$2°C$. The lower the temperature gets at which the salmon is stored the longer the shelf life becomes. Although on temperatures below the freezing point of water, ice crystals will begin to form within the flesh of the fish. Water in the form of ice crystals takes up a bigger volume than water in liquid form. Therefore ice crystals formed in the fish will result in destroying the texture of the fish flesh. By super chilling the fish the temperature of the flesh is reduced to $-2°C$ in a short amount of time. Cooling the fish down fast is important, to minimize the size of the ice crystals that form and thereby reducing damage to the flesh [10].

2.3 Transportation and slaughtering

Currently, fresh salmon is transported from Norway to Europe mainly by trailers.

2.3.1 Landtransport

The fish in today's transportation system will be picked up at one slaughtering location and will be delivered directly to one refinery or a few stores. Transporting small quantities makes this transportation chain less vulnerable to variations in the production and almost no planning is needed to deliver the load. A load can be transported directly from the slaughtering facility to the market in Europe. Transporting smaller amounts of salmon decreases the time spent at the slaughtering facility. Transportation on land will also be faster than transportation on sea. When using ships one will be more dependent on weather conditions. The load will need to be transported to a Port in Europe where it will need to be distributed to the rest of the market by land-based transportation alternatives. Most routes require the use of a ferry, which increases the cost and time spent on transportation [19].

2.3.2 Seatransport

By using ships to transport salmon fewer trailers will be on Norwegian roads. In Norway cold winters with much snow, a landscape with mountains makes road-building expensive and difficult. By reducing the number of trailers on Norwegian roads will, therefore, reduce the number of accidents caused by trailers, reduce the abrasion of the roads, reduce the total load of the road network and give a reduced environmental footprint. The Norwegian government is, therefore, giving subsidies to companies that can transfer transport from the road to the sea, while also increasing costs for using Norwegian roads [12].

When using ships one will be more dependent on weather conditions. The load will need to be transported to a Harbour in Europe where it will need to be distributed to the rest of the market by land-based transportation alternatives.

Transport with a RoRo-vessel

Time is a very important aspect when delivering the salmon, using a RoRo-vessel will make the loading and unloading procedure go faster than many other types of vessels. In order to handle rough sea, the vessel needs to be at a certain size. A RoRo-vessel with the capacity of 2500 tonnes of salmon is needed to be able to traverse the north-sea [19]. RoRo stands for Roll on Roll off and it has its name because of its unloading and loading procedure. The vessel consists of a single or multiple decks on which wheeled cargo is placed and secured [42]. In this case, the use of reefer containers that can easily be connected to a trailer will be chosen. Each trailer has a capacity of 19tonnes of salmon [23], this means that a RoRo-vessel will need a capacity of around 132 trailers to get a total load of 2500 tonnes of salmon.

The procedure of using a RoRo-vessel will be that it will enter one or multiple ports in Norway, where it will be filled with trailers containing salmon. When the vessel is completely filled it will sail to a port in Europe where all the load is unloaded and return cargo is loaded onto the vessel. This load will then be delivered before entering the first port where salmon is picked up again.

The Hav Line method

Hav line is one of the first companies that are trying to transport salmon from Norway to the continent by sea [7].

Table 2.2: Hav line vessel specification

Length	94m
Width	18m
Depth	7,5m
Speed	18kn
Tonage	4000tonnes
Number of decks	7
fabrik area	500m^2
Number of RSV tanks	10
Volume of RSV tank	1900m^3
Temperature inside the RSV tank	-1 to 0°C
Pump capacity	100 tonnes/hour
Number of el. anaesthetizers	8
Number of slaughtering machines	14
Slaughtering capacity of each machine	25fish/min

Hav Line will use a slaughtering vessel, with specifications given in Table 2.2 to transport the fish directly from the fish farm to a refinery in Hirtshals in Denmark. This means that the process described in 2.7 will look different. Compared to using the conventional method no time is used for well boat operations and no time is used in a waiting pen. Therefor costs from these operations will not occur, the fish will get less stressed and the mortality will shrink. In this case, the fish farm itself will act as the waiting pen where fish is pumped directly onto the vessel. Lice will be removed and the fish will get stunned before it is slaughtered and gutted. The fish entrails are stored in a separate tank, while the slaughtered fish is stored in refrigerated tanks. The filthy water will be filtered for lice and cleansed before released at the location. When the slaughtering is done, the vessel will sail to Hirtshals and pump the salmon onshore, where the fish either can be packed directly and further distributed or it could be refined. The fish entrails will be used to produce fish oil and meal. The remaining water is pumped back to the vessel where it will be cleansed. They expect to spend 11 hours spent on slaughtering 22 hours for transportation to Hirtshals and 12 hours for unloading and packing the fish at Hirtshals. When the fish is ready for further transport to the market the time since slaughtering the first salmon is 45 hours.

It would be hard to find a fitting return load for this type of vessel and the round trip time would be increased considerably because one will need to visit a port that otherwise would not be visited.

2.3.3 Slaughtering

One of the biggest slaughtering facilities in Norway is Salmars Innovamar [32], which claims to have an annual slaughtering capacity of 150 000 tonnes of salmon. The slaughter facility has 4 waiting pens with a capacity of 350tonnes of salmon each. They slaughter about 7000-8000 fish an hour[28], when active. With an average salmon weight of 4 to 5 kg, this means that slaughtering 1000 tonnes of salmon will take around 30 hours when working nonstop. Today the fish is slaughtered in 2 shifts a day, which means that they are not slaughtering around the clock. Workers are mostly needed to control the process it is therefore assumed that running the facility without breaks can be accomplished.

Hav Line has 14 slaughtering machines, each of these have a slaughtering capacity of 25 fish a minute [7]. Slaughtering 1000 tonnes of salmon will, in this case, take around 11 hours.

The reason that the land-based slaughter facility has such a low slaughtering rate is that today's distribution of fresh salmon is mainly done with trailers. Based on a previous study a trailer will have a capacity of 15 tonnes of fresh salmon. Slaughtering this amount of fish will take less than an hour. Considering Hav Lines example transport of salmon by trailer from the slaughter facility to Hirtshhals will take approximately 12 hours [7]. This means that a total time of 13 hours is used since the first fish was slaughtered until the fish arrives in Hirtshals. Slaughtering time will therefor only stand for about 8% of the time spent. When transporting the fish to markets further south in Europe the time used for slaughtering gets diminishing small.

Today's slaughtering facilities have so far not had the need to be able to slaughter big amounts of salmon in a short time period, because trailers have been the main transportation method. In 2013 Innovamar produced 130000 tonnes of salmon, which means they produced around 2500 tonnes a week. Transporting this amount will need around 167 trailers, with a capacity of 15 tonnes each, which can be evenly distributed throughout the week. If transporting this amount by ship one will need no more than 1 ship, but this also means that the weekly production must be produced in a much shorter amount of time. Alternatively, multiple slaughtering facilities can supply a ship, but this also means that the fish must be transported from multiple locations to one harbor. The system will, however, be less exposed to variations in the production when using multiple slaughtering facilities.

2.4 Ports

Relevant ports for the RORO-vessel.

2.4.1 Norway

When picking ports in Norway one should consider them based on the distance from the slaughtering facilities to the port and the distance from the port to the market in Europe. The 5 biggest producers of salmon are Troms, Nordland, Trøndelag, Møre og Romsdal and Hordaland. Troms and Nordland will not be included because they are considered too far away from the European market.

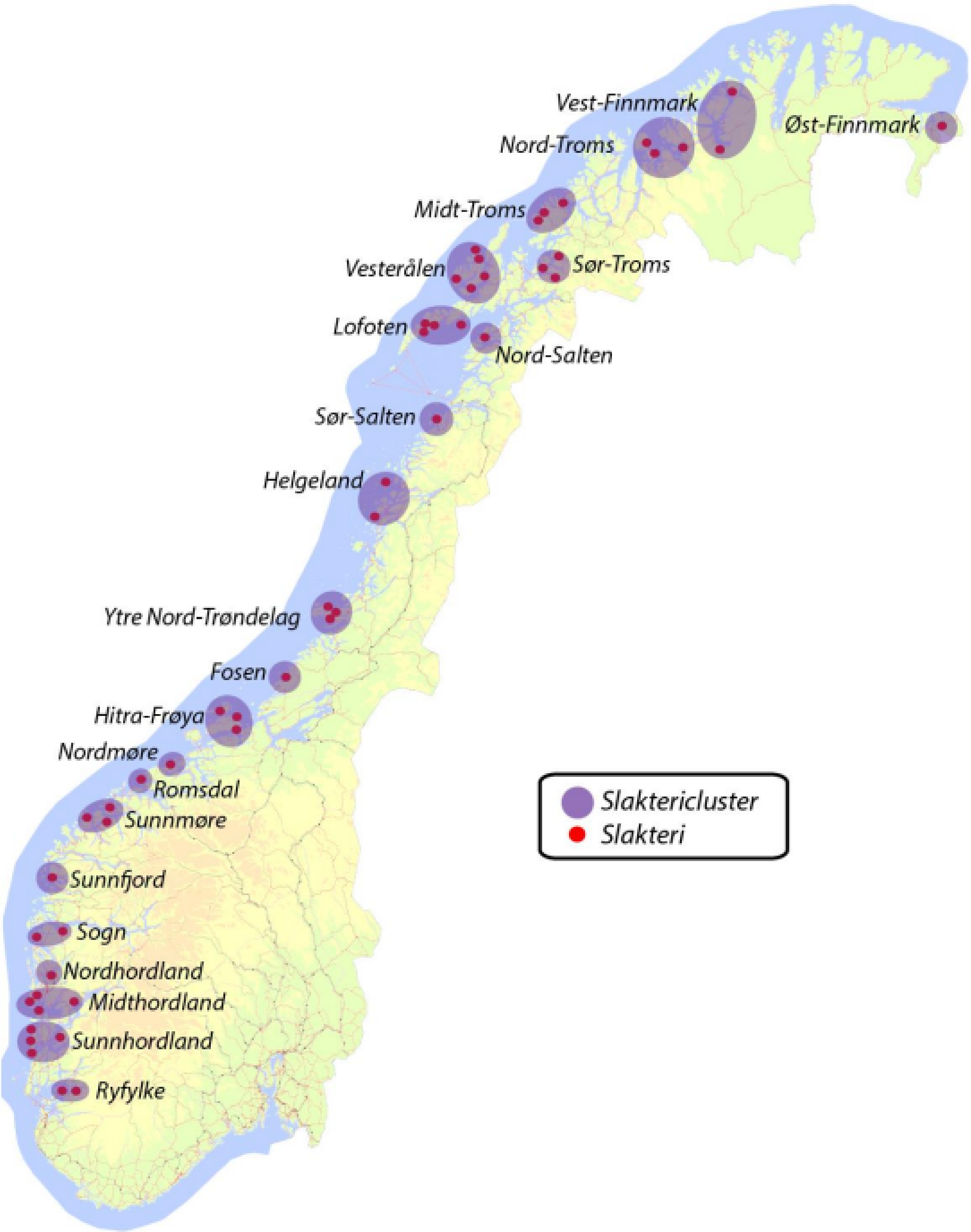


Figure 2.9: Slaughter facility locations in Norway [14]

In Figure 2.9 one can see slaughtering clusters marked by the purple bubble and specific slaughtering facilities marked with the red dots. For Trøndelag most facilities are located at Hitra-Frøya and Ytre Nord-Trøndelag, which is located near Rørvik. These locations are good for the use of ports because distances between the locations are short, the production rate is high and no ferries for feeding are needed. At Møre og Romsdal slaughtering locations are more spread, but there is a big cluster located around Ålesund. The locations in this cluster is separated with fjords, therefor feeding to a common port would probably take more time than in Trøndelag. In Hordaland, the slaughtering locations are even more spread. With fjords in between the locations, transportation to a common port will take even longer time and therefore a port at this location will not be considered further on.

For the slaughtering vessel, a port is not needed and the pickup location will be located directly at a given fish farm. Salmon produced further south in the country can for this method be used and traveling distance to the continent will be reduced, compared to the RoRo alternative, which depends on picking up salmon further north.

From-To	Distance[Nm]	Sailing Time[h]
Rørvik-Hitra	100	5,5
Hitra-Ålesund	100	5,5

Table 2.3: average speed of 18 knots

2.4.2 Europe

When choosing a port in Europe one should look at how part big of a market one can reach from that port and the sailing time. Choosing a port which is in the northern part of Central Europe would be preferable, to ensure that only small parts of the market are located north of the port and to minimize total transportation time. Relevant countries in which ports could be located could be Denmark, Germany, Belgium, Netherlands or Poland. In Figure 2.10 four possible ports in Europe are marked. The distance and the estimated time to sail from Ålesund to one of the selected ports at a speed of 18knots is shown in Table2.4. To reach the port of Swinoujscie one will need to pass the Drogden channel, therefor the sailing time to this port will probably be higher than estimated depending on the traffic. The routes to the other ports are on open sea and traffic is, therefore, no complication other than at the ports.

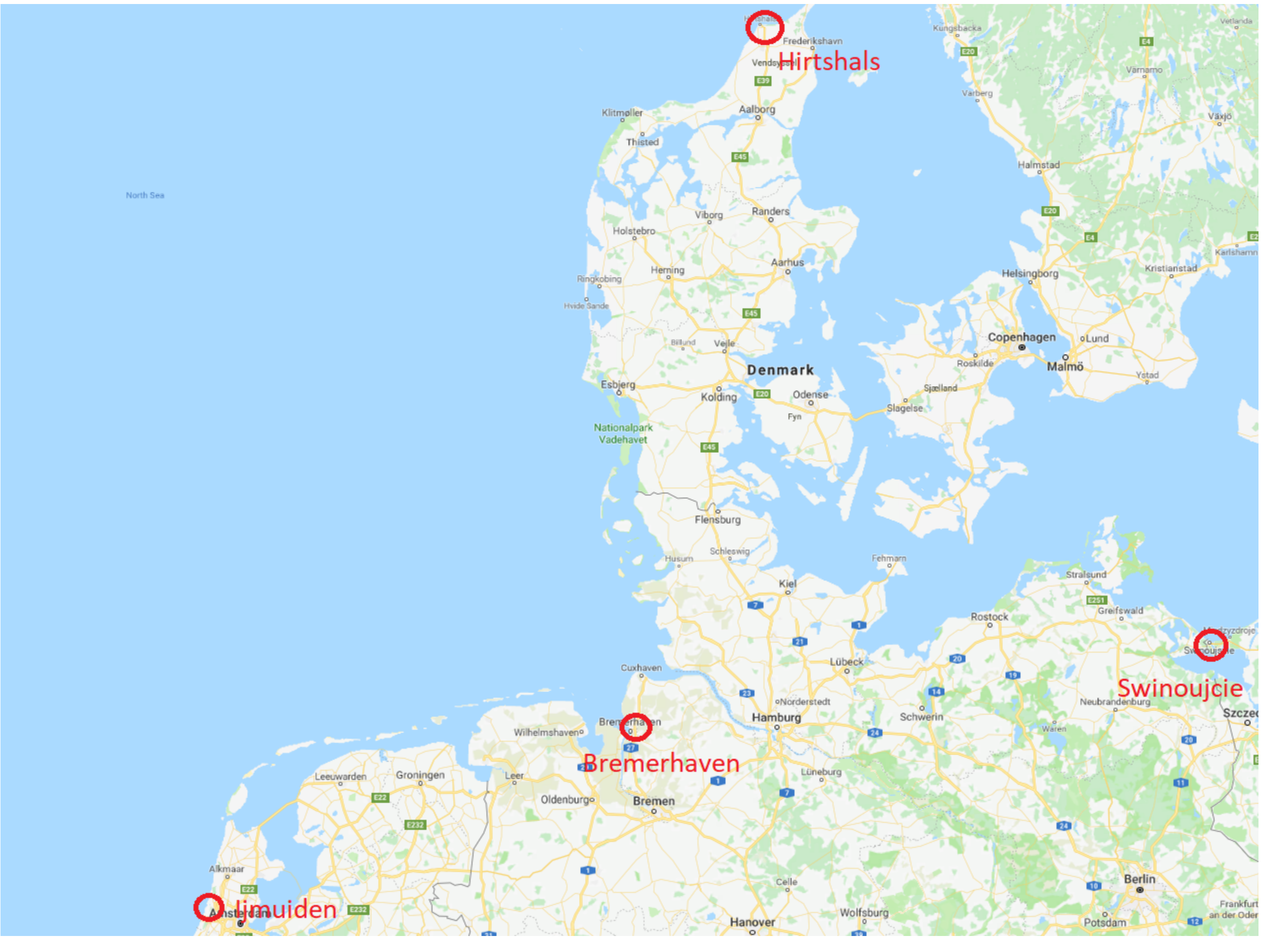


Figure 2.10: Ports in Europe

From-To	Distance[Nm]	Sailing Time[h]
Ålesund-Bremerhaven	587	33
Ålesund-Hirtshals	450	25
Ålesund-Ijmuiden	639	36
Ålesund-Swinoujscie	728	40

Table 2.4: average speed of 18 knots

2.4.3 Further transportation

When the fish has arrived at the port it will still need to be transported further. In this thesis, only trailers are considered for this task. Speed limits for trailers are different from country to country, but most countries have a speed limit of 80km/h [17]. The driver of a trailer can drive a maximum of 4,5 hours before taking a break of 45 minutes and there is a resting restriction of at least 11 hours a day [41]. Within 24 hours one will then be able to drive in 3 periods in total 2 periods of 4,5 hours and one period of 2,5 hours, which in total gives 11,5hours of driving each day. This means that one can roughly drive 900km in one day and 1800km in two days. Based on this one is able to find out which markets can be reached within one or two days further transportation from the port as presented in Table 2.5. Based on distances on the road network from the different ports, it was estimated how much of each country could be covered within one or two days of further transportation.

Table 2.5: Reach of delivery within one or two days from the different ports in Europe

Market/Port	Ijmuiden		Bremerhaven		Hirtshals		Swinoujscie		Annual salmon import
Days of transport	1	2	1	2	1	2	1	2	
Poland [Percent]	25	100	50	100	0	100	100	100	18,47
France [Percent]	75	100	33	100	0	67	0	100	13,35
Denmark [Percent]	100	100	100	100	100	100	100	100	12,20
Spain [Percent]	0	50	0	33	0	0	0	0	9,04
Great Britain [Percent]	67	100	33	100	0	67	0	67	8,19
Neatherlands [Percent]	100	100	100	100	50	100	100	100	8,01
Italy [Percent]	0	67	0	50	0	20	0	67	6,85
Germany [Percent]	100	100	100	100	67	100	100	100	5,26
Lituania [Percent]	0	100	0	100	0	100	67	100	5,21
Belgium [Percent]	100	100	100	100	0	100	67	100	0,71
Total [Percent]	46,30	80,51	42,52	77,81	19,73	65,66	47,91	73,29	87,29

In Bremerhaven, Ijmuiden and Swinoujscie over 40% of the market can be reached within 1 day and up to 80% can be reached within 2 days(ref). From Hirtshals, only 20% of the market can be reached within 1 day and 65% after 2 days. When comparing Ijmuden with Swinoujscie, the market reached within 1 day is slightly higher for Swinoujcie, but within 2 days one can reach around 80% of the market in the EU from Ijmuiden and only 73% from Swinoujscie. The port of Swinoujscie will not be considered any further, because the sailing time is considered too long and the market available is to low compared to Ijmuiden.

Chapter 3

Optimization Theory

3.1 What is Optimization

Optimization is the process of attempting to find the best solution with regards to an objective and with given constraints. The structure of an optimization problem consists of an objective function and a number of constraints. The constraints of the problem define the boundaries of the solution space. All solutions that are within these boundaries are allowed solutions to the problem. Each solution will have a certain value based on the objective of the problem. Depending on whether the objective is to minimize or to maximize the problem is considered solved when the best solution within the allowed solution space is found.

3.2 Fleet size and mix

The problem partly consists of finding an optimal fleet of vessels. *M.Christiansen et al. (2007)* [8] describes a fleet size and mix problem for a liner shipping company, where several customers need to be serviced frequently, with predefined feasible routes. The loading and unloading part of the problem is not included directly in the problem and is included as part of the routes. The model consists of a set of vessels V, a set of feasible routes for each vessel R_v and a set of origin-destination port pairs called N. D_i describes how many times a port pair must be serviced, based on predefined production amounts delivered from one port to the other in the production pair. Loading constraints are also predefined and included in each route. $C_{\mathrm{V}vr}$ is the variable sailing cost for vessel v on route r, while $C_{\mathrm{F}v}$ is the fixed cost of vessel v in the planning horizon T. A voyage with vessel v on route r takes $T_{\mathrm{V}vr}$ time units. A_{ir} is a binary parameter equal to 1 if route r visits origin-destination port pair i. u_vr is a integer variable describing the number of times route r is voyaged by vessel v. s_v is a binary variable equal to 1 if a vessel is used during the planning horizon. The model presented by *M.Christiansen et al.(2007)*[8] for a strategic fleet size and mix problem with predefined routes is presented below.

$$\min \left[\sum_{v \in \mathcal{V}} \sum_{r \in \mathcal{R}_v} C_{\mathrm{V}vr} u_{vr} + \sum_{v \in \mathcal{V}} C_{\mathrm{F}v} s_v \right] \tag{3.2.1}$$

$$\sum_{\epsilon' \in \mathcal{R}_V} u_{vr} - U_v s_v \leq 0, \quad \forall v \in \mathcal{V} \tag{3.2.2}$$

$$\sum_{v \in \mathcal{V}} \sum_{r \in \mathcal{R}_v} A_{ir} u_{vr} \geq D_i, \quad \forall i \in \mathcal{N} \tag{3.2.3}$$

$$\sum_{r \in \mathcal{R}_v} T_{\mathrm{V}vr} u_{vr} \leq T, \quad \forall v \in \mathcal{V} \tag{3.2.4}$$

$$u_{ur} \geq 0 \text{ and integer}, \quad \forall v \in \mathcal{V}, r \in \mathcal{R}_v \tag{3.2.5}$$

$$s_v \in \{0, 1\}, \quad \forall v \in \mathcal{V} \tag{3.2.6}$$

The objective function 3.2.1 minimizes the cost. The cost consists of a variable sailing cost and a fixed cost related to the vessels used. It is ensured that the fixed cost of vessels used is paid for by constraint 3.2.2. Constraint 3.2.3 ensures each origin-destination port pair to be serviced the number of times demanded. Constraint 3.2.4 makes sure that the total time each vessel is in use is within the planning horizon. Variable restrictions are presented in 3.2.5 and 3.2.6.

