Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Synne Vestre

The Fishing Vessel

Optimising Design and Functionality Based on Profit Optimisation of Fishery Selection, Routing and Change of Equipment Configuration

Master's thesis in Marine Technology
Supervisor: Bjørn Egil Asbjørnslett, Kjetil Fagerholt (co)
July 2020

NTNU
Kunnskap for en bedre verden

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MASTER THESIS IN MARINE TECHNOLOGY

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For stud.techn.

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Background

The fishing industry is one of Norway's most important export industries and have been for decades. With the rapid pace of technological development within fishing gears, the aquatic wildlife has hit its upper limit on how much it can withstand. Many fisheries are open for only limited periods during a year, with limited quotas and specified gear types that can be used. The cost drivers of a fishing vessel are linked to the sailing and operational costs, whereas the profits are directly linked to the quantity of delivered fish. The overall quantity of captured fish is stagnating, which has led the government to lift some regulations regarding the design of the vessel in order to uphold the profitability within the industry. This allows ship owners to make freer choices regarding the equipment onboard.

Objective

By combining possible equipment configurations with a proper routing model, well-educated choices can be made. Hence, the main objective of this thesis is to create an optimisation model that creates an optimal route based on the gear configuration of a given vessel. The model shall be used to gain insight into the routing of fishing vessels with a changing operation mode.

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

a. Present the problem at hand by:
    a. Presenting an overview of the Norwegian fishing industry, both historically and the present situation.
    b. Introducing the main features of Norwegian fishing vessel.
    c. Creating a problem description capturing the boundaries and characteristics of the problem
b. Review state of art within the topic of both vessel design and operations research.
c. Develop the methodology used to solve the problem based on relevant approaches and methods found through the literature review.

d. Develop an optimisation model that can be used to gain insight, and to obtain possible solutions to the problem.
e. Conduct a computational study showing how the model will solve a given case.
f. Discuss strengths and improvement potential in one's approach and work – with respect to conclusions.

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.

Supervision:
Main supervisor: Bjørn Egil Asbjørnslett

Sub-supervisor: Kjetil Fagerholt

Deadline: 01.07.2020

Preface

This thesis concludes my Master of Science Degree from the Norwegian University of Science and Technology, at the Department of Marine Technology. The degree specialization is within Marine Design and Logistics and has been written during the spring semester of 2020.

The thesis is a continuation of my Project Thesis from the fall semester 2019, where a thorough background study on the fishing industry was conducted. Thus, much of the background information used in this thesis was obtained during the work with the Project Thesis.

I would like to thank my supervisor, Professor Bjørn Egil Asbjørnslett, at the Department of Marine Technology for guidance and advice throughout this year, and for always being available for questions. I would also like to extend my gratitude to my sub-supervisor, Professor Kjetil Fagerholt, at the Department of Industrial Economics and Technology Management for giving me advice on how to model the Fishing Vessel Routing Problem, and for providing support literature relevant to this issue. I have also received input on both background material and data from different actors within the fishing industry, and I am very grateful for all advice that I have received.

Ålesund, June 2020

Synne Vestre

Summary

During the last few years, the Norwegian fishing industry has seen steady economic growth. However, an upper limit on the available fishery resources have been met. To overcome this challenge, and to ensure future economical growth, the Norwegian government has allowed ship owners to explore possible combinations of operation modes that previously have been prohibited. By combining operation modes, the vessel can become more robust when facing the large uncertainties in the fishing industry, as the functionality of the vessel is increased, as well as the number of fisheries it can participate in can be expanded. Since the number of quotas available is held constant, a vessel can only enter the industry by replacing an already existing one, hence making a combined vessel desirable for ship owners. With added operating modes, there exist a potential to use decision tools to better plan the operation of the vessel.

The objective of this thesis is to relate the extended operating context to a routing model, to achieve a more robust solution for a continuously changing market. Based on the Norwegian quota system and possible equipment configurations, the operation cycle of a typical Norwegian fishing vessel is investigated. Optimisation methods are utilized to develop a mathematical model that illustrates a vessel's operation cycle and will give valuable insight and knowledge about a combined problem that has not been explored before. The model is developed as a mixed-integer programming (MIP) problem and implemented by the use of the commercial optimisation software Xpress-IVE.

The vessel will aim to fulfill its acquired quotas, which is decided based on the gear types installed and the fish species that is targeted. The planning horizon is set to be 30 days, which is assumed to be long enough to capture the entirety of the cycle. Additionally, specific fish species require a given gear type, which again will affect the possible revenue. The type of gear being used is a deciding factor for both how much the vessel is capable of capturing during a day and on the quality of the fish product. The capacity of the vessel limits how long the vessel can be at sea before returning to a landing site for deliveries.

A computational study is conducted on a normal equipment combination operated today, and an attempt was made to also incorporate larger configuration changes. The results from the first test case illustrated that the vessel was able to fulfill it quotas, and conduct equipment changes while sailing from one location to another.

The problem is very complex and consequently not easy to either model or solve. Because the problem consists of multiple parameters that should have been modeled stochastically, the results were inconclusive for the second test case. Further research on both the model creation and the equipment configurations is needed before this model can be implemented in a decision making process.

Sammendrag

Norsk fiskerinæring har de siste årene hatt en jevn økonomisk vekst, men en øvre grense på hvor mye havområdene tåler har blitt nådd. Norske myndigheter har derfor gitt norske fartøy større muligheter til å ta i bruk nye redskapskombinasjoner gjennom et friere redskapsvalg. Ved å kombinere flere typer redskap, og dermed utvide tilgjengelige fiskerier, vil fartøyet oppleves mer fleksibelt i møtet med usikkerheter i industrien. Siden det i dag ikke blir delt ut nye kvoter, må et nybygg erstatte allerede eksisterende fartøy dersom det ønsker å operer innad i industrien. Dette kan medføre en større interesse etter fartøy med muligheter for kombinert drift i årene som kommer.

Formålet med denne rapporten er å kombinere de økte operasjonsgrensene med en optimeringsmodell i håp om å kunne generere robuste løsninger for en fiskerinæring i endring. Basert på kvotene tildelt fartøyet, samt de mulige utstyrskonfigurasjonene, forsøker modellen å forklare operasjonssyklusen til et fiskefartøy. I oppgaven benyttes det optimering til å utvikle en matematisk modell for å løse problemstillingen. Problemet som presenters i denne oppgaven, er modellert som et heltallsproblem, også kalt et Mixed-Integer Programming (MIP) problem, og er implementert og løst i den kommersielle programvaren Xpress-IVE.

Siden inntjeningen til et fiskefartøy er basert på hvor mye fisk den får solgt, er det ønskelig at kvotene fiskes opp. Kvotene baseres på hvilket fiskeslag som fiskes, i tillegg til utstyret som brukes. I ruteplanleggingen benyttes det en tidshorisont på 30 dager. Redskapet som benyttes påvirker i noen tilfeller kvaliteten på fisken, som igjen vil føre til en variasjon i salgsprisen. Fartøyets kapasitet setter begrensninger på hvor lenge det kan fiske før det må returnere til et fiskemottak for lossing.

For å illustrere hvordan modellen fungerer, samt dens begrensninger, er det konstruert to casestudier. Den ene tar for seg en normal driftskombinasjon som brukes i dag, mens den andre ser nærmere på hvordan en fremtidig løsning kan se ut. Resultatene fra den første kjøringen viste at fartøyet var i stand til å oppfylle kvotekravene, samt gjennomføre redskapsbyttet til havs. For det andre casestudiet viste resultatene at modellen har noen mangler relatert til de større redskapsbyttene, og det er ikke mulig å trekke noen konklusjoner basert på dette.

Problemet som undersøkes i denne rapporten er komplekst, noe som vanskeliggjør modelleringen av problemet. Siden problemet består av flere parametere som burde modelleres stokastisk, kan det lede til at resultatene er mangelfulle. Videre arbeid relatert til utvidelse og forbedring av modellen er nødvendig før modellen kan brukes i en beslutningsprosess, og det anbefales at de mulige redskapskombinasjoner utvikles i mer detalj.