3.2.1 Spot charters

Today's transport of cargo is done with trailers. For some customers, it might be cheaper to transport the cargo directly from the production facility to the customer. All cargo should, therefore, be considered optional, in such a way that the seaborn solution transports only the amount of salmon which reduces the total costs of transporting the total volume of salmon the most. *M.Christiansen et al.(2007)*[8] introduces a new variable s_i for scheduling problems for industrial and tramp shipping. This variable is binary and describes if the cargo is being handled by a spot charterer at a given cost.

3.3 Set partitioning approach

Brønmo et al.(2007)[5] presents the set partitioning approach. The set partitioning approach divides an optimization problem into a master problem and a subproblem. Different routing constrictions for vehicles define what routes are feasible for a given vehicle. Instead of using arcs a problem can be reformulated by using predefined paths for each vehicle. The number of feasible paths will, in general, be larger than the number of arcs, because arcs can be rearranged in multiple ways to create a feasible path. The problem can now be redefined based on feasible paths instead of arcs and is called the master problem. Routing based constrictions will no longer be part of the master problem, which simplifies the problem. The subproblem handles the generation of feasible paths, based on the routing constrictions and arcs of the original problem. The set partitioning approach reduces the complexity of the model, thereby reducing solving times for bigger problems.

3.4 intermodal transportation

The main focus of the model is to see if seaborn transport is cost-efficient to use compared to the established transport of fresh salmon by trailer. Therefore the model consists of both trailers and vessels. The salmon can be transported with 2 alternatives, either transport directly from the production facility to a customer or with a ship from the production facility to a port, which acts as a hub and then from the hub to the costumer. Having a total supply and a total demand which is identical. *Calvete et. al.(2016)*[6] Presents a two-stage transportation problem with a fixed charge at depots. The problem consists of a set of plants, a set of depots and a set of customers. A given amount of product will be produced at each plant, which is then transported to a depot, from where the product will be distributed further to the customer. The distribution network is illustrated as seen in figure 3.1

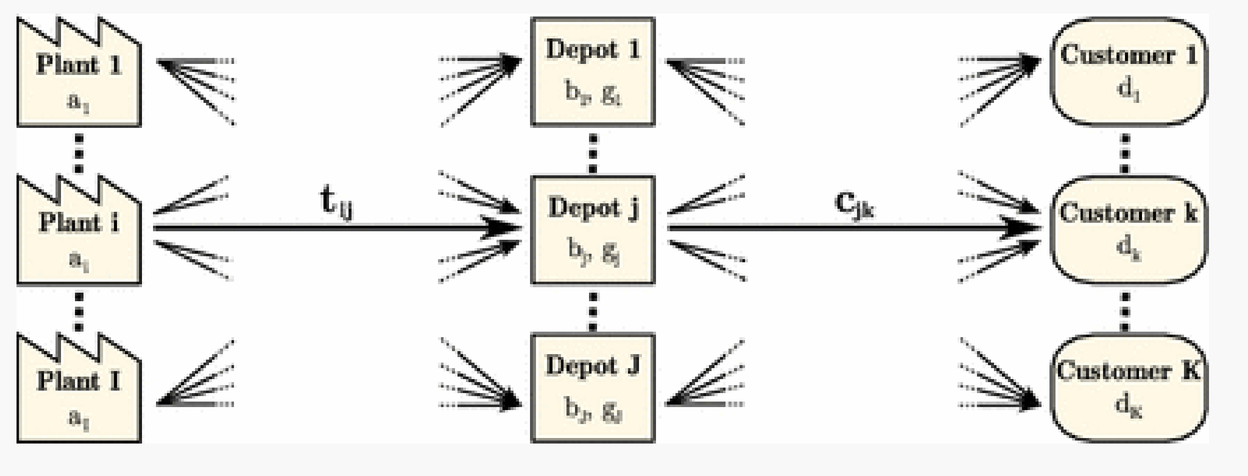


Figure 3.1: Diagram of a two-stage transportation problem with fixed charge at depots[6]

a_i describes the amount of product to be distributed from each plant i and d_k the amount demanded at customer k. A variable x_{ij} describes the amount of product shipped from plant i to depot j, while t_{ij} is the unit cost of transportation from i to j. Using a depot comes at a fixed cost of g_j and has a capacity b_j. A variable y_{jk} describes the amount transported from depot j to customer k, with c_{jk} being the respective unit cost between those two nodes. Additionally, a variable z_j describes if a depot will be used or not.

$$\min_{z_j, x_{ij}, y_{jk}} \sum_{i=1}^{I} \sum_{j=1}^{J} t_{ij} x_{ij} + \sum_{j=1}^{J} \sum_{k=1}^{K} c_{jk} y_{jk} + \sum_{j=1}^{J} g_j z_j \tag{3.4.1}$$

$$\sum_{j=1}^{J} x_{ij} \leq a_i, \quad i = 1, \ldots, I \tag{3.4.2}$$

$$\sum_{k=1}^{K} y_{jk} \leq b_j z_j, \quad j = 1, \ldots, J \tag{3.4.3}$$

$$\sum_{j=1}^{J} z_j \leq W \tag{3.4.4}$$

$$\sum_{j=1}^{J} y_{jk} \geq d_k, \quad k = 1, \ldots, K \tag{3.4.5}$$

$$\sum_{i=1}^{I} x_{ij} = \sum_{k=1}^{K} y_{jk}, \quad j = 1, \ldots, J \tag{3.4.6}$$

$$z_j \in \{0, 1\}, \quad j = 1, \ldots, J \tag{3.4.7}$$

$$x_{ij} \geq 0, \quad i = 1, \ldots, I, j = 1, \ldots, J \tag{3.4.8}$$

$$y_{jk} \geq 0, \quad j = 1, \ldots, J, k = 1, \ldots, K \tag{3.4.9}$$

The objective 3.4.1 is to minimize the cost of transportation, consisting of transportation costs from the plants to the depots and the cost of transporting from the depots to the customers and the fixed cost of using a depot. Constraint 3.4.2 ensures that transported volume from each plant does not exceed the amount produced. Constraint 3.4.3 ensures the capacity at the depot is not exceeded and ensures that a used depot will be paid for. Constraint 3.4.4 limits the number of used depots to W and constraint 3.4.5 ensures demand for each customer is satisfied. Constraint 3.4.6 guarantees that all the product transported to a depot must also be transported out. Variable ranges are are set in constraints 3.4.7,3.4.8 and 3.4.9.

3.5 Translation to the model presented in this thesis

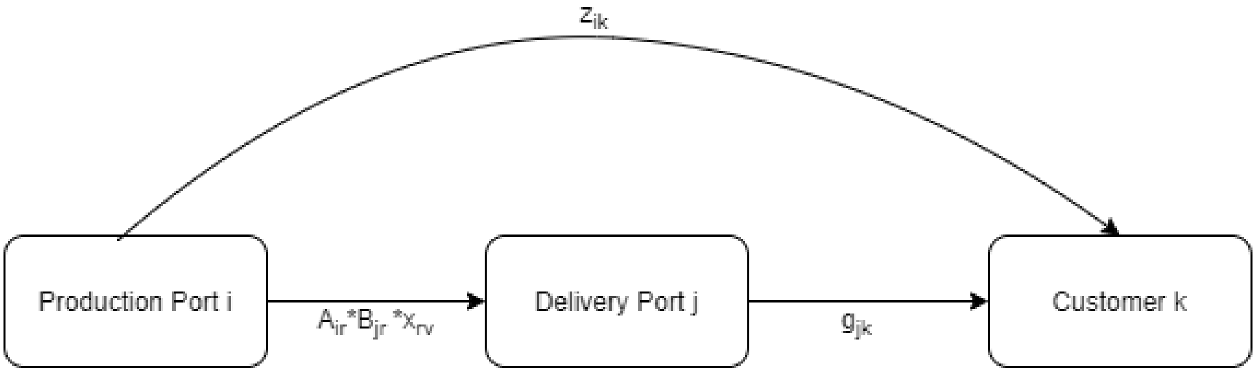


Figure 3.2: Flow diagram

The overlying problem is a transportation problem consisting of delivering the product either by seaborne transport combined with further trailer transportation from the delivery port to the customer or direct transport from the production facility to the customer by trailer. This is illustrated in the diagram above, where each arrow illustrates how much product is being shipped between the different nodes of the model. All land-based transport is modeled as a transportation problem, where each arc has a cost per ton transported on the arc associated with it. This means that one can, in theory, deliver half a trailer at half the cost. This is a simplification made because the total amount of trailers used in the system amounts to many thousand, which means that if some of the loads delivered are fractional loads this will amount to a minimal cost difference. The vessel associated costs, on the other hand, can not be simplified in this way, because much higher amounts of product are transported per vessel, which means such a simplification can make a significant impact on the model. The part of the model which consists of transporting the salmon from individual production ports to the delivery port acting as a deposit is therefore modeled as a strategic fleet size and mix problem. Since trailers are available these can be used to transport any cargo, which is not handled by vessels and will act as a spot charterer.

The seaborne part of the model is formulated as a path flow formulation, instead of the conventional arc flow model. Based on the routing constrictions presented in 4 feasible routes will be constructed, where each route consists of one or multiple loading ports and one delivery port. Feasible routes must be found prior to solving the model. There being more possible paths than possible arcs results in there being more pre-calculations to be done in a path-flow model than for an arc-flow model. The model will be a less complicated model and pre-solving feasible routes results in a faster running model, caused by fewer constraints.

Chapter 4

Problem description

In this chapter, the problem is described in a simplified way and is mainly based on the background study presented in chapter 2. The problem description lays the base for the optimization problem created in chapter 5. It was decided that an optimization problem on the transport by RoRo-vessels would be the most interesting, the use of slaughtering vessels is therefore not considered any further in this thesis. Figure 4.1 illustrates the transportation problem. Salmon is transported either by trailer or ship from production facilities in Norway. Fish transported by sea will be delivered to a delivery port in Europe, from where the fish is distributed to the end customer by trailers. Fish transported from the production facilities by trailers, will, on the other hand, be transported directly to the end customer. Since today's transport of salmon mainly is done by trailers it is important one considers the logistics chain from when the fish has been slaughtered until delivery at the end customer, to better be able to compare the two transportation alternatives.

Figure 4.1: Problem description illustration

All trailers are considered identical, which means that the fleet of trailers used is homogeneous. The speed of trailers is mainly restricted by rules and regulations of different countries and therefore the main difference between trailers will be the capacity they are able to take. To best being able to compare seaborne transportation with land-based transport all trailers are assumed to be identical. For the seaborne transport different RoRo-vessels will be considered, with different sailing speeds and capacities, because these parameters can have a large impact on the age of the salmon at delivery. Because trailers have relatively small capacities compared to the demand at a given customer, the trailer load transported on an arc by trailers is simplified by modeling it as a continuous flow, instead of transporting unit loads.

4.1 Routing

It is assumed that trailers used will take the fastest, cheapest route from the pickup location directly to the end customer, which can consist of ferry connections. The routing for a vessel will be different, because of the much larger capacity, which opens the possibility of visiting multiple production ports in Norway. To reduce the number of possible routes for a vessel, routes are restricted in such a way that it is not allowed to pick up load located north of the last pick up location because this will only give solutions, where salmon is transported longer than necessary. Splitting the load between loading ports means less load must be produced at each port, reducing the time it takes to produce the needed load. Splitting the load between ports in Norway may be necessary in order to reduce the age of the salmon at pickup. Land-based transport in Norway takes on average a longer time than in central Europe. This is because fjords, mountains and lacking road infrastructure make land-based transport less compelling than in Europe. This makes transport by trailer between the main slaughtering locations time consuming and costly. Sailing between the locations, on the other hand, comes with fewer obstacles. Splitting the load between multiple locations will also mean that the age of the salmon at pickup will be lower. To load the entire ship a good option in Norway will, therefore, be to load the ship at the different locations. In Europe, the different end costumers can be reached easily by trailers, because a good road infrastructure makes it possible to reach each end customer without any big obstacles, which makes splitting up the delivery on multiple ports less attractive. Therefore, splitting the delivery is not considered further.

4.2 Perishable goods

Fresh salmon is a perishable goods and has a limited shelf life. This means that the time used from the salmon first is slaughtered until delivery needs to be kept low to ensure good quality of the product. When using seaborne transportation the age of the oldest fish delivered can not exceed a predefined limit at the delivery port. The total load delivered will consist of different aged fish, which will depend on the production rate and the load picked up at the different ports. It is assumed that the oldest load will be transported to the end customers located closest to the delivery port and the less aged fish will be transported to customers located further away. Additionally, some customers refine the fish, while others sell the fish fresh. The age of the salmon at delivery is assumed less important for the refineries than for the fish market. Therefore fish markets are prioritized to get the fresher fish delivered. This assumption is made to avoid having to track every fish delivered, which would create a more accurate but way more complex model. Different time limits for delivering the fish at the port in Europe will be used to see what impact this has on the optimal solution. This way the costumers can be guaranteed a certain freshness of the salmon. The salmon must be delivered within the predefined limit. This way one can see how much cost reduction can be achieved at different age limits and evaluate if the reduced cost a seaborne alternative gives is better or worse than the increased age of the salmon.

4.3 Production and demand

A constant production rate can be assumed in the planning period because there won't be big seasonal production variations in a planning period of 4 weeks. This makes calculating the age of the fish picked up at a given port easier. The total amount produced at the chosen production ports within the planning period is used and can be scaled up and down for modeling different scenarios.

The total demand in Europe is set equal to the total production at the considered production ports, which implies that all the product must be distributed according to the demand of the different customers. In Figure 4.2 the demand in Europe is illustrated. As one can see different demand regions are created. The biggest importing countries are considered. The percentile demand of each region is based on the annual import of each of these countries. In reality, the demand of each country consists of hundreds of customers, but it will, in this case, be simplified to one big customer located centrally in each region. The cost of transporting all trailers to one central point in the country is assumed close to the cost of transportation to all the small customers. The distance to this central costumer will be around the same as the average distance to all customers located in the region. The production ports in reality also consist of multiple smaller slaughtering facilities, but they are considered so close to each other that they have been simplified to one big slaughtering facility.

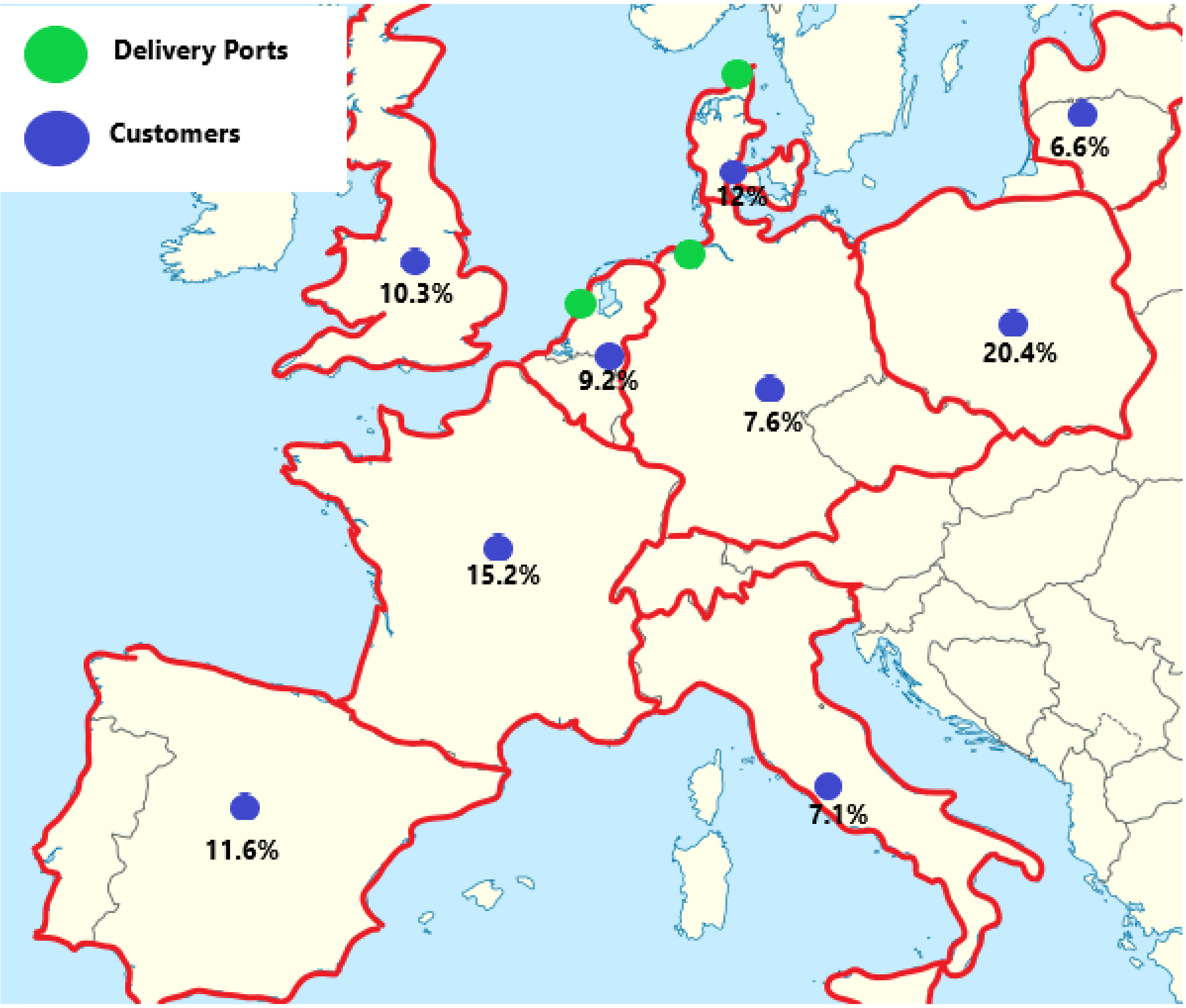


Figure 4.2: Demand in Europe

The total production at a production port will need to be picked up either by trailer or vessel to ensure no product is wasted. The total demand of each customer will also need to be fulfilled, combined by the load delivered by trailers directly from the production facility and the load delivered by trailers from delivery ports.

4.4 Time

The vessels can only be operated within the defined planning period of 4 weeks, therefore the number of round trips a vessel takes must be restricted according to the available time.

4.5 Objective

The objective of this model is to minimize the cost of transporting the product available to the end costumers. The cost can be divided into two categories. The seaborne related costs are the costs occurring when using ships to transport the salmon. There will be a chartering cost for using a vessel for the time period. The vessel will need to be paid for for the entire period independent of how much it is used. The chartering cost will vary depending on the size and the service speed of the vessel and consists of the capital expenses, maintenance, wages, and insurance. There will also be a sailing cost which will vary depending on how much the vessel is used. These costs are mainly fuel costs and costs related to visiting ports. The other category is the land-based transport costs. The cost of transporting by trailer can also be divided into fixed costs and varying costs. The fixed costs cover capital expenses, maintenance, and insurance. Fuel costs, wages, toll costs, and ferry costs depend on the time the trailer is in use and the selected route. The land-based transportation cost will also need to be included for the seaborne solution, to account for further transportation to the customer.

Chapter 5

Mathmatical problem description

5.1 Definitions

Sets

V	Set of vessels v
R	Set of feasable routes r
I	Set of production ports i
J	Set of delivery ports j
K	Set of end customers k

Parameters

C_v^{FC}	Fixed cost of chartering vessel v
C_{rv}^{VAR}	Variable cost of sailing route r with vessel v
C_{ik}^{TR}	Cost of delivering a ton of salmon by trailer from production port i to end customer k
C_{jk}^{FT}	Cost of delivering a ton of salmon by trailer from delivery port j to end customer k
Q_v	Capacity of vessel v
T^{TOT}	Total planning period
T_{rv}^{RT}	Roundtrip time of route r with vessel v
T_{rv}^{DEL}	Time to deliver product from the first pick up to the delivery port for route r with vessel v
FAL_{irv}	Age of the oldest salmon when loading
FAD_{rv}	Age of the oldest salmon after delivery
MFA	limit of the maximum fish age at the delivery port
A_{ir}	Binary parameter, which describes if production port i is visited on route r
D_i^{PRO}	amount of product produced at port i in the planning period
D_k^{DEL}	amount of product demanded at customer k in the planning period
L_{irv}	Amount of salmon loaded by vessel v at production port i on route r
B_{jr}	Binary parameter, which describes if delivery port j is used on route r

Decision Variables

x_{rv}	Integer number of times route r is used by vessel v
w_{rv}	Binary variable describing if vessel v can sail route r
y_v	Number of vessels v that are chartered
z_{ik}	Amount of salmon transported from port i by trailer to customer k
g_{jk}	Amount of salmon transported from delivery port j to customer k

5.2 Model formulation

5.2.1 Objective Function

The objective is to minimize the total cost and can be formulated as followed:

$$minz = \sum_{v\in V} C_v^{FC} y_v + \sum_{r\in R}\sum_{v\in V} C_{rv}^{VAR} x_{rv} + \sum_{i\in I}\sum_{k\in K} C_{ik}^{TR} z_{ik} + \sum_{j\in J}\sum_{k\in K} C_{jk}^{FT} g_{jk} \tag{5.2.1}$$

The first two terms of the objective function describe the total cost of seaborne transportation. The first term ensures that each vessel that is charted is paid for. The second term is the variable cost that occurs. The third term is the cost of transporting salmon by trailer directly from the Norwegian ports to the customer. The last term is the cost of transporting shipped salmon from a delivery port to the end customer.