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Chapter 1

Introduction

1.1 Background

For centuries the ocean has played a huge role in the Norwegian society. Today, all major industries in Norway are based on resources harvested from the ocean or ocean floor, including industries such as oil and gas, aquaculture, and fishery. Together with aquaculture, fishery is one of few export industries that has sustained an overall growth, thus being an important industry in Norway today (Tveteras et al., 2019). However, the quantity caught within the fishing industry has stagnated, as the graph in Figure 1.1 illustrates. While the whitefish fisheries has been somewhat stable, pelagic fisheries has seen a drastic decrease over the past 20 years. An upper limit for how much pressure the aquatic wildlife can withstand has been reached, and regulations and license regimes for participation in fisheries has been implemented several times. This has lead to a highly competitive industry, and in order to maintain a high profitability, shipowners has had to re-think how they operate their vessels.

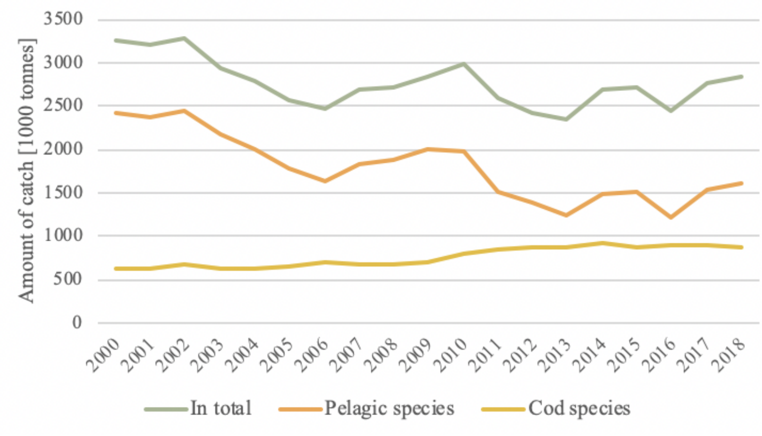


Figure 1.1: The amount of fish caught between the years of 2000-2018

For the past few years, the Norwegian government has investigated the possibilities for making it easier for ship owners to choose their desired gear combination. Now, the results from their efforts are starting to show. For example the newly build *M/S Atlantic*, an autoliner with capabilities of using a Scottish seine, recently started its operation (Lindbæk, 2020). The pay off from this innovative configuration is yet to be discovered, as the vessel mainly has been using its autoline so far. However, this shows that there are both possibilities and willingness to introduce new concepts and ways of thinking into an old, and traditional industry.

1.2 Problem Description

Today, fishing vessels are both designed and routed based on the ship owner's experience and existing know-how. The route planning of the vessel is performed after the vessel has been designed, taking the installed equipment, quotas, and statutory regulations restricting the number of licenses within a specified fishery into account. This implies that vessels are vulnerable in terms of the uncertainty of stock estimations. By better planning, ship owners may achieve a competitive advantage in a shifting market. In other words, there may be a large, unexploited potential of relating fishing gear combinations to the routing of vessels. In this thesis, optimisation methods are being utilised to gain insight of the operation's of a vessel, with the aim of achieve a more robust solution in a continuously changing market.

1.3 Objectives

This thesis will attempt to create a solution to the routing problem of a fishing vessel, when also considering the design and possible equipment configurations of the vessel. This means that the problem is two-sided, with the design aspect on one side and the routing problem on the other. The task of combining the process of vessel design with a routing model is something that has not been done before.

In order solve the problem at hand, the following set of minor objectives will be addressed:

- Present an overview of the importance of the Norwegian fishing industry, both historically and the present situation
- Introduce the main features of Norwegian fishing vessels, as well as the current rules and regulations
- Create a thorough problem description that captures the boundaries and characteristics of the problem
- Present relevant ship design theory and the concept of modularisation
- Give an overview of relevant routing problems solved in the past, and how these can be treated as an aid in solving the problem at hand
- Develop a routing model that can be used to optimise the fishing operation of a vessel
- Conduct a computational study showing how the model will optimise a given case

1.4 Limitations and Assumptions

This thesis is limited to Norwegian fishing vessels only, meaning that foreign vessels operating in Norwegian waters will not be considered. Further, the thesis will not include the Norwegian coastal fleet, but focus on the vessels participating in the offshore fishing industry. Choices taken during the creation of either the model or the modules, that in someways limits the real problem will be discussed when they are made.

It is assumed that the reader has a basic understanding of both the concept of ship design and modularisation, as well as simple vehicle routing theory. However, routing theory and relevant design methodologies will be presented in greater detail throughout the thesis, as it is important that the reader has a thorough understanding of the theories and concepts applied.

1.5 Thesis Structure

The master thesis is divided into nine chapters. Chapter 2 will provide an introduction and overview of the Norwegian fishing industry and current vessels, so that the reader will obtain the necessary knowledge needed to understand the full problem at hand. Additionally, it will be attempted to explain the complex rules and regulations related to the industry, especially regarding the quota licenses. Characteristics of the different gears will also be presented here, as these can make it clear which ones that can be combined on a vessel.

The problem description is given in Chapter 3, where the boundaries of the problem are set and the approach used to convert the real problem into an optimisation model is explained. An extensive literature review has been conducted in Chapter 4. This chapter will contain both literature regarding vessel design methodologies and modular approaches, as well as previous work done on the field of vessel routing. The overall methodology followed within this thesis is provided in Chapter 5, which also includes a thorough theory base.

In Chapter 6 the mathematical model developed to solve the problem is described along with an explanation of the modeling approach used. A computational study has been conducted in order to be sure that the model provides reasonable results. A full description of this study, along with the results obtained can be seen in Chapter 7. The overall discussion of the results obtained and approaches conducted will be given in Chapter 8, while Chapter 9 presents the final conclusions of this thesis.

Chapter 2

An Introduction to Fishing Vessels and Fisheries

In order to obtain a better understanding of the problem at hand, a more in-depth explanation of the fishing industry will be given. In Section 2.1, current rules and regulations in Norwegian fisheries is presented together with an explanation to why these were implemented and how they will impact the future development of the Norwegian fishing industry. The most important fisheries in Norway is presented in Section 2.2. An overview of the different types of fishing vessels operating in Norway will be given in Section 2.3. This section will also present typical characteristics for different fishing gears, which will form the basis for the later development of equipment modules as explained in Chapter 4. Lastly, a systematic breakdown of the operation of a fishing vessel is given in Section 2.4.

2.1 Laws and Regulations

Over the years, the Norwegian fishing industry has evolved from a virtually free fishing regime to strict regulations. For instance, Norway was the first country in the world to implement a quota system (Norwegian Seafood Council, 2020). In addition to the quota system, which will be further explained in Section 2.1.1, several other laws and regulations must be complied with. This section will briefly explain the most important ones, so that the reader have a basic understanding of how the industry is regulated.

The two most important laws are the Marine Resources Act and the Participation Act. Both acts are there to protect marine resources, and to ensure employment and settlement within the coastal societies of Norway. The Marine Resources Act is the legislation which allows the government to restrict total allowable catch, while the Participation Act regulates the vessels whom are allowed to participate in Norwegian fisheries. Together, the laws form the foundation of the so-called *license system* used in Norway. Simply put, the license system decides the number of licenses a vessel must obtain to operate in Norwegian waters. This includes licenses for participation, allowable quotas, and more.

2.1.1 The Quota System

As briefly mentioned in the introduction to this section, the Norwegian fishing industry was an open-for-all industry for a long time. Since there was no regulations within the industry, around 40,000 vessels were operating at its peak (SSB.no, 2018). With the technological development of both gears and equipment onboard the vessels, the efficiency of the fisheries went through the roof. For example, the implementation of the power block within pelagic fisheries lead to overfishing of several herring species during the 1960s, and the Norwegian government was forced to take action. An upper limit for the total allowable catch herring was set, and a ban on NSS-herring fishery was implemented. In addition, the so-called decommissioning scheme was introduced (Iversen et al., 2018). The main goal of the decommissioning scheme was to reduce the number of operating vessels by offering an economical compensation to ship owners and was mainly focused on purse seiners. A similar scheme was introduced for trawlers after a drastic decrease in the cod and saithe stock in the Norwegian- and the Barents sea during the late 80s. As illustrated in Figure 2.1, the number of operating ocean-going vessels decreased from about 1000 to approximately 590 vessels between 1960-1993. The decommissioning scheme implemented by the government was the direct cause for the discharging of 393 of these vessels, according to NOU 2006:16 (2006, p. 34).