5.2.2 Constraints

Time and Vessel constraint

$$\sum_{r\in R} T_{rv}^{RT} x_{rv} \leq T^{TOT} y_v \qquad v \in V \tag{5.2.2}$$

Constraint 5.2.2 ensures that the total time a vessel is used does not exceed the length of the planning period, as-well-as it ensures that a vessel only can be used when it is chartered. In case a vessel is not being chartered y_v will be 0, which makes the right-hand side of this constraint 0. In that case, every x_{rv} for this vessel will need to be 0 in order to fulfill the constraint. When on the other hand one or multiple vessels are chartered the constraint makes sure that the total time of all round-trips chosen by the vessels needs to be less than the total time available for each vessel. This constraint is a combination of the constraints 3.2.2 and 3.2.4 of the strategic fleet size and mix problem presented in 3. However, it is decided that multiple of the same type of vessel can be used, which makes the variable y_v represented as s_v an integer variable instead of a binary variable. This is done to shrink down the size of the vessel set, so no duplicates are needed in the set.

Loading constraint

$$\sum_{r\in R}\sum_{v\in V} L_{irv} x_{rv} + \sum_{k\in K} z_{ik} \geq D_i^{PRO} \qquad i \in I \tag{5.2.3}$$

Constraint 5.2.3 is used to make sure that the total amount of salmon produced at each port must be picked up. The term of the constraint on the left-hand side describes the total amount of salmon transported from a port with ship and trailer must be equal or above the amount produced. L_{irv} is a predefined amount of salmon that will be taken when a vessel v visits port i on route r. Near the end of the planning period, the remaining amount of salmon in stock can be less than the predefined amount a vessel should take and therefore allowing to deliver more than is produced will make it possible for these vessels to still pick up the remaining load at the production port. This constraint is a combination of the demand constraint in 3.2.3 with zik acting as spot charters and constraint 3.4.2.

5.2.3 Perishable constraint

The salmon has a limited shelf life, which limits the total time that can be spent before the salmon is delivered. It is assumed that the salmon must reach the delivery port in Europe within a certain number of days. This limit is called MFA(MaximumFishAge atdelivery). The time it takes to deliver the salmon consists of the time the salmon is stored before being picked up by a vessel and the time it takes to transport the salmon down to Europe. The longer time is used for transport to the delivery port, the lower the age of the salmon at pickup must be. When the transport time is long the opposite applies. w_{rv} is a binary variable that describes if a route r is used by a vessel v. Constraint 5.2.5 ensures that a route only can be used in a solution when w_{rv} is 1. While constraint 5.2.4 ensures that a certain route r can only be used by a vessel when all the load is delivered to the delivery port within the time limit. It is assumed that the oldest fish is transported to the end customers located closest to the delivery port, while younger fish will be transported to the end customers located further away.

$$FAD_{rv} * w_{rv} \leq MFA \qquad v \in V, r \in R \tag{5.2.4}$$

$$x_{rv} \leq 100 w_{rv} \qquad v \in V, r \in R \tag{5.2.5}$$

An alternative to use this is to define the set of routes based on vehicles. This means instead of having a set R one will have v different sets of routes R_v. Each vessel will then have a set of routes, consisting only of routes that are feasible with regards to the routing constrictions, but also ensuring that the fish will be delivered in time. This would, however, require more pre-calculations.

Further Transportation

Including the transport from the delivery ports to the end customer will make the comparison between transporting the salmon from Norway by land and by sea more realistic and delivery to ports further south may become more attractive because this can shorten the distance to some markets.

One will need to assure that the total amount of salmon that is shipped to a port is transported further, which is assured with constriction 5.3.6

$$\sum_{k \in K} g_{jk} \leq \sum_{r \in R} \sum_{V \in V} Q_v x_{rv} * B_{jr} \qquad j \in J \tag{5.2.6}$$

B_{jr} is a binary parameter, which is 1 if delivery port j is part of route r and 0 otherwise. Each end customer has a predefined demand D_k^{DEL}, which must be fulfilled. This constraint is the same as presented in 3.4.6, which ensures all product going into a port must also go out. However since constraint 5.2.3 was formulated in such a way that a vessel could pick up more load at a port than in total produced there can be more salmon at the port than actually shipped there. Therefor the amount going out of the port is in this case defined as being less or equal to the amount going in. This being a minimization problem the extra amount of salmon shipped which actually is not produced will stay at the delivery port, since delivering it out to the customers would is not necessary.

Constraint 5.3.7 describes that the demand of each end customer needs to be met and represents constraint 3.4.5. The entire flow of product coming from delivery ports and/or directly from the production facility in Norway to the customer must be greater or equal to the amount demanded.

$$\sum_{j \in J} g_{jk} + \sum_{i \in I} z_{ik} \geq D_k^{DEL} \qquad k \in K \tag{5.2.7}$$

Optional additions

The way the model is formulated delivering salmon earlier gives no direct benefit. Trailer costs are dependent on the time, which makes it more beneficial to transport product to a customer with the shortest route possible. One can introduce a cost which penalizes long transportation times. This cost will depend on the total time spent on transporting and the total amount delivered and is given in $[NOK/(tonn * h)]$. Equation 5.2.8 shows how this cost would be implemented in the objective function. The first part of the equation are the total ton hours for the shipping and Storage part of the seaborne alternative, the second part is the total amount of ton hours of the further transportation of the salmon and the last part is the amount of ton hours for the trailer alternative.

$$(\sum_{r \in R} \sum_{v \in V} FAD_{rv}^{avg} * \sum_{i \in I} L_{irv} * x_{rv} + \sum_{j \in J} \sum_{k \in K} T_{jk}^{TRE} * g_{jk} + \sum_{i \in I} \sum_{k \in K} T_{ik}^{TRN} * z_{ik}) * C^{PEN} \tag{5.2.8}$$

FAD_{rv}^{avg} is the average age of the salmon at the delivery port and is calculated as shown in equation

$$FAD_{rv}^{avg} = FAL_{rv}^{avg} + T_{rv}^{DEL} \tag{5.2.9}$$

FAL_{rv}^{avg} is the average fish age at pick up and is equal $\frac{1}{2}FAL_{rv}$ half the age of the oldest fish at pick up.

5.3 Final Model

$$minz = \sum_{v \in V} C_v^{FC} y_v + \sum_{r \in R} \sum_{v \in V} C_{rv}^{VAR} x_{rv} + \sum_{i \in I} \sum_{k \in K} C_{ik}^{TR} z_{ik} + \sum_{j \in J} \sum_{k \in K} C_{jk}^{FT} g_{jk} \tag{5.3.1}$$

$$\sum_{r \in R} T_{rv}^{RT} x_{rv} \leq T^{TOT} y_v \qquad v \in V \tag{5.3.2}$$

$$\sum_{r \in R} \sum_{v \in V} L_{irv} x_{rv} + \sum_{k \in K} z_{ik} \geq D_i^{PRO} \qquad i \in I \tag{5.3.3}$$

$$FAD_{rv} * w_{rv} \leq MFA \qquad v \in V, r \in R \tag{5.3.4}$$

$$x_{rv} \leq 100 w_{rv} \qquad v \in V, r \in R \tag{5.3.5}$$

$$\sum_{k \in K} g_{jk} \leq \sum_{r \in R} \sum_{V \in V} Q_v x_{rv} * B_{jr} \qquad j \in J \tag{5.3.6}$$

$$\sum_{j \in J} g_{jk} + \sum_{i \in I} z_{ik} \geq D_k^{DEL} \qquad k \in K \tag{5.3.7}$$

$$x_{rv}\ integer \qquad r \in R, v \in V \tag{5.3.8}$$

$$y_v\ integer \qquad v \in V \tag{5.3.9}$$

$$w_{rv} \ \in \ \{0, 1\} \qquad r \in R, v \in V \tag{5.3.10}$$

$$z_{ik} >= 0 \qquad i \in I, k \in K \tag{5.3.11}$$

$$g_{jk} >= 0 \qquad j \in J, k \in K \tag{5.3.12}$$

Chapter 6

Pre-Calculations

In this chapter, all parameters used in the model are estimated and explained. This is done as a preparation of the computational study presented in chapter 7.

6.1 Routes

As described in the problem description a feasible route can consist of each delivery port at most once. A feasible route needs to consist of at least one loading port and one delivery port only. The route will, therefore, consist of one or more loading ports in Norway and one delivery port in Europe. The starting port of the route must be a loading port and any additional loading ports that are part of a feasible route must be located south of the starting port. With these restrictions the following feasible routes are available for each delivery port in Europe:

Table 6.1: Feasable routes

Route number	Route
1	Rørvik-Europe
2	Rørvik-Hitra-Europe
3	Rørvik-Hitra-Ålesund-Europe
4	Rørvik-Ålesund-Europe
5	Hitra-Europe
6	Hitra-Ålesund-Europe
7	Ålesund-Europe

Having 3 optional delivery ports gives a total amount of 21 different possible routes.

The number of feasible routes available with i being the number of production ports and j being the number of delivery ports included in the model can be calculated with the following expression

$(2^i - 1) * j$. Increasing the number of production ports increases the feasible amount of routes exponentially. An increase of delivery ports on the other hand only increases the feasible amount of routes linearly.

Which loading and unloading ports are used on the different routes will be defined as the binary parameters A_{ir} and B_{jr} respectively. Where a value of 1 describes that a port i or j is part of a route r and a value 0 excludes the port from the route.

6.2 Production and Demand

The production D_i^{PRO} is generated for each production port i, based on the production rates found in chapter 2. The production in today's market over a period of 4 weeks is shown in Table 6.2

Table 6.2: Production at each port in Norway in 4 weeks

Port	Production[tonnes]
Rørvik	10512
Hitra	7534
Ålesund	6514

The demand in Europe is divided into multiple different stores and refining facilities. This means that there would be hundreds or thousands of costumers with varying demand and varying locations. To simplify the problem the continent has been divided into 9 different regions as seen in Figure 4.2. Each region consists of one or multiple countries and the fractional demand of each region is based on the yearly demand of all countries the region consists of. With the annual demand of each region, the percentile demand of each region can be calculated in such a way that the total percentile of all regions combined is a 100% as depicted in Table 6.3.

Since an exact distance between the ports and the costumers must be known, a city approximately in the middle of each region is chosen as a delivery point. The distance to these locations reflects the average distance to all costumers in these regions, assuming a uniform spread of costumers.

Table 6.3: Demand of each region

Region of costumers	Yearly demand [tonnes]	percent
France	105 586	15,2
Poland	142437	20,4
Italy	49205	7,1
Spain/Portugal	80926	11,6
Great Britain	71795	10,3
Germany/Czech	52583	7,6
Belgium/Netherlands	64389	9,2
Denmark	83708	12
Lithuania/Latvia	46163	6,6
Total	696792	100

Setting the total demand equal to the total production the demand of each region is calculated by multiplying the total production by the percentile demand of each region.

6.3 Vessels

One will also need to generate a pool of different vessels. These vessels differ in average sailing speed and their capacity. The *Sea-web* database [24] was used to create a database shown in Appendix D consisting of 67 RoRo-vessels operating in Europe. The database consists of vessels built between 1995 and 2011, with capacities ranging from 1500 to 2900 lane meters and service speeds ranging from 16 to 22 knots. This data is used to estimate the required engine power for a vessel with a given capacity and speed.
To get the most accurate results one should divide the database into different sizes and different speeds. One should then plot the size against the installed engine effect for each speed, where the speed is held constant in each plot, or plot the speed against the installed engine effect at a constant size. Since the database was too small it was decided to divide the database into two size segments one ranging from 1500-2250 LM and the other ranging from 2250-2900 LM, this was done to ensure that all possible speeds where represented in each collection. First, the registered service speed was plotted against the installed engine effect, where there was calculated a strong correlation of 0.87 between the service speed and the engine effect for the vessels of low capacity and a weaker correlation of only 0.49 for the high capacity vessels.

Some vessels in the data set of the vessels from 2250-2900 LM had a registered service speed far below the registered maximum speed, which led to the poor correlation of 0.49 between the speed of the vessel and the installed engine effect. Therefore the plots were created again, but using the maximum speed of the vessel instead of the service speed for vessels where the maximum speed was given. The correlation for the high capacity vessels was increased to 0.73, while the correlation for the low capacity vessels decreased minimally to 0.85.

Below different Equations are presented which are used to calculate the required amount of engine effect when designing a vessel [2].

$$\eta_T * BkW = R_T * Vl \tag{6.3.1}$$

$$R_T = C_T * \frac{1}{2} * \rho_{saltwater} * Vl^2 * S \tag{6.3.2}$$

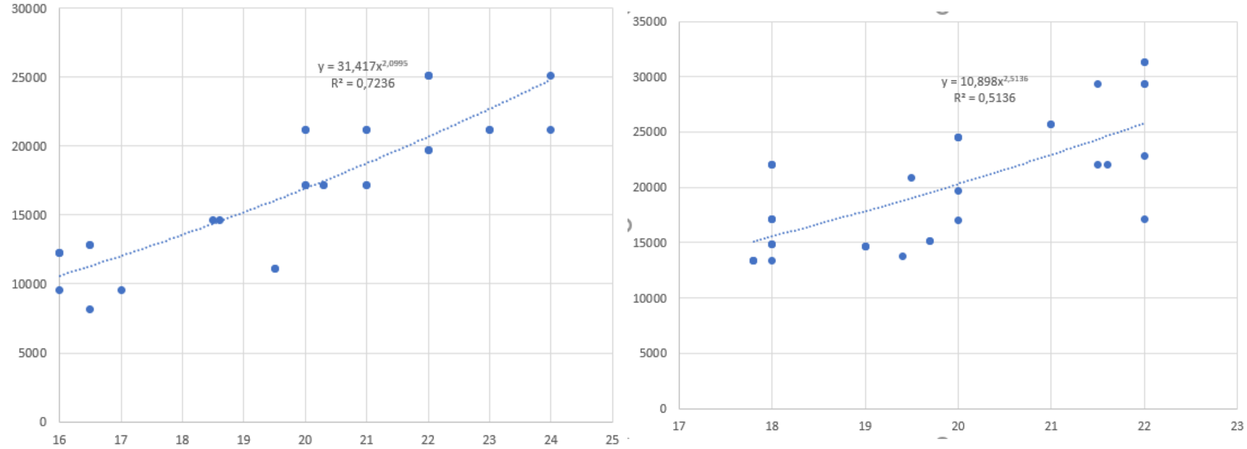
$$C_T = C_R + \frac{0.075}{(log(R_n) - 2)^2} \tag{6.3.3}$$

$$R_N = \frac{Vl * L}{\upsilon} \tag{6.3.4}$$

For vessels of varying service speeds, that are otherwise identical the total resistance coefficient C_T described in 6.3.3 will decrease very minimal with increasing vessel speed. Since Reynolds number as seen in 6.3.4 is a large number increasing it further will have a minimal effect on its logarithm. C_T is therefor assumed constant. The total resistance of the vessel 6.3.2 consists of S which is the wet surface area and is independent of the speed but will increase with bigger sized vessels. Assuming a constant total efficiency eta_T the installed engine effect BkW 6.3.1 depends on the 3 power of the speed Vl^3. From this, we know that the regression line of the plots should be dependent on the third power of the vessel speed.

The regression lines created were dependent on $Vl^{2.1}$ and $Vl^{2.5}$ for the low capacity vessels and the high capacity vessels respectively. These regression lines were then used to estimate the installed engine effect for all considered vessel speeds for both vessels. The percentile difference of installed engine effect between the two size segments for each speed was calculated and used to estimate the required engine effect for the different sizes of vessels in each speed category by using linear regression. The regression plots used are presented in Figure 6.1a and 6.1b representing the plots for the low and the high capacity vessels respectively.

One can clearly see less spread in the data points for the low capacity plot, than for the high



(a) Regression model of low capacity vessels

(b) Regression model of high capacity vessels

Figure 6.1: Regression models

capacity plot, which is also reflected by the R^2 values of 0.72 and 0.51 respectively. A R^2 value of 1 would represent a regression line where all points lay on the line, which means that the closer the number is to 1, the more accurate the regression line reflects the data.

The salmon capacity of each vessel was calculated by estimating each trailer to occupy 14 meters in length and with each trailer transporting 19 tonnes of salmon the amount of salmon per lane meter was calculated to 1.3571 ton/LM. It was found that on average a vessel had 8.39 GT/LM gross ton per lane meter. Which was used to calculate the size of the ship in gross ton, which is required for port cost calculations.

Things that have affected the accuracy of the engine effect analysis were first of all not enough available data. The estimated required engine effect is quite uncertain because many other design elements of a vessel will affect the required installed engine effect. Where the vessel is operational will also have an effect, since rough seas will require more engine effect than calm seas. Having only a limited amount of vessels, simplifications must be made in order to estimate the required power for a vessel. A RoRo-vessel is designed based on requirements. This can cause vessels that have the same trailer capacity and speed to have different sizes of engines installed. Ideally, the engine power is estimated by comparing nearly identical vessels with different service speeds to each other, but this is not possible with the limited set of data available.

6.4 Load

Since the amount loaded at a port is defined as a parameter and not a variable, to avoid nonlinear constraints the predefined load for each route should be selected in such a way that the age of the fish at pick up is relatively evenly distributed.
The model is formulated in such a way that a given vessel must be fully loaded before transporting the salmon to a delivery port. When a route consists of one loading port only the vessel will only have the choice to load the entire capacity of the vessel at that loading port. When a route consists of multiple loading ports then one should divide the amount of salmon picked up at each port based on the production rate, which results in having as fresh salmon as possible. Therefore the load a vessel will take from each loading port on a route L_{irv} will be based on the capacity of the vessel, the number of loading ports the route consists of and the production rate at the port and is defined as seen in Equation 6.4.1.

$$L_{irv} = \frac{A_{ir} D_i}{\sum_{m=1}^{|I|} A_{mr} D_m^{PRO}} * Q_v \qquad i \in I, r \in R, v \in V \tag{6.4.1}$$

The load picked up at each port is relative to the production of the port compared to the production at the other ports part of a route. This way the age of the salmon when picked up by the vessel is equal for all ports visited. This also gives the advantage that all ports on the route are emptied at the same rate.

6.5 Time

The round trip time T_{rv} can be defined as seen in Equation 6.5.1

$$T_{rv}^{RT} = \frac{Dist_r}{Vl_v} + [\sum_{i \in I} T^D * A_{ir} + T^D] + \frac{2 * Q_v}{R} \qquad i \in I, r \in R, v \in V \tag{6.5.1}$$

$Dist_r$ is the distance of the entire round trip, starting and ending at the same loading port. Distances between the ports are given in chapter 2 and distances for each route are based on these. Vl_v is the sailing speed of vessel v. T^D is the docking time at each port, which is assumed equal to be 2 hours at every port. Assuming the use of 2 Tugmasters each being able to unload a trailer, containing 19 tonnes of salmon, every 5 minutes the loading/unloading rate R becomes 456 tonnes

of salmon per hour.
The first term of the expression is the time used for sailing a round trip on the given route, the second term is the total time used docking on the route, which depends on the number of ports visited. The last term is the total time used loading and unloading the vessel on the route.
A vessel can be chartered from any loading port in Norway, this means that the distance for traveling from the origin of the ship to its first port where the load is picked up is equal to 0. It is also required that the vessel ends up at the same port where it started. This way no matter how many different routes a vessel chooses to take the total distance traveled will be the sum of the distances of all chosen routes. The distance of a round trip is therefore equal to the distance of the first loading port to the delivery port and back to the first loading port of the route.
The time it takes to from visiting the first port until leaving the delivery port in Europe is the same expression as above, but excluding the time it takes to sail back to the origin and is defined in Equation 6.5.2 below.

$$T_{rv}^{DEL} = \frac{Dist_r}{2 * Vl_v} + \sum_{i \in I} T^D * A_{ir} + T^D + \frac{2 * Q_v}{R} \qquad i \in I, r \in R, v \in \tag{6.5.2}$$

To account for uncertainty in weather conditions the sailing time in the model will be increased by 10%.