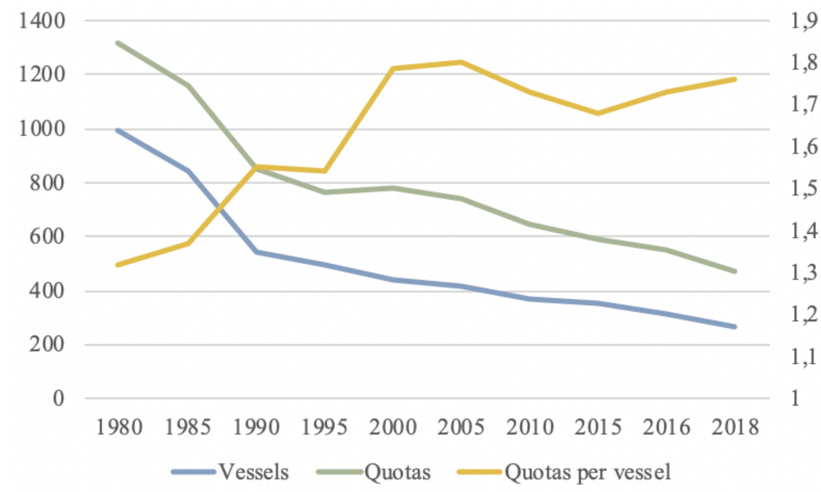


Figure 2.1: Graph showing the development of Norwegian fishing vessels within the ocean-going fishing fleet and the amount of quota licenses from 1980 to 2018 (Norwegian Directorate of Fisheries, 2019).

Due to restrictions limiting the herring fisheries, more pressure was put on the remaining pelagic species. Consequently, other pelagic fisheries gradually faced the same problems as herring. Thus, licenses for both participation and quotas was established for all fisheries. The number of quotas are illustrated as the green line in Figure 2.1. A quota is defined as a set quantity of fish that a vessel is allowed to catch during one calendar year (Norwegian Directorate of Fisheries, 2020). In addition, a unit-quota system was introduced to most of the vessel fleets. This system made it possible to transfer quotas from one vessel to another, for either a limited period or permanently, given that the vessel the quotas transferred from was scrapped (Norwegian Directorate of Fisheries, 2019). Up until the 1980s, the license per vessel ratio was close to one, meaning that most vessels only had one quota. With the new initiative, combined with the decommissioning scheme, this ratio has increased to 1.8, as illustrated in Figure 2.1. Over the years, this system has been redeveloped several times, and today a vessel is allowed to hold up to four quotas within a certain fishery, with some exceptions.

As previously mentioned, Norway was the first country in the world to implement a quota system on fisheries. Today, most fisheries around the world are regulated to some extent, and countries are dedicated to meet these quotas to ensure the future of fisheries. (Norwegian Seafood Council, 2020). The size of the quotas are based on research and are decided as a result of international negotiations. In Europe, it is the International Council for the Exploration of the Sea (ICES) that determines the total allowable catch for the different species in the different catching areas, while the Institute of Marine Research (HI) decides the sizes of quotas for Norwegian waters. The quotas are, in most cases, given as a quantum of fish, but can also be given as a number of individuals, or the number of days allowed to fish.

As illustrated by the map in Figure 2.2, Norway has control over the majority of the areas within the North Atlantic and the Barents Sea due to its vast coastline and the sovereignty of Svalbard and Jan Mayen. This means that Norway has jurisdiction over a huge amount of marine resources. However, the overall quotas set by ICES are to be distributed between all parties in an area, sparking discussions between nations located at the border lines. ICES and the North-East Atlantic Fisheries Commission (NEAFC) are central when it comes to dividing the total allowable catch (TAC) between neighbouring countries. Therefore, Norway have cooperation agreements with Russia, Iceland, Greenland, and the EU, meaning that registered vessels within these countries are assigned a small quota for fishing in Norwegian waters, and vice versa (Norwegian Seafood Council, 2020).

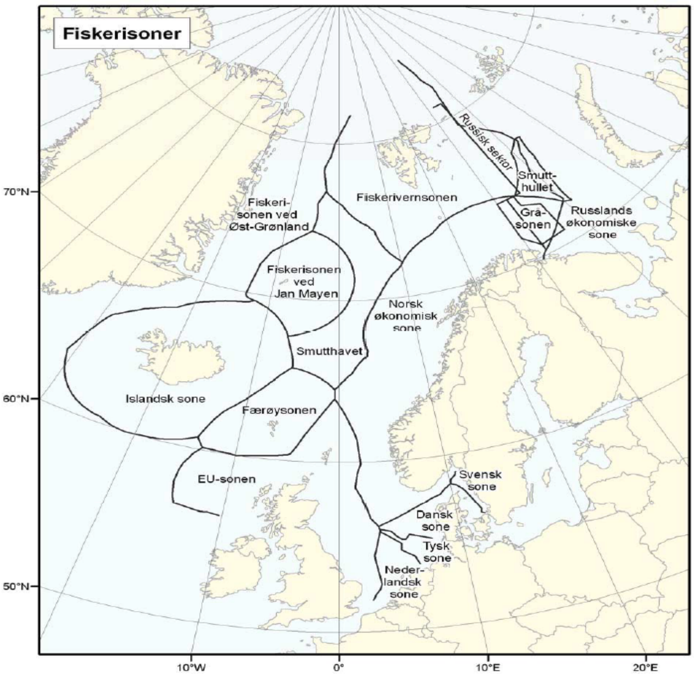


Figure 2.2: The fishery zones in the North-East Atlantic and Barents Sea, which are all relevant for the distribution of quotas for Norwegian vessels (Lilleng et al., 2010).

Distribution of the Norwegian Total Allowable Catch

Out of the total allowable catch assigned to Norwegian vessels, the quotas are divided as illustrated in Figure 2.3. 30% of the TAC is allocated to the trawler fleet through the structural quota system. The remaining 70% is allocated to the conventional fleet, which are further divided into two sub-groups, Group I and Group II. Group II, consisting of vessels that are under 11 meters and registered as fishermen, is given 10% of the TAC. Group I is further divided into conventional vessels above and under 28 meters, where the vessels above 28 meters mostly belong to the ocean-going fleet. The ones under 28 meters belong to the coastal fleet, and will not be included in this thesis.

This division of the TAC remains somewhat constant, although the size of the quotas will vary due to both the decisions made by ICES and NEAFC, and the number of actors within each group. Furthermore, there are some special agreements between countries, leading to some extra quotas for certain vessels. Some examples of this are participation in fisheries on East and West Greenland, Flemish Cap and the Irminger Sea. These quotas are divided between trawlers, and will give each trawler an extra trip each third year. The quota sizes are given for each species, and will be shown for the most prominent species in the following section.