6.5.1 Age of the salmon

The age of the salmon is calculated at two different points. The first point when the age of the salmon is relevant is at the production port when the fish is loaded FAL_{irv}. Having a constant production rate at all ports the age of the first slaughtered salmon is the amount Loaded divided by the production rate at the port as described in Equation 6.5.3, where the production rate equals the production divided by the time period.

$$FAL_{irv} = \frac{L_{irv}}{D_i^{PRO} / T^{TOT}} \tag{6.5.3}$$

since the age at pickup is equal at every port the fish age at pick up is independent of the port

and can be described as below instead.

$$FAL_{rv} = \frac{Q_v}{\sum_{i \in I} * A_{ir} * D_i^{PRO} / T^{TOT}} \tag{6.5.4}$$

To calculate the age of the oldest fish at delivery in Europe FAD_{rv} one will firstly find what age each of the different loads has at the last point of loading, which means taking into account the time spent between the pickups of the fish. In this case, however, the age of the fish at pickup is equal at each port, resulting in the fish picked up at the first port visited being the oldest. The age of the oldest salmon at delivery will, therefore, consist of the time it takes to deliver the salmon from the first port to the destination port seen in Equation 6.5.2 and the age of fish picked up at the first port presented in Equation 6.5.4 creating the following expression 6.5.5.

$$FAD_{rv} = FAL_{rv} + T_{rv}^{DEL} \tag{6.5.5}$$

6.6 Cost of trailers

Based on TØI-2016 [13] cost of transporting the salmon from either a delivery port j or a production port i to the end customer k will depend on the distance, time spent, ferries used and toll on the roads. The time-dependent cost consists of the capital expenses of the trailer, driver wages, insurance, administration, and fees. The distance-related cost occurs based on the distance the trailer will travel, which impacts the cost of maintenance and fuel. To transport salmon a thermo-trailer will need to be used in order to keep the fish at the desired temperature. Extra machinery is needed to cool the salmon, which leads to higher capital expenses and higher fuel consumption, than regular trailers of the same size.
The cost of transporting a trailer with salmon will be defined in Equation 6.6.1.

$$Trailertransportationcost = Distancecost + Timecost + Ferrycosts + Tollcosts \tag{6.6.1}$$

In this case, the cost of loading and unloading the trailer is not taken into consideration, because this cost will occur for the sea transport alternative as well and is therefore not relevant for the

comparison between the two transport alternatives.
The distance in Equation 6.6.1 is the total distance the trailer has to drive to reach its destination, this means that distance traveled on ferries is not included. The time the trailer is in use is the time the vehicle is driving, which means it is the distance divided by the average speed on the entire route. The time-dependent cost will vary from country to country, because of different wages. On average a thermo-trailer costs 356 NOK per hour in Europe, while it costs 500 NOK per hour in Norway [23]. All distances considered have its end destination outside of Norway, therefore it is assumed that all routes are operated by European trailer operators, with a time-dependent cost of 353 NOK per hour. The distance-dependent cost is set to 6,55 NOK per km.
Shells eToll-calculator [36] was used to generate distance and toll for each route. The distance calculated is the total distance traveled excluding the distance traveled at sea with ferries. The time the vehicle is in use is based on the distance in each country and the average speed in these countries. In chapter 2, the trailer speed used was based on the speed limit and delays caused by traffic were not considered. This was considered unrealistic and therefore the average speed for trailers outside of Norway and Sweden is set to 74.43 km/h, which is based on the speed used in the TØI report [43]. For Norway and Sweden, this speed seemed too high and was therefore set to 70 km/h.
On the trailer routes from the ports in Europe to the end customer, no ferries were used and therefore no additional cost occurred. The only route which did not use a ferry from Norway to Europa was the routes from Norway to Kolding in Denmark. The routes from Norway to Bourges, Rome, Madrid, Leicester, Erfurt, and Eindhoven uses the ferry from Rødby in Denmark to Puttgarden in Germany at a cost of 2058 NOK per Trailer [33]. The routes from Norway to Lodz use the ferry from Gedser in Denmark to Rostock in Germany at a cost of 2331 NOK per trailer [33]. The longest sea passage used on a trailer route is from Norway to Siauliai, where a ferry is used between Nynashamn in Sweeden and Ventspils in Latvia at a cost of 6912 NOK per trailer [11].

All calculations for the trailer related costs were done in Excel and can be seen in Appendix E. The costs presented are the cost of using a single trailer. In the model, however, these costs are simplified to a cost based on tons of salmon transported. The costs presented in Appendix E are therefore divided by the salmon capacity of the trailer.

6.7 Shipping costs

The cost of using a vessel is categorized into the capital cost (CAPEX), operational cost (OPEX) and voyage cost (VOYEX). In this thesis, the cost will be divided into fixed costs and variable costs, where capital costs and operational costs are considered fixed, while the VOYEX is considered variable. A shipment by sea requires much higher volumes of salmon than transporting it with trailers, this means that one will also need to consider costs associated with storing the salmon, which will be included in the variable costs.

To acquire a ship one can either charter a vessel from a shipowner or buy a vessel. There are different chartering possibilities, but in this thesis, we will focus on the time charter option. In a time charter, a shipowner will charter the vessel for a given amount of time to a charterer at a daily charter rate. The shipowner is in this case responsible for Capital costs and Operational costs. The charterer will be responsible to pay the daily charter rate to the shipowner and any voyage costs, which includes fuel costs and port dues. Off-hire duo to maintenance will only affect the shipowner [18].

In Appendix F, most vessel-related costs are estimated, but there are also further calculations done in Matlab shown in Appendix G and some are calculated directly in the implemented model in Xpress presented in Appendix B.

6.7.1 Fixed Costs

As mentioned above the fixed costs will be calculated differently depending on if one decides to charter or to buy a vessel.

Time charter option

The daily time charter cost for different vessel sizes is presented in Appendix F. With linear interpolation, the average charter cost for all vessels considered in the model is estimated. One can, however, assume that the engine size of the vessel will have an impact on the capital costs as well. In the presented database in Appendix D we have that the average service speed of the considered vessels lay at 19 knots. The chartering cost presented in [30] is the average cost of chartering a RoRo-vessel of a given size segment in 2015. One can, therefore, assume that these prices are representative for an average engine size. One should, therefore, make an estimate of how a bigger or smaller engine would impact the chartering cost. In [2] the price of an engine is estimated to be 2500 to 3500 NOK per Horsepower in the year 1999. Based on a cost of 3000 NOK per BHP in 1999 this would be equal to 4211 NOK per BHP in today's market, using the inflation rate in this time period. The Capital Recovery Factor is used to calculate the annual capital costs [13] and is shown in Equation 6.7.1, where a represents the annual interest and n represents the expected lifetime. The interest is set to 8% to account for the broker's return and the risk, while the expected lifetime is set to 20 years. Having an estimate on the required engine effect of each vessel the annual capital cost of the engine can be calculated with Equation 6.7.2.

$$CRF = \frac{a * (1+a)^n}{(1+a)^n - 1} \tag{6.7.1}$$

$$annualEnginecost = Enginecost * CRF \tag{6.7.2}$$

The daily chartering cost can then be adjusted for vessels having servicing speeds lower and higher than the average. Additionally, yearly piloting preparedness taxes of 75,71 NOK/GT for each vessel have been included in the calculated daily costs as discussed later in section 6.7.2. The estimated daily charter cost can be seen in Figure 6.2.

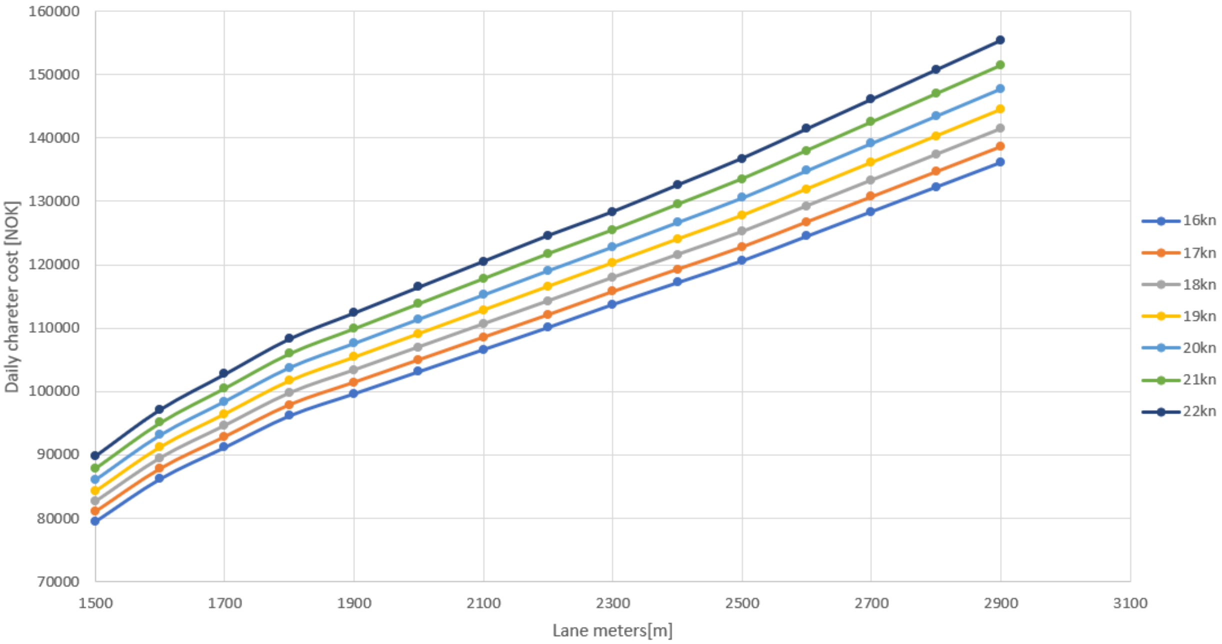


Figure 6.2: Daily charter cost for each vessel

Shipowner option

The Capital costs for a vessel is calculated with the Capital Recovery Factor, but in the case of being a shipowner, the interest a represents the annual interest for the loan, either by investors or the bank. Broker return and risk are not included in these interests so one can expect it to be lower than in the time charter option. With a given cost for the vessel, the annual CAPEX can be calculated as the annual engine cost in Equation 6.7.2. To get the daily Capital cost one will need to divide the annual CAPEX by the number of days the vessel is operational, which are the total number of days a year minus Off-Hire days for maintenance.

Operational costs are based on the 2018/19 annual report on ship operating costs by *Drewry* [9]. The Operational costs can be divided into manning, insurance, stores, spares, lubrication oils, repair maintenance, dry-docking and management administration as presented in Table 6.4. The manning is dependent on the vessel and will vary mostly dependent on the size of the vessel. On average the cost of a crew member on a RoRo-vessel is in total 140 Dollars consisting mainly of wages and other costs shown in Table 6.5. *Drewry* only estimates the operational cost for one size segment of Ro-Ro vessels. So no numbers are given for the different size segments of RoRo-vessels. To estimate the operational costs of different sized RoRo-vessels one can look at the manning requirement and calculate the manning cost based on this. When looking at other ship types presented one can see that the operational cost will increase based on the capacity. The Operational cost per capacity of the vessel will, however, be smaller for bigger vessels than for smaller vessels. This means that the operational cost does not increase linearly with the vessel capacity.

Table 6.4: Daily Operational cost for RoRo-vessel with 10000dwt

Type	Cost per day
Manning	2740
Insurance	290
Stores	250
Spares	310
Lubricating Oils	340
Repair & Maintenance	180
Dry Docking	350
Management & Administration	550
Total	5010

Table 6.5: Average daily Manning cost per crew member

Wages	110
Victualling	10
Travel	10
Miscellaneous	10
Total	140

From the database created on RoRo-vessels in Appendix D the average crew size of vessels from 1500 lane meters to 2000 lane meters lays at 13.4 men, while it lays at 16.7 men for vessels from 2000 to 2900 lane meters. The manning cost for the different vessels can, therefore, be adjusted based on the size of the vessel. The other operational costs will most likely also depend on the size and speed of the vessel. How the cost is affected by the size and speed could be estimated by using data of other vessels presented in *Drewry*, where costs of different sizes and speeds are given. This would give an indication of how to scale the RoRo costs presented in Table 6.4. This will however not be explored any further, because the model in this thesis will be based on time chartered vessels, where the operational costs will be included in the charter rate.

6.7.2 Variable costs

The variable shipping costs consist of fuel costs, costs related to port visits and storage costs and is dependent on the route and the vessel used and is described in Equation 6.7.3, where FC_{rv}, PC_{rv} and $SCrv$ are the fuel cost, port cost and storage cost on round trip r for vessel v.

$$C_{rv}^{VAR}[NOK] = FC_{rv} + PC_{rv} + SC_{rv} \tag{6.7.3}$$

Fuelcosts

To be able to estimate the fuel costs on a round trip for a vessel one will need the fuel consumption of the vessel, the price of the fuel, taxes on the fuel and the distance of the round trip.
The fuel consumption for each vessel will be based on the Equation 6.7.4 presented below [13].

$$FuelConsumption_v[\frac{l}{km}] = 0,15 * enginePower_v[HP] * \frac{1}{Speed_v[\frac{km}{h}]} * (1 + 0,15) \tag{6.7.4}$$

The fuel consumption is dependent on the installed engine effect of the vessel and its speed. The load at which the engine is driven will also influence the fuel consumption, but it is assumed that the engine is loaded at 80% of its capacity when it is in use. To take fuel use of auxiliary engines into consideration the total fuel consumption is increased by 15%. The estimated engine effect for each vessel can be seen in the excel sheet in Appendix F.

Based on the fuel consumption for each vessel the fuel cost for each route can be estimated based on the distance and the cost of the fuel. The fuel cost consists of the price for the Marine diesel oil, NO_x, SO_x and CO_2 fees. The NO_x fees are based on the amount of NO_x emitted, which variate depending on the age of the engine and the speed(RPM) of the engine [15]. All vessels included in the database are built before 2011 and most of the vessels have an RPM around 500, which means the emissions for all vessels can be estimated to $12,9843\frac{g}{kWh}$. Since these emissions are based on the time the engine is in use and the power of the engine in kW, one can divide it by the speed in km/h of the vessel and multiply it with the installed engine effect in kW. With the fee of each emitted kg of NOx being $22.27\frac{NOK}{kg}$ [40]. This way one will get a NOx cost per km as seen in Equation 6.7.5, which can be included in the other fuel-related costs.

$$\begin{aligned} NO_xCost_v[NOK/km] = \\ NO_xEmission[\frac{g}{kWh}] * Speed[km/h] * 0.8 * enginePower_v[kW] * NO_xTax[\frac{NOK}{g}] \end{aligned} \tag{6.7.5}$$

The CO_2 fee is $1.35\frac{NOK}{l}$ for diesel, while the SOx fee is 0,1355 NOK/l for each started 0.1% of sulfur content. The routes all lay in the SECA region, which regulates fuel oils used to contain less than 0.1% sulfur [16]. To accomplish this one will need to use Low Sulphur Fuel Oils(LSFO) or install scrubbers which cleans the exhaust for sulfur. Alternative fuels like LNG can also be used. For simplification, it is assumed that all vessels use Marine Gas Oil(MGO) which is an LSFO with sulfur contents lower than 0.1%. This means that no SOx fee needs to be paid. The current price lays at 609,5 $\frac{\$}{mt}$ of MGO in Rotterdam [37]. With a dollar costing around 9NOK and an average fuel density of $860\frac{kg}{m^3}$ the price of the fuel lays at 4.72 $\frac{NOK}{l}$ without taxes and $6.07\frac{NOK}{l}$ with CO_2 taxes. The total fuel cost per km for each vessel can be described by Equation 6.7.6

$$\begin{aligned} TotalFuelCost_v[NOK/km] = \\ FuelConsumption_v[l/km] * (FuelPrice[NOK/l] + CO_2Tax[NOK/l]) + NO_xCost[NOK/km] \end{aligned} \tag{6.7.6}$$

The total fuel cost per km including all fees for each vessel is shown in Figure 6.3 below.

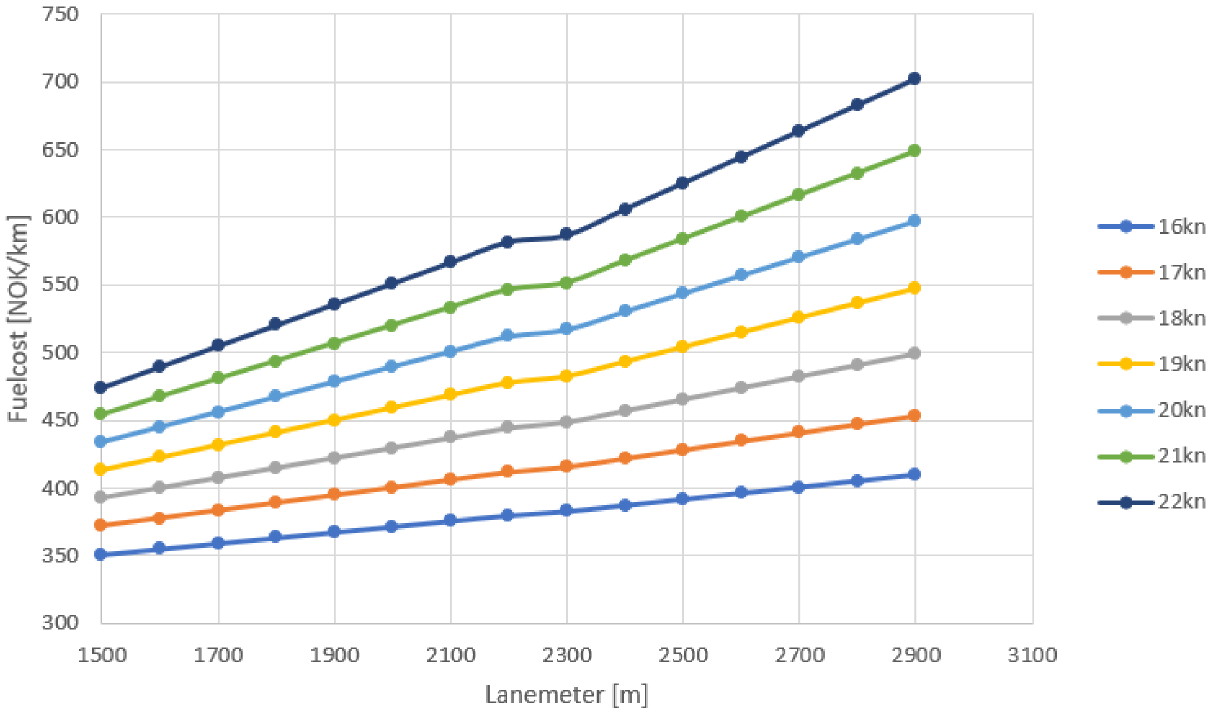


Figure 6.3: Distance fuel cost for each vessel

The estimated installed engine effect for each vessel is based on two regression models, one for vessels below 2200 LM and one for vessels above 2300 LM, which crates the misalignment seen between 2200 LM and 2300 LM. This is most noticeable for vessels of higher speeds.
Lastly, the total fuel cost for each round trip and vessel is calculated in Equation 6.7.7, with TotalFuelcost beeing dependent on the vessel v used and the distance being dependent on the round trip r chosen.

$$FC_{rv} = TotalFuelCost * Distance \tag{6.7.7}$$

Port costs

The port charges for a round trip will depend on how many ports are visited and the amount of product loaded/unloaded at each port. The port charges consist of the charges listed in 6.7.2.

- Calling fee
- Wharfage fee
- Cargo fee
- ISPS fee
- Garbage disposal
- Rental of Port equipment

The calling fee and the wharfage fee are mostly dependent on the size of the vessel in gross ton (GT) and will occur at each visit of a port. The cargo fee depends on the type of product that is loaded/unloaded and the amount of product in tonnes, it is given as a cost per ton of product loaded and unloaded. ISPS charges are to be paid at each port visit and can be set in form of a fixed amount, an amount dependent on the size of the vessel in gross ton or dependent on the calling fee or wharfage fee. The garbage disposal is a relatively small cost that is paid for the amount of garbage disposed of in form of regular garbage and oil. To load or unload the vessel port equipment must be rented at a cost per ton loaded or unloaded. Traffic fees are only applicable for vessels transporting goods from outside the EØS region, Passenger fees will not apply since it is not a passenger ship and it is assumed that icing is of little concern at the considered ports, which leads to the icing fee not being considered.

Since all vessels considered are bigger than 8000 GT Piloting taxes must be paid when sailing close to shore [1], which will happen when entering or leaving a port. The piloting tax consists of a piloting preparedness tax and costs of hiring a pilot for the area. Since the vessel is traversing between all the ports relatively frequently it is assumed that all vessels will have a navigator with a fairway certification for each port the vessel will visit. This will allow vessels that require piloting to enter ports without hiring an external pilot at each port.

It is expected that vessels will visit ports in Norway very frequently and the piloting preparedness tax should, therefore, be paid on a yearly basis instead of per visit, which amounts to 75,71 NOK/GT a year for vessels bigger than 10000 GT. This cost is therefore included in the fixed cost of each vessel. Some regions in Norway have an additional security fee in the region of Oslofjorden and Rogaland. No ports in this model are located in that area, which means that this will not be considered further.

The port charges in Norway are based on the average of 11 Norwegian ports [13] and the port costs at the ports in Europe are based on the charges at Bremerhaven. The cargo fee and cost of equipment rental for all ports in both Norway and Europe are based on the average cost of the 11 Norwegian ports. The average cargo fee for fresh fish of the 11 Norwegian ports lays at 12,8 NOK per ton loaded/unloaded. Renting a Tugmaster with driver costs around 2000 NOK per hour and uses on average 5 minutes to load or unload a trailer. This means that the average cost per trailer unloaded is 166.66 NOK. With each trailer loaded with 19 tonnes of salmon, this gives an additional cost of 8.77 NOK per ton of salmon loaded/unloaded. The total loading/unloading charge is therefor 21.57 NOK per ton. Since the model is formulated in such a way that the vessel will only sail to Europe fully loaded, the cost on a round trip for a given vessel capacity can be described as seen in Equation 6.7.8.

$$Load/UnloadCost_v[NOK] = 21.57[\frac{NOK}{ton}] * Q_v[ton] * 2 \tag{6.7.8}$$

The capacity of the vessel Q_v is defined as the capacity of salmon a vessel can take. Since the vessel is both loaded and unloaded on a round trip the expression is multiplied by 2.

It was found that the average total cost of the calling fee, wharfage fee, and ISPS at the 11 ports in Norway lay at 0.99 NOK/GT per visit for vessels between 10000GT and 20000 GT. For Bremerhaven, these costs were found by using the integrated calculator given on their website [4]. Since each route can consist of one, two or three port visits in Norway and one port visit in Europe, routes can either consist of two, three or four ports. Figure 6.4 illustrates the total port costs for round trips consisting of two, three and four ports.

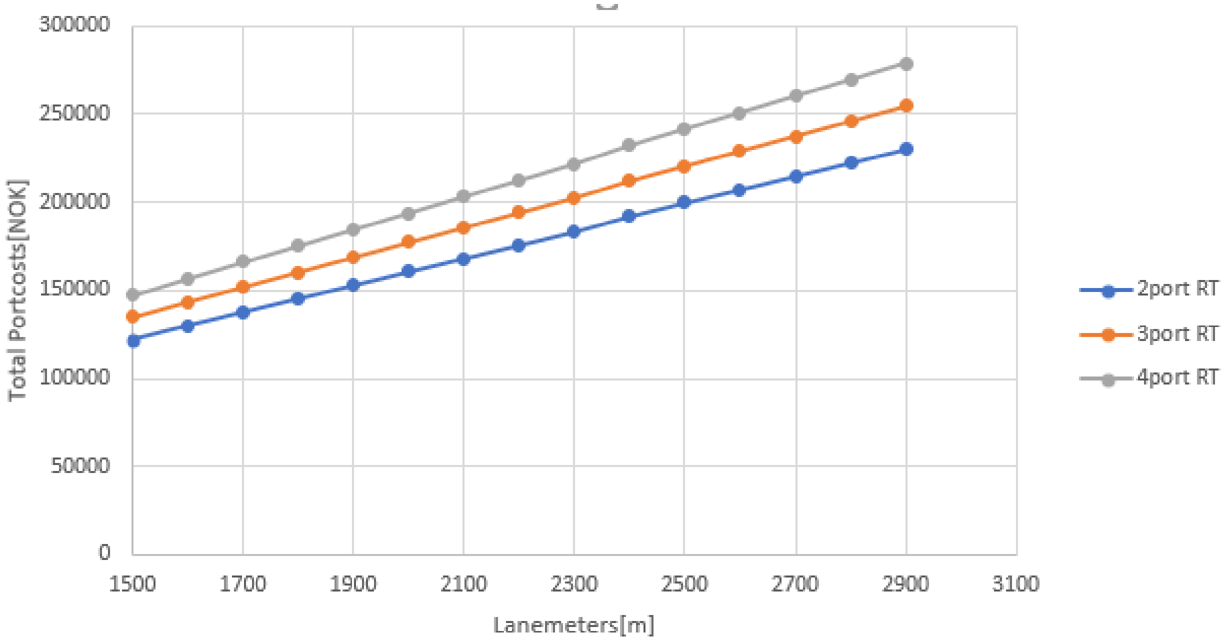


Figure 6.4: Round trip port costs

Port costs for each round trip and vessel can be formulated as seen in Equation 6.7.9, where $PortCostNOR_v$ and $PortCostEU_v$ represent the cost of visiting a port by vessel v excluding the load/unload related cost in Norway and Europe respectively. While $Load/UnloadCost_v$ is the cost related to loading and unloading the vessel on the entire round trip.

$$PC_{rv} = \sum_{i \in I} A_{ir} * PortCostNOR_v + PortCostEU_v + Load/UnloadCost_v \tag{6.7.9}$$

Storage costs

When having big amounts of salmon being slaughtered for one shipment and relatively low slaughtering rates, the time between the first fish was slaughtered until enough volume has been generated for a ship to pick it up can be multiple days. Therefore the fish must be stored in cooled areas until it is ready for transport. Storage space for each ton of fresh salmon costs on average 9769 NOK a year, which equals 0.2842 NOK per hour. The time from, when the first salmon was slaughtered until the vessel arrives FAL_{irv} was described earlier. With a constant slaughtering rate, the fish ready for pick up has an average age of $1/2 FAL_{irv}$ and that the amount stored on average throughout this time equals half of the amount that will be loaded at this port L_{irv}. Predefining the amount loaded at each port as in Equation 6.4.1 the age of the salmon at pick up FAL_{irv} is identical at each port. Therefor the storage cost for each round trip and vessel can be calculated as followed:

$$SC_{rv}[NOK] = 0.2842[\frac{NOK}{ton * h}] * Q_v[ton] * 1/2 * FAL_{rv}[h] \tag{6.7.10}$$

Since the average age of the salmon at pick up is equal at all the ports one can use the capacity of the vessel instead of calculating the costs at each port.

Chapter 7

Computational Study

The mathematical problem description presented in chapter 5 was implemented and solved in Xpress-IVE presented in Appendix B.

7.1 Model description

The model is run for multiple different scenarios presented in this chapter. To run a given optimization scenario the text file called ”InputData.txt”, with input for the scenario is read in. All the results are based on 3 production ports in Norway and 3 delivery ports in Europe with a total of 21 different routes presented in Table 6.1. The production and demand is for each scenario based on the values presented in Table 6.2 and scaled up and down for different production scenarios. The set of customers is unchanged from what is presented in Table 6.2 in every calculation. Varying input parameters are the set of vessels used based on the 105 different RoRo-vessels available with speeds ranging from 16 to 22 knots and capacities ranging from 1500 to 2900 lane meters. A Matlab script is used to calculate new parameters for the input file based on the selected vessels and is shown in Appendix G. The parameters in the text file that must be updated are ”nVessels”, ”Chartercost”, ”VesselSpeed”, ”Capacity” and ”VarCost” based on the set of vessels used. An example of the ”InputData.txt” file is presented in Appendix I. Data presented is for a set of one vessel with a speed of 19 knots and a capacity of 1900 LM

The model is formulated in such a way that the produced salmon in Norway can be handled either by trailers transporting the fish directly to the costumers or by vessels, which transport the salmon to a delivery port in Europe. From the delivery port in Europe, the salmon will be transported to the different end costumers. The objective of the model is to minimize the cost, which means that any feasible sea born solution which has a higher cost than the alternative land-based transport will not be considered. This means that the highest objective cost will be defined as the cost of transporting all the produced salmon by trailer, which only varies with different production rates. To better be able to compare the results of different scenarios this cost, therefore, represents a cost of 100%.

7.2 Impact of capacity and speed

The model is run for vessels of 1500 LM, 1900 LM and 2900 LM with a sailing speed of 19 knots and varying limits on the age of the salmon at delivery. In Figure 7.1 3 graphs are presented. Each of the graphs represents a vessel type. Since the model is formulated in such a way that vessels only will be used if they cost less than transporting the salmon directly by land. Using today's production and demand numbers presented in Table 6.2 and Table 6.3 respectively the minimum cost of transporting all the salmon from Norway to Europe by trailer becomes 40,429,849 NOK, which represents the upper limit of the objective cost.

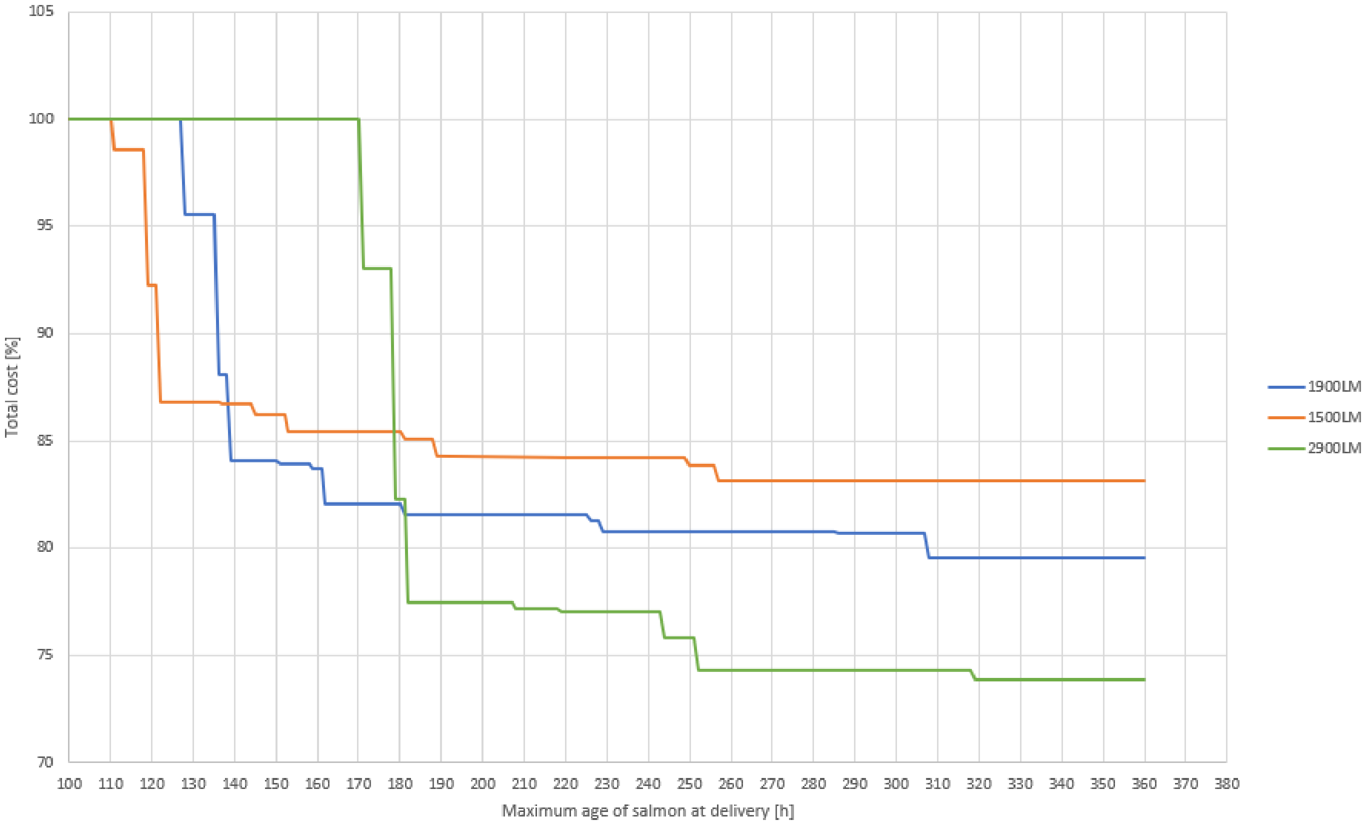


Figure 7.1: Plot of optimal solution for varying MFA at different vessel capacities

When looking at the blue graph which represents vessels of 1900 lane meter at a sailing speed of 19 knots, one can see that the total cost lays at 100% as long as the age limit of the salmon at the delivery port (MFA) is lower than 128 hours. This means that all combinations of routes and fleet sizes of this type of vessel come at a higher cost than the land-based transport option, or that the solution is infeasible because the selected solution does not fulfill all the constraints. One can see that the older the fish is allowed to be at delivery the better the solution becomes. The graph is decreasing stepwise, with the objective value staying constant for a range of delivery time limits. Using vessels with lower capacity decreases the MFA limit down to 111 hours, while the seaborne alternative only becomes profitable for high capacity vessels at 2900 LM at 171 hours. Since the amount loaded is linked to the capacity of the vessel and the amount loaded again is linked to the age of the salmon at pick up, this leads to high capacity vessels needing a high MFA limit while low capacity vessels need lower limits in order to get feasible solutions. Considering those 3 vessels, having a MFA limit between 111 hours and 138 hours, the 1500 LM vessel will give the lowest cost, while the other vessels either have infeasible or worse solutions at this MFA limit. At the point where the graph between the 1500 LM vessels and the 1900 LM vessel intersect at 138 hours, the mid-sized vessel becomes more profitable, while the high capacity vessel becomes the most profitable after the MFA exceeds 182 hours. The high capacity vessels perform better at higher MFA limits while low capacity vessels perform best when the age of the salmon needs to be low at delivery. This is because the cost of each ton transported will shrink with increasing vessel size.

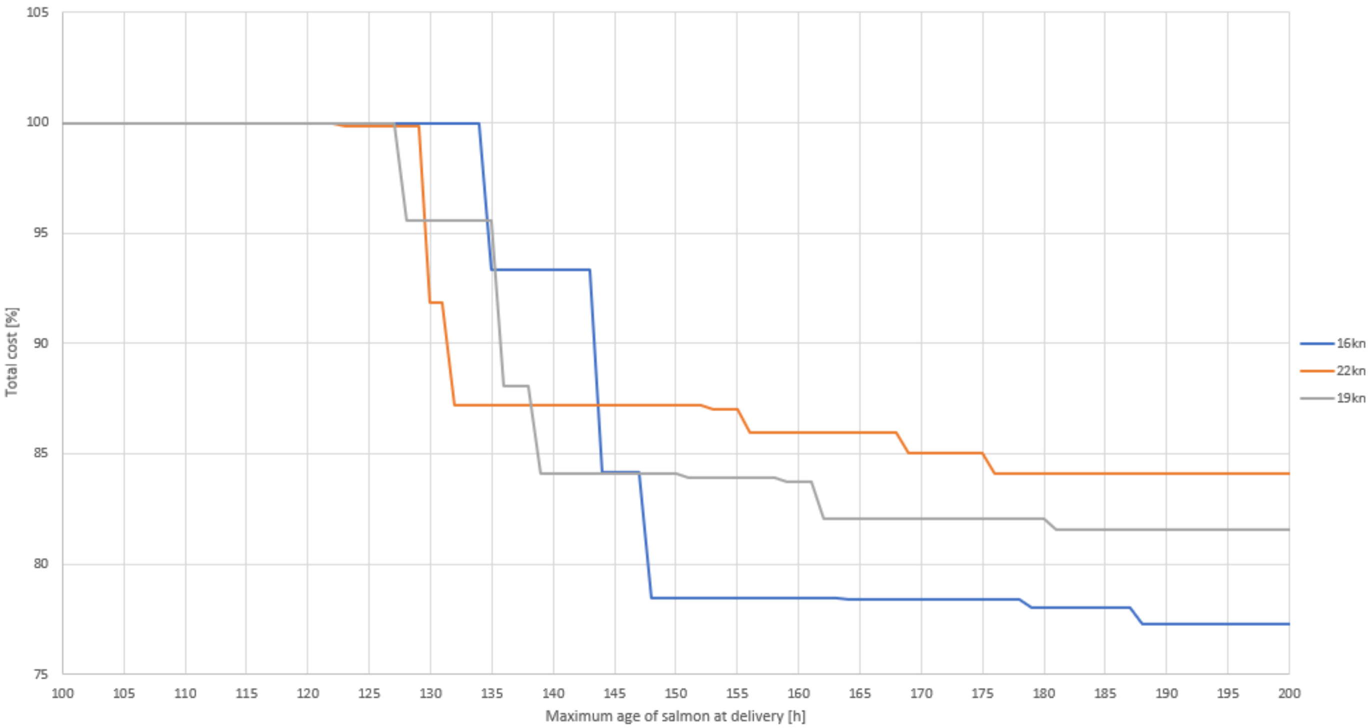


Figure 7.2: Plot of optimal solution for varying MFA at different vessel speeds

Similarly when comparing vessels of the same size with different speeds as presented in Figure 7.2 to each other one can see a trend of high speeds reducing the needed MFA, while low speeds increase the MFA. Having a faster-going vessel will decrease the sailing time and the age of the salmon at delivery, but the fuel costs of the vessel will be higher which leads to worse-performing solutions at high MFA limits.

To investigate how the solution will differ when increasing the MFA limit. Four specific solutions of the vessel at 1900 LM with a speed of 19knots are inspected in Table 7.1 below.

Table 7.1: Optimal solutions for vessels of 1900 LM at 19 knots at 4 different ranges of the MFA

Solution	A	B	C	D
Range of MFA[h]	128-135	139-150	184-225	308-360
Nr of Vessels used	1	1	1	1
Routes used for each vessel	R-H-Å-HH	R-H-Å-HH R-H-Å-B R-H-Å-I	R-H-B R-H-I H-Å-I	Å-B R-I H-I H-Å-I
Nr of times each route is traversed	7	1 1 4	1 4 1	2 2 2 1
Total Cost [NOK]	38636309	33995974	32973657	32167234
Fraction transported from Norway[%]	26.5	37	37	26.5
Variable shipping cost [NOK/ton]	521.9	623.6	630.9	549.3
Fixed shipping cost [NOK/ton]	163.5	190.7	190.7	163.5
Cost of further transportation [NOK/ton]	1000.4	595	603.5	595.3
Total seaborne transport cost[NOK/ton]	1685.8	1409.3	1425.1	1308.1
Trailer Cost Norway [NOK/ton]	1260.7	1341.3	1202	941.4

All seaborne solutions use only one vessel. Solution A uses one route only a total of 7 times, containing all ports in Norway, which minimizes the age of the salmon at pickup. The delivery port of the route is Hirtshals and is the port located closest to the ports in Norway. This means that the chosen route is the route which gives the lowest possible age of the salmon. Solution B also uses routes containing all ports in Norway, but delivery is done to all 3 ports in Europe, where Ijmuiden is the most visited delivery port. In solution C and D the MFA limit becomes so high that routes containing only 2 or 1 ports in Norway become feasible. Since solution A and D manage to take more round trips than B and C, more product is transported by sea with solution A and D. With each solution having roughly the same time at sea the total variable cost does not differ too much, but the variable cost per ton transported will be higher for B and C because fewer round trips are made. When comparing A to D and B to C fewer ports are visited on a round trip for higher MFA limits, which leads to somewhat lower port costs, but also higher sailing costs, because less time is used at ports. This overall leads to a slight increase in the variable cost per round trip for increasing MFA limits. The fixed shipping costs are equal for all vessels and therefore the fixed shipping cost per ton transported will decrease the more round trips are taken. The cost of each ton transported from the delivery port to the end customers is very high for solution A compared to the rest. This is because the other solutions use delivery ports located closer to the end customers.

7.3 Optimization Results

The future of the fish farming industry is uncertain as explained in chapter 2. Therefor investigations were made on how different production amounts would impact the cost of a seaborne alternative. New storage technologies like super chilling will also have an impact on the model since this will increase the time available to deliver the salmon. The model was run for a future scenario, where the production of salmon either increased, decreased or stayed at today's level. For each of the production scenarios at a MFA limit of 4, 5, 6 and 10 days. With fresh fish having a shelf life of 10 days a maximum fish age of 4, 5 and 6 days were used as restrictions to investigate how the solutions would differ. When using super chilling technology the shelf life of the salmon is increased to 20 days and a MFA limit of 10 days was chosen, since allowing later delivery only gave marginally lower transportation costs for the vessels and ports considered.

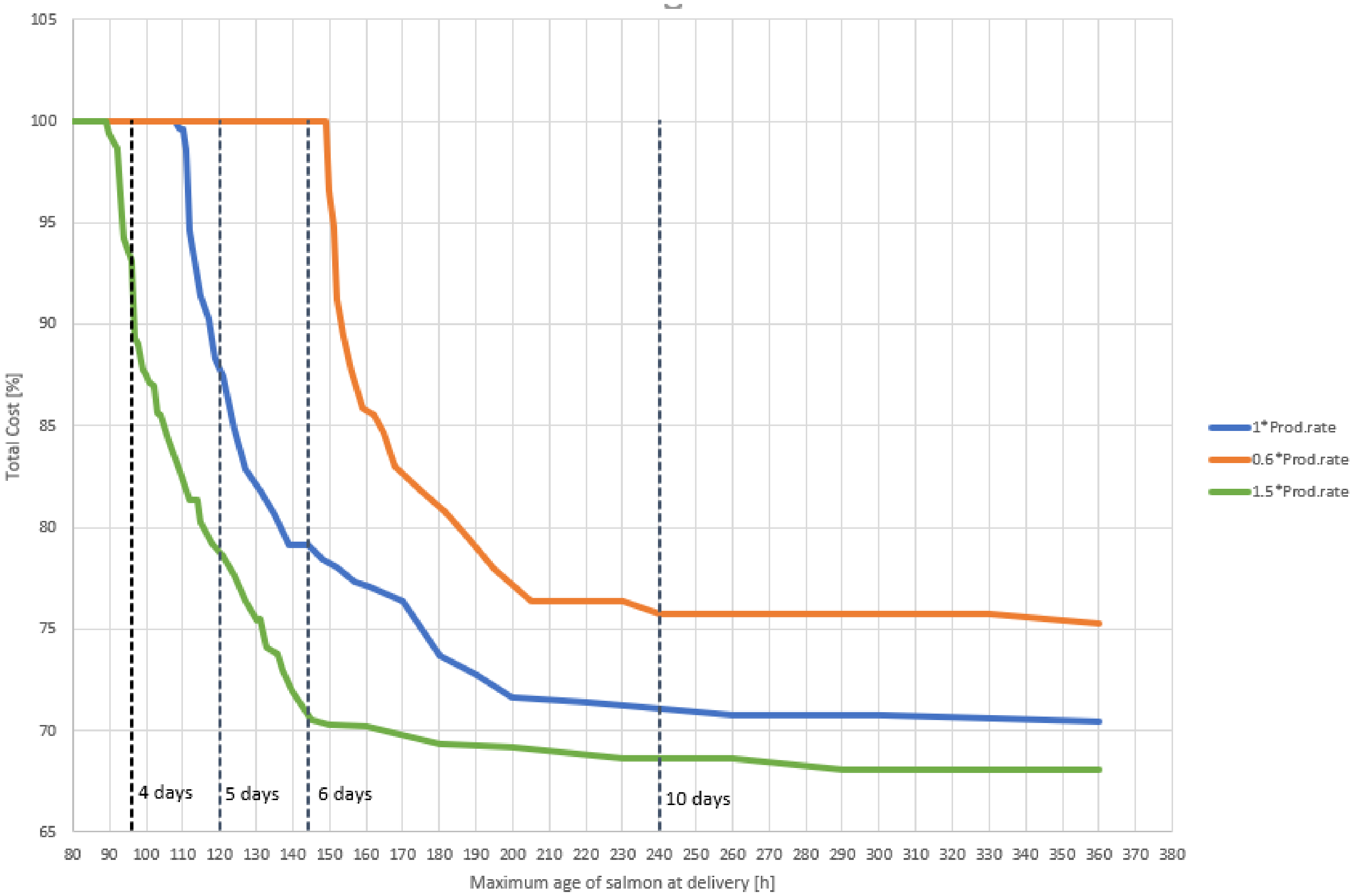


Figure 7.3: Plot of optimal solution at all production scenarios

In Figure 7.3 the fractional minimal total cost for a given production rate is plotted against MFA limits ranging from 80 to 360 hours. The total cost of having a lower than normal production is plotted as the orange graph and is set to 60% of today's production. The blue graph represents a normal production and the green graph represents a higher than normal production set to respectively 100% and 160% of today's production. The production and demand at all ports and customers are adjusted accordingly by a factor of 0.6, 1 and 1.6. The results presented are based on a set of 105 vessels ranging from 1500 to 2900 lane meters and speeds ranging from 16 to 22 knots.

7.3.1 Normal Production scenario

At today's production rate a seaborn solution will be competitive compared to land-based transport when restricted to deliver the salmon before 5,6 and 10 days since it was first slaughtered. The total amount of salmon produced in this scenario equals 24560 tonnes of salmon. With a land-based transportation cost of the entire production of 40,429,849 NOK. In Table 7.2 the optimal solution at each MFA limit is presented.

Table 7.2: Optimal solutions at different MFA limits for the normal production scenario

Delivery within:	4 days	5 days		6 days		10 days
Nr of Vessels used	-	1	1	1	1	1
Vessel Speed [kn]	-	19	20	16	16	16
Vessel Capacity [lane meters]	-	1500	1500	1800	1900	2900
Routes used for each vessel	-	R-H-Å-HH R-H-Å-B	R-H-Å-I	R-H-Å-I	R-H-Å-HH R-H-Å-B	R-Å-HH R-H-I R-H-Å-I
Nr of times each route is traversed	-	1 4	6	5	1 3	1 2 2
Total Cost [NOK]	40429849	35710439		31999334		28749933
Fraction transported by sea [%]	0	91.2		91.7		80.1
Variable shipping cost[NOK/ton]	-	733.1		535		406.5
Fixed shipping cost [NOK/ton]	-	213		243.4		193.8
Cost of further transportation [NOK/ton]	-	565.78		564.85		572.2
Trailer Cost Norway [NOK/ton]	1646.2	854.06		857.3		1163.1

At a MFA limit of 5 days, two low capacity vessels are used, with moderate sailing speeds. The routes chosen, all consist of all 3 ports in Norway and are delivering to all 3 ports in Europe. The first vessel with a slightly lower speed delivers 1 time to Hirtshals and 4 times to Bremerhaven, while the second vessel visits Ijmuiden a total of 6 times. An increased MFA of 6 days gives an optimal solution also containing a fleet of two vessels, but where both have a higher capacity and a lower sailing speed. The same routes are used as before, but visits have changed from 6 to 5, 4 to 3 for Ijmuiden and Bremerhaven respectively. At a 10 day limit, the fleet size shrinks to one vessel with a high capacity going at low speed. The routes chosen do consist of both two and three ports in Norway, but delivery is only done to Hirtshals and Ijmuiden, with 1 and 4 visits respectively. For a MFA limit of 5,6 and 10 days, the total cost of transporting can be reduced by 4,719,410 NOK, 8,430515 NOK, and 11,679,916 NOK compared to transportation on land. Comparing the optimal solutions at a MFA of 5 and 6 days directly, one can see that both options transport about the same amount of salmon. More time to deliver the salmon allows bigger ships and slower ships to be used, which results in fewer round trips and lead to a decreased fuel cost and reduced port costs relative to the amount shipped, but slightly higher storage costs. The total variable cost will however shrink. Reducing the service speed will reduce the fixed costs slightly needing less installed motor effect, the increase in capacity of the vessels will though lead to the fixed costs to increase overall. There is no significant difference in the cost of transporting the salmon from the delivery port to the end customer, and from the production port in Norway to the end customer, because similar routes are used and similar total amounts are distributed between the ports in Europe. Increasing the MFA limit to 10 days results in a reduction in the fleet size to only one vessel with a high capacity of 2900LM, which again reduces the number of round trips, altogether reducing the variable cost per ton transported even further. Selected routes consist of fewer ports which result in fewer ports visited on average for each round trip which also reduces the variable cost. A vessel is used with a higher capacity which increases the fixed costs per vessel, but since the fleet size is reduced to half the fixed cost per ton will shrink. Fewer round trips result in the load being less evenly spread to the delivery ports. The cost of further delivery is minimized by costumers receiving product only from the port which has the lowest cost of transportation to the given customer. Therefor spreading the product less evenly can result in some delivery ports with more or less product than is needed for the costumers located closest to it such that some of the product is transported to customers not located optimally compared to the port, resulting in an increased price of further transportation. Since less product is shipped by sea more is needed to be transported by trailer to locations further away leading to an increased cost per ton transported from Norway.

Table 7.3 depicts the flow of the product at an MFA limit of 6 days between delivery ports and customers and the product flow between all ports in Norway to each customer. The results depicted in this table therefor give a deeper insight into the optimal solution found for delivering salmon within 6 days presented in Table 7.2.

Table 7.3: Amounts of product transported by trailer between the different locations with an MFA limit of 6 days

	Norway	Hirtshals	Bremerhaven	Ijmuiden
Bourges	-	-	-	3722
Lodz	403	307	4310	-
Rome	-	-	-	1734
Madrid	-	-	-	2852
Leicester	-	-	-	2530
Erfurt	-	-	1853	-
Kolding	-	2269	-	-
Eindhoven	-	-	1573	1376,9
Siauliai	1627	-	-	-

In Table 7.2 one can see that the port of Hirtshals is visited once by a vessel of 1900 LM corresponding to delivering about 2579 tonnes of salmon. Most are transported directly to Kolding in Denmark, while 307 tons are transported to Lodz in Poland. Bremerhaven is visited three times by the same vessel which visits Hirtshals, therefore delivering a total of 7736 tons of salmon. From Bremerhaven most of the product is sent to Lodz in Poland, the total demand of 1853 tonnes of salmon in Erfurt is delivered from Bremerhaven and the remaining load of 1573 tonnes is transported to Eindhoven in the Netherlands. Ijmuiden is the delivery port visited the most with a total of 5 visits with a slightly smaller vessel of 1800 LM. The total amount shipped from Norway to Ijmuiden corresponds to 12214 tonnes of salmon. From this port, the entire demand in Borges in France, Rome in Italy, Madrid in Spain and Leicester in England is supplied. Additionally, the remaining demand in Eindhoven is supplied from Ijmuiden. Remaining demand of 403 tonnes of salmon in Lodz is supplied directly from the production facilities in Norway, while the entire demand of 1627 of Siauliai in Lithuania is delivered by trailer from Norway.

In general, it can be seen that customers are served from the closest laying port or production facility. It can, however, be seen that some customers are serviced by ports or production facilities which lay further away. For instance, Lodz is serviced to some degree from Norway and Hirtshals and this is caused by the integer formulation of the shipping.

7.3.2 Low production scenario

With a low production of 14736 tonnes of salmon in total, no seaborne solutions were found for transporting fresh salmon by ship. A lower production rate, leads the time it takes to produce a shipload to increase, which leads to increased salmon age at delivery compared to a normal production. Transporting super chilled salmon increases the MFA to 10 days, at which point shipping the salmon by sea will be more cost-effective than land-based transport as seen in table 7.4.

Table 7.4: Optimal solutions at different MFA limits for the low production scenario

Delivery within:	6 days	10 days
Nr of Vessels used	-	1
Vessel Speed [kn]	-	16
Vessel Capacity [lane meter]	-	2500
Routes used for each vessel	-	R-H-Å-B R-H-Å-I
Nr of times each route is traversed	-	2 2
Total Cost [NOK]	24257909	18371865
Fraction transported by sea [%]	0	92.1
Variable shipping cost[NOK/ton]	-	453.72
Fixed shipping cost [NOK/ton]	-	248.8
Cost of further transportation [NOK/ton]	-	584.4
Trailer Cost Norway [NOK/ton]	1646.16	777.7

Compared to a normal production at a MFA of 10 days, for the lowered production the total cost reduction is reduced from 11,679,916 NOK to 5,886,044 NOK. This is a reduction of more than 40%, which means that the seaborne solution has a higher cost per ton produced than at a normal production amount, which also can be clearly seen in figure 7.3. The fractional cost reduction is more than 4% higher for the normal production.

7.3.3 High production scenario

With an increased production to 36840 tonnes, the amount transported also increases, which is reflected in the increased total cost for transporting all the product by land of 60,644,773 NOK. An increased production overall leads to the constant production rate to increase, which reduces the time it takes to produce enough load for a vessel to be able to pick up the load. This is reflected in the results, where it can be seen that even at a MFA of only 4 days a seaborne solution can be more profitable than the land-based alternative.

Table 7.5: Optimal solutions at different MFA limits for the high production scenario

Delivery within:	4 days	5 days	6 days	10 days	
Nr of Vessels used	2	3	2	1	1
Vessel Speed [kn]	21	16	16	16	16
Vessel Capacity [lane meter]	1500	1700	2200	2500	2600
Routes used for each vessel	R-H-Å-HH R-H-Å-B	R-H-Å-HH R-H-Å-B R-H-Å-I	R-H-HH R-H-Å-B R-H-Å-I	R-B H-Å-B R-I	H-Å-HH H-Å-B H-Å-I
Nr of times each route is traversed	2 11	2 4 9	1 2 7	1 1 3	1 1 3
Total Cost [NOK]	56492584	48065703	44859708	41620283	
Fraction transported by sea [%]	71,8	93.4	81	93.4	
Variable shipping cost[NOK/ton]	743.9	566	478.9	408.44	
Fixed shipping cost [NOK/ton]	186.1	222.6	206.6	199.46	
Cost of further transportation [NOK/ton]	695.36	556.3	549.2	549.4	
Trailer Cost Norway [NOK/ton]	1299.44	735.7	1144.8	740.1	

Same as for the normal production amount one can see an increasing vessel size, reduced speeds, and fewer round trips being taken at increasing MFA limits. Because more salmon is transported overall fleet sizes are in general bigger than for the normal production and total costs are higher. The costs are affected similarly as described for the normal production. The reduced costs for an MFA limit of 4,5,6 and 10 days are 4,152,189 NOK, 12,579,070 NOK, 15,785,065 NOK and

19,024,490 NOK respectively.

7.4 Summarized results

Table 7.6: Transportation cost per kg of salmon transported[NOK]

	Low Production	Normal Production	High Production
Trailer	1.646	1.646	1.646
MFA of 4 days	-	-	1.533
MFA of 5 days	-	1.454	1.305
MFA of 6 days	-	1.302	1.217
MFA of 10 days	1.247	1.171	1.130

One can generally see in Table 7.6 that seaborne transportation costs per kg of transported salmon, shrink with increased product and with extended time available for transport.

Trailer transportation flow for all the presented results above is presented in Appendix H.

Chapter 8

Discussion

In this chapter, the mathematical model and the results of the computational study will be discussed. It will also be discussed how the model can be adjusted in order to get more realistic results.

It was decided that all routes constructed should be based on the routing constraints and be independent on the vessel type. This way it was decided in the model if a route could be used by a vessel or not. One could predefine all routes in such a way that each vessel has a set of feasible routes. This way one would get a model with more sets, but fewer constraints overall and a simpler mathematical model. This would however also result in needing to generate new routes each time a small change was made to the model, which resulted in stricter or more relaxed perishable constraints. Running times of the model were in general very short even without defining feasible routes for each vessel. When running a more complex model with overall more feasible routes, the solving time of the model will increase and therefore predefined routes for each vessel will help to make the model run faster.

When comparing the price of each kg salmon in the different countries in Europe one can see a trend that prices for fresh salmon in countries laying further away from Norway are higher than in countries located closer to Norway. This implies that even though the salmon arrives at the store, with less time available for sale the price of the delivery is not affected. Therefore there was set a fixed time window, for the maximum age of the salmon at the delivery port. It will then be up to the customer to decide if a late delivery of the salmon is worth it compared to the reduced transportation cost.

The model, as it is configured now, does not allow the oldest salmon at delivery to be older than the defined MFA limit. The age of the entire load of the vessel will, however, vary depending on how much time has gone since the first salmon was slaughtered until delivery. It was therefore assumed that the oldest salmon is transported to the customers located closer to the delivery port. There is also a possibility that salmon used for smoking and other refinery does not need to be as fresh as salmon sold as fresh fish on a market, which also opens up to prioritize the freshest fish for the fish markets. Distributing the salmon after delivery at the port in Europe this way has not been implemented in the model.

The model has no constraints on how often a given customer must be serviced within the time horizon chosen. The amount available for shipping in this model accounts for less than half of the total demand in the considered regions. This means that even if the model finds an optimal solution which only supplies the customer once instead of more frequent, this should not be an issue because it only accounts for a fraction of the total demand the customer has. If however the supply in the model is not evenly distributed between the customers or more production ports in Norway are included, the amount delivered to a customer will become closer to the total demand of the customer. In that case, one will need to add constraints which ensure a certain frequency of deliveries or the time horizon can be adjusted down.

Adjusting the time horizon of the model has an impact on the solution the model gives. Reducing the time horizon and adjusting parameters dependent on it accordingly will result in a solution, where a delivery frequency equal to the time horizon can be guaranteed. The seaborne transport is, however, an integer problem, which means that the solution space for the vessels will decrease. On the other hand, having a too high time horizon may result in optimal solutions with less frequent deliveries and a with an increased time horizon follows increased uncertainty in parameters that have been considered constant in this model.

All the results are based on an integer x which means that a vessel only can take whole round trips in the given planning period. If planning to use a vessel for a longer time period than chosen, one can use a continuous x instead to see what the best solution is in the long term. Using a continuous x will give slightly better solutions than the integer solution. The salmon transported by trailer z and g is, on the other hand, modeled as continuous, since it was assumed to have little impact on the cost. To get the model more realistic one could look at amount loaded on either the ship or transported on land as unit loads of 19 tonnes, which would give a slight increase in the cost both for the vessels and for the land-based transport.

The load each vessel takes was predefined in such a way that the age of the salmon on the given route was minimized. For simplification, it was also chosen that vessels would have to be fully loaded before sailing for a delivery port in Europe. With a fixed time window for delivery and a requirement that the vessel should be fully loaded resulted in many routes being unfeasible because producing the needed load for a vessel would take a too long time. Allowing not fully loaded vessel delivery in Europe would make it possible to adjust the load in such a way that infeasible routes would become feasible. Instead of not allowing a vessel to go a certain route it would need to reduce the amount loaded in order to deliver the salmon in time. This would probably give some better solutions, especially at low MFA limits. Solving time would however increase because this would relax the constraints of the model which results in a larger solution space in where it takes a longer time to find the optimal solution.

Uncertainty. All parameters are modeled as constant. Several parameters can though be uncertain at a longer planning period. The production rate for once is not constant throughout the year and has seasonal variations as seen in chapter 2. As seen in the results a drop in the production rate to a production rate of only 60% of today's production leads to no feasible solution found for the transport of fresh salmon by sea. All costs considered can also change over time, which can make a given solution more or less profitable. When transporting products by sea weather will play an important role in how much time is used on sailing. To account for this all sailing times have been increased by 10%. Land-based transport can, on the other hand, be impacted by queues, which increases transportation times and costs. Most uncertainty is related to longer planning periods than 4 weeks. The weather conditions and queues can, however, be varying a lot even within this short time period. Since the seaborne solution, in general, will take more time than the land-based solution, increased sailing time is critical, which is why this is accounted for in the model.

The results show that increased production and increased time available will reduce the cost of transportation by sea. When looking at the transportation cost alone the percentile reduction can be over 30% in a scenario with increased production rates, transporting super chilled salmon. A price reduction of around 0.5 NOK per kg of salmon is in that case achieved. Considering a price per kg of salmon of over 60 NOK the potential reduction in the total price is minimal. It is questionable if customers would care about a cost reduction of 0.5 NOK when the price of the product can change by up to 20 NOK within a few months as seen in chapter 2. Increased production will most likely also result in lower salmon prices, which would make a seaborne alternative more attractive to customers. It might also be necessary to move some of the salmon transport over to ships, such that Norwegian roads do not become overloaded.

It is assumed that fish is being slaughtered constantly at a given rate, in reality, the slaughtering rate will go up and down depending the time of the day and is in general fitted to a land-based transport, where relatively small amounts of salmon are transported, which makes the age difference of the first slaughter salmon and the last slaughtered salmon for a trailer minimal. If vessels are utilized it should be possible to adapt the slaughtering process to this transportation method, which means slaughtering large amounts of salmon in a short period of time before a vessel is expected and a lower production rate in between vessel arrivals. The age of the salmon at delivery would therefore mostly be dependent on the sailing speed of the vessel and not its load. This would shrink the age difference of salmon transported by sea and by land and customers could benefit from the reduced transportation cost without having a big disadvantage of receiving older fish. Transportation by sea would also become less impacted by increases and decreases in production.

Chapter 9

Conclusion

Demand for fresh salmon is increasing and the amounts of salmon produced in Norway are expected to grow. With growing production, an already highly loaded Norwegian road network will become filled with even more trailers. Because of the climate and geography of Norway bettering infrastructure is costly and increased trailer activity on the roads increases the risks of accidents. Lowering the load on the road network, by transferring some of the cargo to vessels can, therefore, be beneficial.

Utilizing optimization one can gain insight into the possibilities of transferring parts of the salmon transport from the road to the sea. The aim of the model is to easily give information about if a seaborn solution can compete with today's transport on roads. A model was constructed based mainly on the transportation problem model and the fleet size and mix problem with predefined routes. The model considers both direct transport from the production facility to customer and seaborn transport from the production facility to delivery ports, with further transportation from the delivery port by trailer to the customer. By doing this it can easily be established which combination of sea and land-based transport gives the lowest cost under different circumstances.

It was found that at today's production rate transporting fresh salmon by sea could be performed with the first slaughtered salmon being no more than 5 or 6 days old at the delivery port. A cost of transporting all the salmon by land of 40,429,849 NOK, would be reduced to a total cost of 35,710,439 NOK and 31,999,334 NOK with a limit of the oldest fish being no older than 5 or 6 days respectively at the destination port. Using super chilling technology would increase the time available for delivery giving a cost of transportation of only 28,749,933 NOK. It was also found that an increase of the production of 50% would result in transportation costs lowering even more and salmon could even be delivered within 4 days after slaughtering at a lower cost than today's transportation alternative. Decreasing production by 40%, on the other hand, resulted in no feasible solutions found for the transport of fresh salmon. In this case, only transport of super-chilled salmon was feasible and at a lower cost than the land-based alternative. A cost reduction of up to 0.5 NOK per kg of salmon on average could be achieved by utilizing vessels for transport. With salmon prices over 60 NOK per kg and able to varying by 20 NOK in just a few months it is uncertain if customers are willing to receive less fresh fish with the benefit reducing the salmon price by such a little fraction.

It was concluded that adjusting the slaughtering process to a seaborne transport by increasing slaughtering rates before expected vessel arrivals, would reduce the impact the production has on the seaborne transport and could lead to lower costs or lower age of the salmon at delivery. This would make seaborne transport less prune to seasonal production variations and the fish delivered would in total be fresher giving the seaborne solution lesser of a disadvantage against the trailer transport through Norway.

Chapter 10

Further Work

In this chapter, possible extensions to this master thesis will be presented. In this thesis, the production rate was considered constant and relatively low. A variable slaughtering rate could be implemented and a cost associated with increasing the slaughtering rate. This would decrease the age of the salmon at pick up and could lead to more feasible seaborne solutions. In this model, a fully loaded ship is required to transport salmon. Allowing vessels to deliver smaller amounts could help to find better solutions to the problem. This thesis looked only on a small number of possible ports. Implementing more ports in both Norway and Europe to the model would give a bigger variety of possible solutions and could lead to finding better solutions. There are many things that can be done to make the model more realistic, but this will also lead to a more complex model, which takes a longer time to solve.

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Appendix A

Background

```
impdata = xlsread('Seasoncountry2.xlsx','A2:A8746');%Import data for all countries
expdata=xlsread('Seasonexport.xlsx','C63:BB63');%export data for norway
denmarkexp=zeros(52,15);
franceexp=zeros(52,15);
italyexp=zeros(52,15);
lithuaniaexp=zeros(52,15);
netherlandsexp=zeros(52,15);
polandexp=zeros(52,15);
spainexp=zeros(52,15);
gbexp=zeros(52,15);
germanyexp=zeros(52,15);

%sorting the data by country
for i=1:52
    for j=1:15
        denmarkexp(i,j)=impdata(j+(i-1)*15);
        franceexp(i,j)=impdata((j+1590)+(i-1)*15);
        italyexp(i,j)=impdata((j+2385)+(i-1)*15);
        lithuaniaexp(i,j)=impdata((j+3180)+(i-1)*15);
        netherlandsexp(i,j)=impdata((j+3975)+(i-1)*15);
        polandexp(i,j)=impdata((j+4770)+(i-1)*15);
        spainexp(i,j)=impdata((j+5565)+(i-1)*15);
        gbexp(i,j)=impdata((j+6360)+(i-1)*15);
        germanyexp(i,j)=impdata((j+7950)+(i-1)*15);
```

```matlab

    end
end

frac=zeros(52,15);

denmarksum=zeros(1,15);
x=[1:1:52];

%fractional import each week for denmark
for i=1:15
denmarksum(1,i)=sum(denmarkexp(:,i));
frac(:,i)=denmarkexp(:,i)/denmarksum(1,i);
plot(x,frac(:,i))
hold on

end
xticks([1:2:52])
xlabel('Week nr')
ylabel('fraction of yearly export')
legend('2000','2001','2002','2003','2005','2006','2007','2008','2010','2011','2012','2013','2014','2016','2017')
hold off


med=zeros(52,9);
fracden=zeros(52,15);
fracfra=zeros(52,15);
fracita=zeros(52,15);
fraclit=zeros(52,15);
fracnet=zeros(52,15);
fracpol=zeros(52,15);
fracspa=zeros(52,15);
fracgb=zeros(52,15);
fracger=zeros(52,15);

%calculating fractional import for each country
    for i=1:52
        for j=1:15
            fracden(i,j)=denmarkexp(i,j)/sum(denmarkexp(:,j));
```

```
            fracfra(i,j)=franceexp(i,j)/sum(franceexp(:,j));
            fracita(i,j)=italyexp(i,j)/sum(italyexp(:,j));
            fraclit(i,j)=lithuaniaexp(i,j)/max(sum(lithuaniaexp(:,j)),0.0000000001);
            fracnet(i,j)=netherlandsexp(i,j)/sum(netherlandsexp(:,j));
            fracpol(i,j)=polandexp(i,j)/sum(polandexp(:,j));
            fracspa(i,j)=spainexp(i,j)/sum(spainexp(:,j));
            fracgb(i,j)=gbexp(i,j)/max(sum(gbexp(:,j)),0.00000000001);
            fracger(i,j)=germanyexp(i,j)/sum(germanyexp(:,j));


        end %using the median of all years combined for each country at a given week
        med(i,1)=median(fracden(i,:));
        med(i,2)=median(fracfra(i,:));
        med(i,3)=median(fracita(i,:));
        med(i,4)=median(fracger(i,:));
        med(i,5)=median(fracnet(i,:));
        med(i,6)=median(fracpol(i,:));
        med(i,7)=median(fracspa(i,:));
        med(i,8)=median(fracgb(i,:));
        med(i,9)=median(fraclit(i,:));




    end

    snitt=zeros(52,8);
    %calculating how the import in each contry at a given week is compared
    %to the export that weeek
    for j=1:8
        for i=1:52
            snitt(i,j)=med(i,j)/expdata(i);
        end
    end

```

```
    %plotting the seasonal demand based on total import
    figure
    for i=1:9
        plot(med(:,i));
        hold on
    end
    xticks([1:2:52])
xlabel('Week nr');
ylabel('fraction of yearly export');
legend('Denmark','France','Italy','Germany','Netherlands','Poland','Spain','Great Britain','Lithuania');
hold off


%plotting seasonal demand compared to export
figure
    for i=1:8
        plot(snitt(:,i));
        hold on
    end
    xticks([1:1:52])
xlabel('Week nr');
ylabel('Import/Export');
legend('Denmark','France','Italy','Germany','Netherlands','Poland','Spain','Great Britain','Lithuania');
hold off
```

Appendix B

Xpress-IVE model

```
model ModelName

options explterm
options noimplicit

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


!optional parameters section
parameters
DataFile = 'InputData.txt';
end-parameters

!sample declarations section

declarations
nRoutes: integer;
nLoadPorts: integer;
nUnloadPorts: integer;
nVessels: integer;
nCostumers: integer;

end-declarations

initializations from DataFile
    nRoutes;
    nLoadPorts;
    nUnloadPorts;
    nVessels;
    nCostumers;
end-initializations




declarations
    Routes:         set of integer;
    LoadPorts:      set of integer;
    UnloadPorts:    set of integer;
    Vessels:        set of integer;
    Costumers:      set of integer;

end-declarations


    Routes := 1 .. nRoutes;   !Set of all routes
    LoadPorts := 1 .. nLoadPorts;       !Set of all loading ports
    UnloadPorts :=1 .. nUnloadPorts;    !Set of all unloading poorts
    Vessels :=1 .. nVessels;        !Set of all vessels
    Costumers :=1 .. nCostumers;        !Set of all costumers



finalize(Routes);
finalize(LoadPorts);
finalize(UnloadPorts);
finalize(Vessels);
finalize(Costumers);



!--------------------------------------------------------------------------------------------------
            !Decalring parameters
!--------------------------------------------------------------------------------------------------

declarations
    Chartercost:            array(Vessels)                      of real;
    VarCost:                array(Routes,Vessels)               of real;
    DockTime:               real;
    LoadRate:               real;
    VesselSpeed:            array(Vessels)                      of real;
    Distanceliter:          array(Vessels)                      of real;
    Litercost:              real;
    Routedistance:          array(Routes)                       of real;
    Truckingcost_NOR:       array(LoadPorts, Costumers)         of real;
    Truckingcost_EU:        array(UnloadPorts, Costumers)       of real;
    Capacity:               array(Vessels)                      of real;
    Planningperiod:         real;
    A:                      array(LoadPorts, Routes)            of integer;
    B:                      array(UnloadPorts, Routes)          of integer;
    Production:             array(LoadPorts)                    of real;
    Demand:                 array(Costumers)                    of real;
    Frequency:              array(LoadPorts, Vessels)           of real;
```

```
    LoadHelp:               array(Routes)                       of real;
    Storageprice:           real;



end-declarations

initializations from DataFile
    Chartercost;
    VarCost;
    DockTime;
    LoadRate;
    VesselSpeed;
    Routedistance;
    Truckingcost_NOR;
    Truckingcost_EU;
    Capacity;
    Planningperiod;
    A;
    B;
    Production;
    Demand;
    LoadHelp;
    Storageprice;
end-initializations

!----------------------------------------------
                !Preprocess
!----------------------------------------------------
declarations
  Load:               array(LoadPorts, Routes, Vessels)   of real;
  Roundtriptime:      array(Routes, Vessels)              of real;
  FishAgeLoad:        array(LoadPorts, Routes, Vessels)   of real;
  FishAgeUnload:      array(Routes, Vessels)              of real;
  MaxFishAge:         array(Routes, Vessels)              of real;
  DeliveryTime:       array(Routes,Vessels)               of real;
  Storagecost:        array(Routes,Vessels)               of real;


end-declarations





!Calculating the amount of salmon picked up at a port on roundtrip r for vessel v
forall (ii in LoadPorts, rr in Routes, vv in Vessels) do
    Load(ii,rr,vv) := (A(ii,rr)*Production(ii)) /(LoadHelp(rr))*Capacity(vv) ;
end-do

!Calculating the age of the oldest fish at the pick up port
forall (ii in LoadPorts, rr in Routes, vv in Vessels) do
    FishAgeLoad(ii,rr,vv) := Load(ii,rr,vv)/(Production(ii)/Planningperiod);
end-do


forall (rr in Routes, vv in Vessels) do
    MaxFishAge(rr,vv):=0;
end-do

!Calculating the time usage of each vessel for each roundtrip
forall (rr in Routes, vv in Vessels) do
    Roundtriptime(rr,vv):=Routedistance(rr)/VesselSpeed(vv)+(sum(ii in LoadPorts)A(ii,rr)+1)*DockTi
end-do

!Calculating the time spent from picking up load at the first port untill delivery in Europe
forall (rr in Routes, vv in Vessels) do
!   DeliveryTime(rr,vv):=Roundtriptime(rr,vv)-0.5*Routedistance(rr)/VesselSpeed(vv);
    DeliveryTime(rr,vv):=0.5*Routedistance(rr)/VesselSpeed(vv)+(sum(ii in LoadPorts)A(ii,rr)+1)*Doc
end-do

!Updating the age of the oldest fish
!MaxFishAge is not necessary to calculate since the predefined Load ensures that the age of the fis
forall(ii in LoadPorts,rr in Routes, vv in Vessels)
        if MaxFishAge(rr,vv)<FishAgeLoad(ii,rr,vv) then
            MaxFishAge(rr,vv):=FishAgeLoad(ii,rr,vv);
        elif MaxFishAge(rr,vv)>=FishAgeLoad(ii,rr,vv) then
            MaxFishAge(rr,vv):=MaxFishAge(rr,vv);
        end-if
!Calculating the age of the oldest salmon at delivery
forall (rr in Routes, vv in Vessels) do
    FishAgeUnload(rr,vv) := MaxFishAge(rr,vv)+DeliveryTime(rr,vv);
end-do
```

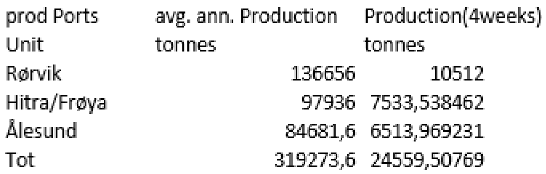
```
!Calculating the cost of storing the salmon that is picked up
forall (rr in Routes, vv in Vessels) do
    Storagecost(rr,vv) := MaxFishAge(rr,vv)/2*Storageprice/(365*24)*Capacity(vv);
end-do






writeln(Load);
writeln(FishAgeLoad);
writeln(FishAgeUnload);






















!---------------------------------------------------------------------------------------------------
                            !Declaring variables
!---------------------------------------------------------------------------------------------------


declarations
x:  dynamic array(Routes, Vessels) of mpvar;
y:  dynamic array(Vessels) of mpvar;
z:  dynamic array(LoadPorts, Costumers) of mpvar;
g:  dynamic array(UnloadPorts, Costumers) of mpvar;
w:  dynamic array(Routes,Vessels) of mpvar;


end-declarations
!creating all variables
forall (rr in Routes, vv in Vessels) do
    create(x(rr,vv));
    x(rr,vv) is_integer;
    create(w(rr,vv));
    w(rr,vv) is_binary;
end-do

forall (vv in Vessels) do
    create(y(vv));
    y(vv) is_integer;

end-do

forall (ii in LoadPorts, kk in Costumers) do
    create(z(ii,kk));
end-do

forall (jj in UnloadPorts, kk in Costumers) do
    create(g(jj,kk));
end-do


!---------------------------------------------------------------------------------------

declarations
    TotalCost:  linctr;
    TimeCon:    dynamic array(Vessels)              of linctr;
    LoadCon:    dynamic array(LoadPorts)            of linctr;
    FreqCon:    dynamic array(Routes, Vessels)      of linctr;
!   VesselCon1: linctr;
    VesselCon2: dynamic array(Routes, Vessels)      of linctr;
    FTCon1:     dynamic array(UnloadPorts)          of linctr;
```

```
    FTCon2:     dynamic array(Costumers)            of linctr;
end-declarations

!Cost function used as the objective function
TotalCost:=
    sum(vv in Vessels) Chartercost(vv)*y(vv)*Planningperiod/24
    +sum(rr in Routes, vv in Vessels) (VarCost(rr,vv)+Storagecost(rr,vv))*x(rr,vv)
    +sum(ii in LoadPorts, kk in Costumers) Truckingcost_NOR(ii,kk)/19*z(ii,kk)
    +sum(jj in UnloadPorts, kk in Costumers) Truckingcost_EU(jj,kk)/19*g(jj,kk);


!Ensuring Vessels used are beeing chartered and ensuring that the time a vessel is in use does not
forall (vv in Vessels) do
        TimeCon(vv):=
            sum(rr in Routes) Roundtriptime(rr,vv)*x(rr,vv)<=Planningperiod*y(vv);
end-do

!Ensuring all fish produced is either picked up by trailer or by ship
!>= is used instead of = to be able to pick up lower loads than the predefined loads for the vessel
!This is done to be able to transport remaining salmon at the loading port at the end of the  plann
forall (ii in LoadPorts) do
    LoadCon(ii):=
        sum(rr in Routes,vv in Vessels) Load(ii,rr,vv)*x(rr,vv)
        + sum(kk in Costumers)z(ii,kk) >= Production(ii);
end-do

!The age of the oldest fish at delivery can not exeed a given time
forall (rr in Routes, vv in Vessels) do
    FreqCon(rr,vv):=
    FishAgeUnload(rr,vv)*w(rr,vv)<=120;
end-do



!VesselCon1 := sum(vv in Vessels)u(vv) <= 1;



!Routes with vessels that do not fulfill the constraint above can not be traversed
forall (rr in Routes,vv in Vessels) do
    VesselCon2(rr,vv) := x(rr,vv) <= 100*w(rr,vv);
end-do

!The amount delivered from delivery port j to the customers can not exeed the amount sent to the po
forall (jj in UnloadPorts) do
!   FTCon1(jj) := sum(kk in Costumers)g(jj,kk)
!    <= sum(rr in Routes, vv in Vessels)Capacity(vv)*B(jj,rr)*x(rr,vv);
    FTCon1(jj) := sum(kk in Costumers)g(jj,kk)
    <=sum(ii in LoadPorts, rr in Routes, vv in Vessels)Load(ii,rr,vv)*B(jj,rr)*x(rr,vv);
end-do


!Costumers salmon demands must be fulfilled
forall (kk in Costumers) do
    FTCon2(kk) := sum(jj in UnloadPorts) g(jj,kk)
        +sum(ii in LoadPorts) z(ii,kk) >= Demand(kk);
end-do

!Objective function
minimize(TotalCost);




writeln;
forall(rr in Routes, vv in Vessels| getsol(w(rr,vv))>0.001) do
writeln('Age at delivery',rr,'Port',vv,'is',getsol(w(rr,vv)*FishAgeUnload(rr,vv)));
end-do



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

writeln;
forall(rr in Routes, vv in Vessels | getsol(x(rr,vv))>0.001) do
writeln('x_',rr,'_',vv,'is equal   ', getsol(x(rr,vv)));
end-do

writeln;
forall(vv in Vessels | getsol(y(vv))>0.001) do
writeln('y_',vv,'is equal   ', getsol(y(vv)));
end-do
```

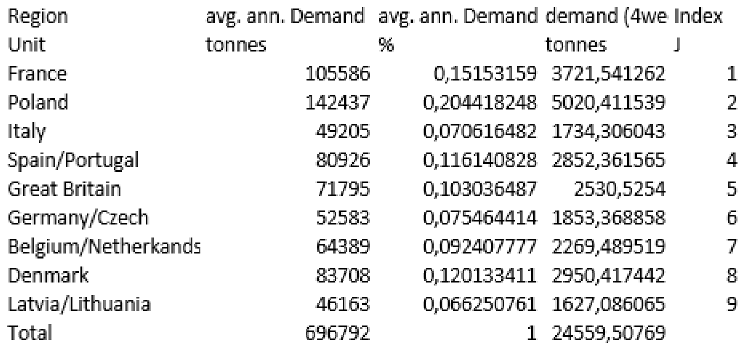
```
writeln;
forall(ii in LoadPorts) do
writeln('Visits at port',ii,'is',getsol(sum(rr in Routes, vv in Vessels)x(rr,vv)*A(ii,rr)));
end-do


writeln;
forall(ii in LoadPorts, kk in Costumers | getsol(z(ii,kk))>0.001) do
writeln('z_',ii,'_',kk,'is equal   ', getsol(z(ii,kk)));
end-do


writeln;
forall(jj in UnloadPorts, kk in Costumers | getsol(g(jj,kk))>0.001) do
writeln('g_',jj,'_',kk,'is equal   ', getsol(g(jj,kk)));
end-do


!writeln;
!forall(rr in Routes, vv in Vessels) do
!writeln('age_',rr,'_',vv,'is equal   ', FishAgeUnload);
!end-do







end-model
```

Appendix C

Production and Demand



prod Ports	avg. ann. Production	Production(4weeks)
Unit	tonnes	tonnes
Rørvik	136656	10512
Hitra/Frøya	97936	7533,538462
Ålesund	84681,6	6513,969231
Tot	319273,6	24559,50769



Region	avg. ann. Demand	avg. ann. Demand	demand (4we	Index
Unit	tonnes	%	tonnes	J
France	105586	0,15153159	3721,541262	1
Poland	142437	0,204418248	5020,411539	2
Italy	49205	0,070616482	1734,306043	3
Spain/Portugal	80926	0,116140828	2852,361565	4
Great Britain	71795	0,103036487	2530,5254	5
Germany/Czech	52583	0,075464414	1853,368858	6
Belgium/Netherkands	64389	0,092407777	2269,489519	7
Denmark	83708	0,120133411	2950,417442	8
Latvia/Lithuania	46163	0,066250761	1627,086065	9
Total	696792	1	24559,50769	

Appendix D

Vessel Database

Vessel Name	IMO	Lane Meter	Service speed[kn]	Revised speed[kn]	Motoreffect[kW]	Motoreff	Crew	RPM	Gross Ton
VOLCAN DE TENEGUIA	9335161	1509	16,5	16,5	6000	8158		750	11197
BORE BANK	9160774	1511	20,2	22	14480	19687	12	500	10585
BORE BAY	9122007	1511	20,2	22	14480	19687	12	500	10572
STENA SCOTIA	9121625	1562	18,6	18,6	10736	14596	18	510	13017
BALTICBORG	9267716	1600	16,5	16,5	9450	12848	12	500	12635
BOTHNIABORG	9267728	1600	16,5	16,5	9450	12845	12	500	12635
SEAGARD	9198977	1605	21	23	15598	21207	14	500	10488
FRIEDRICH RUSS	9186417	1620	20	21	12600	17131	14	500	10471
ELISABETH RUSS	9186429	1624	20	21	12600	17131	14	500	10471
CAROLINE RUSS	9197533	1624	20	21	15600	21210	14		10488
MIRAMAR EXPRESS	9183790	1624	20,3	20,3	12600	17131	12	500	10471
MISTRAL	9183788	1624	20,3	20,3	12600	17131	12	500	10471
PAULINE RUSS	9198989	1624	21	21	15598	21207	14		10488
MN PELICAN	9170999	1690	20	23	15600	21210	14		12076
BLUE CARRIER 1	9186649	1692	18,5	18,5	10740	14602	18	510	13073
CAPUCINE	9539066	1760	16	17	7000	9517		750	16342
SEVERINE	9539078	1760	16	16	7000	9517		750	16342
COLOR CARRIER	9132002	1775	20	20	15600	21210	12		12433
FINNMASTER	9132014	1775	20	24	15600	21210			12433
SC CONNECTOR	9131993	1775	20	20	15600	21210	14		12251
CLIPPER PENNANT	9372688	1830	22	22	18480	25126		514	14759
CLIPPER POINT	9350666	1830	22	24	18480	25126		514	14759
SEATRUCK PACE	9350678	1830	22	22	18480	25126		514	14759
SEATRUCK PANORAMA	9372676	1830	22	22	18480	25126		514	14759
FINNHAWK	9207895	1890	20	20	12600	17131		500	11671
FINNKRAFT	9207883	1890	20	20	12600	17131		500	11671
SCA ORTVIKEN	9087374	1900	16	16	9000	12236	12	500	19887
SCA OBBOLA	9087350	1900	16	16	9000	12236	12	500	19918
SCA OSTRAND	9087362	1900	16	16	9002	12239	12	500	19904
EUROCARGO NAPO	9108568	1960	19,5	19,5	8145	11074		500	21357
EUROFERRY MALTA	9108556	1960	19,5	19,5	8145	11074		500	21664
VENTOUX	9129586	2250	19,7	19,7	11120	15119		428	18469
ESTRADEN	9181077	2270	19	20	14480	19688	14	500	18205
CELESTINE	9125372	2300	17,8	17,8	9844	13384	18	514	23986
CELANDINE	9183984	2307	17,8	17,8	9840	13378	14	514	23987
CLEMENTINE	9125384	2307	17,8	17,8	9840	13378	16	514	23986
MELUSINE	9166637	2307	18	18	9840	13378	14	514	23987
VICTORINE	9184029	2307	17,8	19,4	9840	13780	14	514	23987
ARK FUTURA	9129598	2308	19,7	19,7	11120	15119	15	428	18725
JOLLY EXPRESS	9180190	2378	19,5	19,5	15360	20884	18		20343
BELGIA SEAWAYS	9188233	2475	18	18	10920	14847	18	135	21005
GOTHIA SEAWAYS	9188245	2475	18	18	10920	14847	18	135	21005
SOMERSET	9188221	2475	18	18	10920	14847	18	135	21005
ELIANA MARINO	9226360	2500	22	22	16800	22842	15	500	18265
EUROCARGO ISTAN	9165310	2538	20	20	12511	17010		428	29303
ANVIL POINT	9248540	2606	17,1	18	12600	17130	18	500	23235
EDDYSTONE	9234070	2606	17,1	18	16200	22026	18	500	23235
FINNMERCHANT	9234082	2606	17,1	18	16200	22026	18	500	23235
HARTLAND POINT	9248538	2606	17,1	18	12600	17130	18	500	23235
HURST POINT	9234068	2606	17,1	18	12600	17130	18	500	23235
MASSIMO MURA	9234094	2606	17,1	18	16200	22026	18	500	23235
NORSKY	9186182	2622	20	21	18900	25696	16	500	20296
NORSTREAM	9186194	2622	20	21	18900	25696	16	500	20296
AMILCAR	9207998	2640	21,6	21,6	16200	22026	25	500	22900
ELYSSA	9208007	2640	21,5	21,5	16200	22026	25	500	22900
LPV	9138795	2715	22	22	23040	31324		510	21104
MSC BRIDGE	9138783	2715	22	22	23040	31324		510	21104
CATHERINE	9209453	2750	18	22	12600	17131	12	500	21369
SELANDIA SEAWAY	9157284	2772	21	22	21600	29368	15	450	24803
SUECIA SEAWAYS	9153020	2772	21	22	21600	29368	15	450	24613
TAVASTLAND	9334959	2774	16	20	18000	24472	14	514	23128
THULELAND	9343261	2774	16	20	18000	24472	14	514	23128
TUNDRALAND	9343273	2774	16	20	18000	24472	14	514	23128
BRITANNIA SEAWAYS	9153032	2820	21,5	21,5	21600	29368	17	450	24613
PALATINE	9376701	2907	18,5	19	10800	14684		500	31340
PEREGRINE	9376725	2907	18,5	19	10800	14684		500	25593
VESPERTINE	9376713	2907	18,5	19	10800	14684		500	25593

Appendix E

Trailer Cost

Total time trailers[h]

	Hirtshals	Bremerhaven	Ijmuiden	Rørvik	Hitra	Ålesund
Bourges	41	25	20	85	81	69
Lodz	27	22	25	68	63	61
Rome	50	42	38	104	90	87
Madrid	65	50	45	122	107	105
Leicester	41	26	21	86	81	79
Erfurt	22	7	9	64	60	50
Kolding	4	6	11	47	42	40
Eindhoven	22	7	2	65	60	58
Siauliai	45	40	43	79	69	69

Distance usage trailers[km]

	Hirtshals	Bremerhaven	Ijmuiden	Rørvik	Hitra	Ålesund
Bourges	1643	1057	769	2851	2646	2566
Lodz	1277	893	1129	2259	2053	1973
Rome	2222	1738	1302	3377	3171	3091
Madrid	2670	2084	1800	3876	3670	3590
Leicester	1609	1021	732	2762	2556	2476
Erfurt	907	423	610	2110	1904	1824
Kolding	275	414	726	1642	1436	1356
Eindhoven	986	411	146	2190	1984	1904
Siauliai	1966	1535	1771	1204	1097	1154

Tollcosts for trailers [NOK]

	Hirtshals	Bremerhaven	Ijmuiden	Rørvik	Hitra	Ålesund
Bourges	2099	1776	1281	4257	4607	4793
Lodz	1353	1313	1393	3221	3562	3747
Rome	3380	2724	2074	5064	5415	5600
Madrid	3804	3481	2977	5952	6303	6488
Leicester	3558	3225	2680	5635	6057	6242
Erfurt	817	611	636	2955	3306	3491
Kolding	0	474	666	3200	3551	3736
Eindhoven	848	514	0	2996	3347	3532
Siauliai	889	1102	1183	0	451	691

Ferrycost per trailer[NO

	Norway
Bourge	2058
Lodz	2331
Rome	2058
Madrid	2058
Leicest	2058
Erfurt	2058
Kolding	0
Eindhov	2058
Siauliai	6912

driving hours tru	Hirtshals	Bremerhaven	Ijmuiden	Rørvik	Hitra	Ålesund
Bourges	22,07443235	14,20126293	10,33185543	39,51353333	36,02781904	35,37067619
Lodz	17,15706033	11,99785033	15,16861481	31,55975125	28,07403697	27,41689411
Rome	29,85355367	23,35079941	17,49294639	46,58057619	43,0948619	42,43771905
Madrid	35,872632	27,99946258	24,18379686	53,28486209	49,79914781	49,14200495
Leicester	21,6176273	13,71758699	9,834744055	38,31777893	34,83206464	34,17492179
Erfurt	12,18594653	5,683192261	8,195620046	29,55787029	26,072156	25,41501315
Kolding	3,694746742	5,562273277	9,754131399	23,27008311	19,78436882	19,12722596
Eindhoven	13,2473465	5,521966949	1,961574634	30,63270571	27,14699142	26,48984856
Siauliai	26,41408034	20,62340454	23,79416902	17,48011746	16,70868889	17,15154604

avg spe	74,43
avg spe	70
Trailerc	500
Trailerc	353
Trailerc	6,55

Total cost for trailers[NOK]

	Hirtshals	Bremerhaven	Ijmuiden	Rørvik	Hitra	Ålesund
Bourges	20652,92462	13712,39581	9965,094968	36879,32727	34656,12012	34086,14869
Lodz	15773,79229	11397,39117	14142,47103	29158,04219	26919,28505	26348,31362
Rome	28472,40445	22350,73219	16777,11008	43626,29339	41397,53625	40826,56482
Madrid	33955,5391	27015,01029	23303,88029	50149,35632	47920,59918	47349,62775
Leicester	21727,97244	14754,85821	10946,26465	37252,27596	35094,51882	34523,54739
Erfurt	11059,48912	5387,816868	7524,553876	27209,42821	24980,67107	24409,69964
Kolding	3105,4956	5149,182467	8864,508384	22169,43934	19940,68219	19369,71077
Eindhoven	11982,61331	5155,304333	1648,735846	28153,84511	25925,08797	25354,11654
Siauliai	23090,47036	18436,3118	21182,39166	14056,68146	13534,51718	14304,19575

Appendix F

Vessel Cost

Parameters

EUR to NOK	10
2015EUR to 2019EUR	1,0429
NOK per BHP	4211
rent	0,08
lifespan in years	20
CRF	0,101852209
days a year	365
Fuelcost[NOK/l] incl. CO2	6,06753
Noxfee[NOK/g]	0,02227
Noxemm[g/kWh]	12,9843
knots to kmh	1,852
årlig Losavgift[NOK/GT]	75,71
BHP-->kW	0,745699872

Fixed cost found by linear regression (without Loscost)

LM	2015EURO	2019EURO	NOK
1000	5500	416405	771182,06
1100	5833	441616,43	817873,6284
1200	6167	466903,57	864705,4116
1300	6500	492115	911396,98
1400	7167	542613,57	1004920,332
1500	7833	593036,43	1098303,468
1600	8500	643535	1191826,82
1700	9000	681390	1261934,28
1800	9500	719245	1332041,74
1900	9857	746273,47	1382098,466
2000	10214	773301,94	1432155,193
2100	10571	800330,41	1482211,919
2200	10928	827358,88	1532268,646
2300	11285	854387,35	1582325,372
2400	11642	881415,82	1632382,099
2500	12000	908520	1682579,04
2600	12400	938804	1738665,008
2700	12800	969088	1794750,976
2800	13200	999372	1850836,944
2900	13600	1029656	1906922,912
3000	14000	1059940	1963008,88

Estimating the percentage increase of HP per LM by linear regresion

	1750	2575		%increase per LM
16	10597,77307	11588,3817	0,09347328	0,0001133
17	12036,27835	13495,9423	0,12127203	0,000147
18	13570,92144	15581,1595	0,14812834	0,00017955
19	15202,25095	17849,3274	0,17412398	0,00021106
20	16930,78863	20305,5988	0,19932977	0,00024161
21	18757,03209	22954,9961	0,22380747	0,00027128
22	20681,45695	25802,4208	0,24761137	0,00030013

BHP for each vessel

	16	17	18	19	20	21	22
1500	10297,58863	11593,9559	12961,7584	14400,1066	15908,1189	17484,92179	19129,6497
1600	10417,6624	11770,8849	13205,4236	14720,9643	16317,1868	17993,76591	19750,3726
1700	10537,73618	11947,8139	13449,0888	15041,8221	16726,2547	18502,61003	20371,0955
1800	10657,80995	12124,7428	13692,754	15362,6798	17135,3226	19011,45415	20991,8184
1900	10777,88373	12301,6718	13936,4193	15683,5376	17544,3905	19520,29827	21612,5413
2000	10897,9575	12478,6008	14180,0845	16004,3953	17953,4584	20029,14239	22233,2642
2100	11018,03128	12655,5297	14423,7497	16325,2531	18362,5263	20537,9865	22853,9871
2200	11138,10505	12832,4587	14667,4149	16646,1108	18771,5942	21046,83062	23474,71
2300	11227,31368	12950,3822	14811,8224	16813,3287	18956,4287	21242,49617	23672,7632
2400	11358,61115	13148,7677	15091,5813	17190,0555	19447,036	21865,22341	24447,1842
2500	11489,90861	13347,1532	15371,3403	17566,7823	19937,6433	22487,95065	25221,6051
2600	11621,20608	13545,5387	15651,0992	17943,5091	20428,2506	23110,67788	25996,0261
2700	11752,50354	13743,9242	15930,8581	18320,2358	20918,8579	23733,40512	26770,447
2800	11883,801	13942,3097	16210,6171	18696,9626	21409,4652	24356,13236	27544,8679
2900	12015,09847	14140,6952	16490,376	19073,6894	21900,0725	24978,85959	28319,2889

Total daily fixed cost

	16	17	18	19	20	21	22
1500	79479,3202	81002,6393	82609,8996	84300,0559	86072,0722	87924,92208	89857,5885
1600	86199,52847	87789,6563	89475,3362	91256,1989	93131,8681	95101,96176	97166,0933
1700	91178,09374	92835,0303	94599,1297	96470,6989	98450,0209	100537,3584	102732,955
1800	96156,65901	97880,4042	99722,9233	101685,199	103768,174	105972,7551	108299,817
1900	99643,87728	101434,431	103355,37	105408,352	107594,98	109916,8048	112375,332
2000	103131,0956	104988,458	106987,816	109131,505	111421,786	113860,8545	116450,846
2100	106618,3138	108542,485	110620,263	112854,658	115248,591	117804,9042	120526,361
2200	110105,5321	112096,512	114252,71	116577,811	119075,397	121748,9539	124601,876
2300	113737,0189	115761,741	117949,059	120300,964	122819,251	125505,5347	128361,263
2400	117171,7759	119275,331	121558,268	124024,117	126676,221	129517,7549	132551,733

2500	120616,9619	122799,35	125177,906	127757,699	130543,621	133540,404	136752,633
2600	124500,1659	126761,387	129235,562	131929,299	134849,038	138001,0712	141391,55
2700	128383,3698	130723,424	133293,219	136100,899	139154,455	142461,7384	146030,468
2800	132266,5738	134685,461	137350,875	140272,499	143459,873	146922,4055	150669,385
2900	136149,7778	138647,497	141408,531	144444,099	147765,29	151383,0727	155308,303

NOx cost per hour

	16	17	18	19	20	21	22
1500	1776,349231	1999,9745	2235,92245	2484,03963	2744,17398	3016,174805	3299,8928
1600	1797,062135	2030,49501	2277,95506	2539,38806	2814,73879	3103,951166	3406,96841
1700	1817,775038	2061,01552	2319,98767	2594,7365	2885,30361	3191,727527	3514,04403
1800	1838,487941	2091,53603	2362,02028	2650,08493	2955,86843	3279,503889	3621,11964
1900	1859,200844	2122,05653	2404,05288	2705,43337	3026,43324	3367,28025	3728,19526
2000	1879,913748	2152,57704	2446,08549	2760,7818	3096,99806	3455,056611	3835,27087
2100	1900,626651	2183,09755	2488,1181	2816,13024	3167,56287	3542,832973	3942,34649
2200	1921,339554	2213,61805	2530,15071	2871,47867	3238,12769	3630,609334	4049,4221
2300	1936,728174	2233,96003	2555,06121	2900,32401	3270,01192	3664,36193	4083,58659
2400	1959,377181	2268,18182	2603,32004	2965,30994	3354,6424	3771,783297	4217,17534
2500	1982,026187	2302,40361	2651,57887	3030,29586	3439,27288	3879,204664	4350,76409
2600	2004,675193	2336,6254	2699,8377	3095,28179	3523,90337	3986,626031	4484,35285
2700	2027,3242	2370,84719	2748,09653	3160,26771	3608,53385	4094,047398	4617,9416
2800	2049,973206	2405,06899	2796,35536	3225,25364	3693,16434	4201,468765	4751,53036
2900	2072,622212	2439,29078	2844,61419	3290,23956	3777,79482	4308,890132	4885,11911

Total fuelcost per km

	16	17	18	19	20	21	22
1500	350,9286342	371,865574	392,640114	413,252372	433,702657	453,9914244	474,119248
1600	355,0205946	377,540409	400,021268	422,460306	444,855065	467,203429	489,503569
1700	359,1125551	383,215244	407,402423	431,66824	456,007473	480,4154336	504,88789
1800	363,2045156	388,890079	414,783577	440,876173	467,159881	493,6274381	520,272211
1900	367,2964761	394,564915	422,164731	450,084107	478,312289	506,8394427	535,656532
2000	371,3884366	400,23975	429,545885	459,292041	489,464697	520,0514473	551,040853
2100	375,4803971	405,914585	436,92704	468,499974	500,617105	533,2634519	566,425174
2200	379,5723576	411,589421	444,308194	477,707908	511,769513	546,4754565	581,809495
2300	382,6124733	415,371709	448,682613	482,506706	516,808652	551,5558612	586,718151
2400	387,0869228	421,734743	457,157126	493,317962	530,184067	567,7248112	605,911805
2500	391,5613723	428,097777	465,631638	504,129217	543,559482	583,8937612	625,105459
2600	396,0358217	434,460811	474,10615	514,940473	556,934897	600,0627111	644,299112
2700	400,5102712	440,823845	482,580663	525,751729	570,310312	616,2316611	663,492766
2800	404,9847207	447,18688	491,055175	536,562984	583,685727	632,400611	682,68642
2900	409,4591702	453,549914	499,529687	547,37424	597,061142	648,569561	701,880074

Port costs at different ports in Norway excluding cargo costs

	calling fee		wharfage fee		ISPS		TOT	
BT	10000	20000	10000	20000	10000	20000	10000	20000
Grenland	10000	19500	6350	8150	750	750	17100	28400
Bergen	1300	2600	5000	10000	900	900	7200	13500
Drammen	2140	2740	9378	12978	250	250	11768	15968
Karmsund	1500	3000	4298	7798	2100	4200	7898	14998
Mo i Rana	11791	18391	4635	8635	2535	3210	18961	30236
Oslo	0	0	6419,6	12069	0	0	6419,6	12069
Kristansund	2509	5709	8208	16208	2462,4	4862,4	13179,4	26779,4
Ålesund	1991	3291	3071	5271	767,75	1317,75	5829,75	9879,75
Risvika	456,6	786,6	4837	4837	1451,1	1451,1	6744,7	7074,7
Kristiansand	5031	7231	3726	7146	600	600	9357	14977
Trondheim	6200	11800	7200	14400	1000	1000	14400	27200
avg	3901,690909	6822,6	5738,41818	9772	1165,11364	1685,568182	10805,2227	18280,1682
per GT	0,390169091	0,34113	0,57384182	0,4886	0,11651136	0,084278409	1,08052227	0,91400841
								0,99726534

Portcost per visit for Norway and Europe excluding Cargofee

LM	Europe	Norway
1500	18000	12547
1600	18937	13383
1700	19578	14220
1800	20218	15056
1900	20881	15893
2000	21522	16729
2100	22185	17566
2200	22825	18402
2300	23466	19239
2400	25276	20075
2500	25964	20912
2600	26675	21748
2700	27364	22585
2800	28051	23421
2900	28763	24258

Appendix G

Pre-calculations Matlab

```
Speed=[16,17,18,19,20,21,22];
Capacity=[1500  1600    1700    1800    1900    2000    2100    2200    2300    2400    2500    2600    2700    2800    2900
];
SpeedIn=[4];%select the speed for the vessels 1=16, 2=17...
CapIn=[5];%select the capacities for the vessels 1=1500, 2=1600....

nVessels=length(SpeedIn)*length(CapIn);%nVessels

Charterprice=[79479 86200   91178   96157   99644   103131  106618  110106  113737  117172  120617  124500  128383  132267  136150
81003   87790   92835   97880   101434  104988  108542  112097  115762  119275  122799  126761  130723  134685  138647
82610   89475   94599   99723   103355  106988  110620  114253  117949  121558  125178  129236  133293  137351  141409
84300   91256   96471   101685  105408  109132  112855  116578  120301  124024  127758  131929  136101  140272  144444
86072   93132   98450   103768  107595  111422  115249  119075  122819  126676  130544  134849  139154  143460  147765
87925   95102   100537  105973  109917  113861  117805  121749  125506  129518  133540  138001  142462  146922  151383
89858   97166   102733  108300  112375  116451  120526  124602  128361  132552  136753  141392  146030  150669  155308
];
```

```

Fuelprice=[371  376 380 384 389 393 397 402 405 410 414 419 424 429 433
394 400 406 412 418 424 430 436 440 446 453 460 467 473 480
416 423 431 439 447 455 462 470 475 484 493 502 511 520 529
437 447 457 467 476 486 496 506 511 522 533 545 556 568 579
459 471 483 494 506 518 530 542 547 561 575 589 604 618 632
480 494 508 522 536 550 564 578 584 601 618 635 652 669 686
502 518 534 551 567 583 599 616 621 641 662 682 702 722 743];

Portcosts=[118368   125995   133328   140659   148014   155345   162700   170031   177363   185864   193244   200646   208026   215404   222808
130915   139378   147548   155715   163907   172074   180266   188433   196602   205939   214156   222394   230611   238825   247066
143462   152761   161768   170771   179800   188803   197832   206835   215841   226014   235068   244142   253196   262246   271324];



DistanceRoutes=[1300    1300    1300    1300    1100    1100    900 1574    1574    1574    1574    1374    1374    1174    1678    1678    1678    1678    1478    1478    1278];

nRoutes=length(DistanceRoutes);
A_ir=[1,0,0;1,1,0;1,1,1;1,0,1;0,1,0;0,1,1;0,0,1;1,0,0;...
    1,1,0;1,1,1;1,0,1;0,1,0;0,1,1;0,0,1;1,0,0;1,1,0;...
    1,1,1;1,0,1;0,1,0;0,1,1;0,0,1;];





Vessels=zeros(8,nVessels);
for i=1:length(CapIn)
    for j=1:length(SpeedIn)
        d=j+(i-1)*length(Speed);
    Vessels(1,d)=Speed(1,SpeedIn(j));%VesselSpeed
    Vessels(2,d)=Capacity(1,CapIn(i));
    Vessels(3,d)=Capacity(1,CapIn(i))*1.3571;%Capacity
```

```
    Vessels(4,d)=Charterprice(SpeedIn(j),CapIn(i));%Charterprice
    Vessels(5,d)=Fuelprice(SpeedIn(j),CapIn(i));
    Vessels(6,d)=Portcosts(1,CapIn(i));
    Vessels(7,d)=Portcosts(2,CapIn(i));
    Vessels(8,d)=Portcosts(3,CapIn(i));

    end
end

VarCost=zeros(nRoutes,nVessels);






for i=1:nRoutes
    for j=1:nVessels
        VarCost(i,j)=DistanceRoutes(1,i)*1.852*Vessels(5,j)+
           Vessels(5+sum(A_ir(i,:)),j)%VarCost
    end
end
```

Appendix H

Flow of trailer transport

MFA of 5days at Normal production

	Norway	Hirtshals	Bremerhaven	Ijmuiden
Bourges				3722
Lodz	302,8		4717,2	
Rome				1734
Madrid				2852
Leicester				2530
Erfurt			1853	
Kolding	233,2	2035,8		
Eindhoven			1573,1	1376,9
Siauliai	1627			

MFA of 6 days at Normal production

	Norway	Hirtshals	Bremerhaven	Ijmuiden
Bourges				3722
Lodz	403,3	306,7	4310	
Rome				1734
Madrid				2852
Leicester				2530
Erfurt			1853	
Kolding		2269		
Eindhoven			1573	1376,9
Siauliai	1627			

MFA of 10 days at Normal production

	Norway	Hirtshals	Bremerhaven	Ijmuiden
Bourges				3722
Lodz	3253,74	1663,82		102,44
Rome				1734
Madrid				2852
Leicester				2530
Erfurt				1853
Kolding		2269		
Eindhoven				2950
Siauliai	1627			

MFA of 10 days at Low production

	Norway	Hirtshals	Bremerhaven	Ijmuiden
Bourges				2233
Lodz			3012	
Rome				1040,4
Madrid				1711,2
Leicester				1518
Erfurt			1111,8	
Kolding	187,69		1173,7	
Eindhoven			1486,75	283,3
Siauliai	976			

MFA of 4 days at High production

	Norway	Hirtshals	Bremerhaven	Ijmuiden
Bourges			5583	

Lodz	7529			
Rome	399		2201,6	
Madrid			4278	
Leicester			3795	
Erfurt		668	2111	
Kolding		3403,5		
Eindhoven			4425	
Siauliai	2445			

MFA of 5 days at High production

	Norway	Hirtshals	Bremerhaven	Ijmuiden
Bourges				5583
Lodz		997,14	6532,85	
Rome				2601
Madrid				4278
Leicester				3795
Erfurt			2696	83,3
Kolding		3403,5		
Eindhoven				4425
Siauliai	2440,5			

MFA of 6 days at High production

	Norway	Hirtshals	Bremerhaven	Ijmuiden
Bourges				5583
Lodz	4118,7		3411,3	
Rome				2601
Madrid				4278
Leicester				3795
Erfurt			2560,5	219
Kolding	417,7	2985		
Eindhoven				4425
Siauliai	2445			

MFA of 10 days at High production

	Norway	Hirtshals	Bremerhaven	Ijmuiden
Bourges				5583
Lodz			7530	
Rome				2601
Madrid				4278
Leicester				3795
Erfurt			2779,5	
Kolding		3403,5		
Eindhoven				4425
Siauliai	2440,5			

Appendix I

InputData

```
nRoutes  : 21
nLoadPorts  : 3
nUnloadPorts : 3
nVessels : 1
nCostumers : 9

Chartercost : [105408]


DockTime : 2

LoadRate : 456

Storageprice : 1926


VesselSpeed : [19]


Routedistance      : [1300 1300 1300 1300 1100 1100 900 1574 1574 1574 1574 1374 1374
1174 1678 1678 1678 1678 1478 1478 1278]

Truckingcost_NOR :[36879 29158 43626 50149 37252 27209 22169 28154 14057
34656 26919 41398 47921 35095 24981 19941 25925 13535
34086 26348 40827 47350 34524 24410 19370 25354 14304]

Truckingcost_EU :[20653 15774 28472 33956 21728 11059 3105 11983 23090
13712 11397 22351 27015 14755 5388 5149 5155 18436
```

```
9965 14142 16777 23304 10946 7525 8865 1649 21182]

Capacity : [2578.49000000000]
Planningperiod : 672

A : [1 1 1 1 0 0 0 1 1 1 1 0 0 0 1 1 1 1 0 0 0
0 1 1 0 1 1 0 0 1 1 0 1 1 0 0 1 1 0 1 1 0
0 0 1 1 0 1 1 0 0 1 1 0 1 1 0 0 1 1 0 1 1]

B :[1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 1 1 1 1 1 1 1 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1]

Production : [10512 7534 6514]

Demand : [3722 5020 1734 2852 2530 1853 2269 2950 1627]


LoadHelp :[10512 18045 24558 17025 7533 14046 6513 10512 18045 24558 17025 7533 14046
6513 10512 18045 24558 17025 7533 14046 6513]

VarCost : [1294031.60000000
1309924.60000000
1325817.60000000
1309924.60000000
1117721.20000000
1133614.20000000
941410.800000000
1535576.84800000
1551469.84800000
1567362.84800000
1551469.84800000
1359266.44800000
1375159.44800000
1182956.04800000
1627258.25600000
1643151.25600000
1659044.25600000
1643151.25600000
1450947.85600000
```

```
1466840.85600000
1274637.45600000]
```