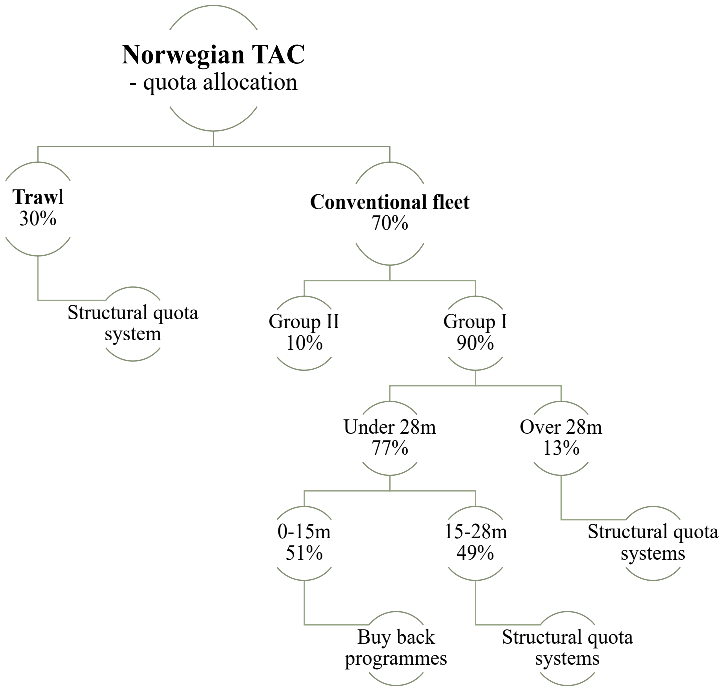


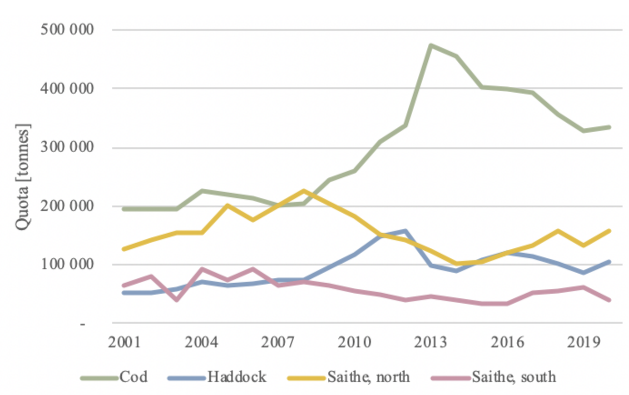
Figure 2.3: Quota allocation of the total allowable catch (TAC) in Norway. By Trawl it is referred to ocean-going vessels. Illustration made based on information given in lectures.

2.2 Fisheries

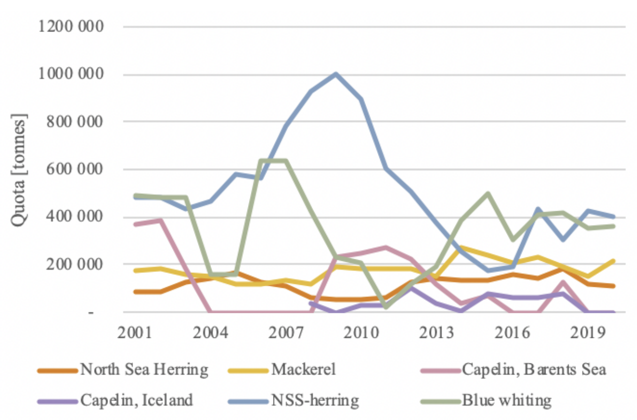
In addition to the quantities that are allowed to catch, some fisheries have restrictions on when and where they are allowed to be targeted. This will be further explained in this section.

Within the Norwegian fisheries, there are two main fisheries to consider: the pelagic and the whitefish fisheries. The two groups are defined by where the fish is located within the water column, but can also be divided based on their size. In pelagic fisheries, meaning species living most of their lives within the pelagic zone of the ocean (being neither close to the bottom nor the shore), the most important species are the mackerel, blue whiting, the North Sea herring, and the Norwegian spring spawning (NSS) herring. Moreover, the capelin has been an important species, but due to overfishing and a large cod stock, the capelin stocks have been critically low. Since the capelin is quite important for the ecosystem in the Barents Sea, a ban on the fishery has been in place for several years. The possibility of a re-opening of the fishery has been discussed, and small quotas both within Icelandic waters and in the Barents Sea has been given. However, there are no signs of a permanent reopening, and the species will not be included in further works. The whitefish fisheries consist of the three main species Atlantic cod, haddock and saithe, with additional by-catch quotas on various species. In addition, Atlantic shrimp is often mentioned in the same breath, as many whitefish trawlers also have the capability of fishing shrimps.

The development of the total quota sizes can be seen in Figure 2.4 below. Here, we can see that cod and herring are the most important species in terms of quantity. However, while the cod quotas have had a positive development, the quotas for NSS-herring have gone through a drastic decrease. This is a direct consequence of working with a living biomass, which will have huge fluctuations in both whereabouts and size. In addition, pelagic species are often a part of the diet of more prominent species such as the cod, meaning that a high stock of cod can lead to a decrease in the size of some pelagic stocks. Overall, the whitefish stocks can be said to be more stable, whereas the pelagic ones are more fluctuating.



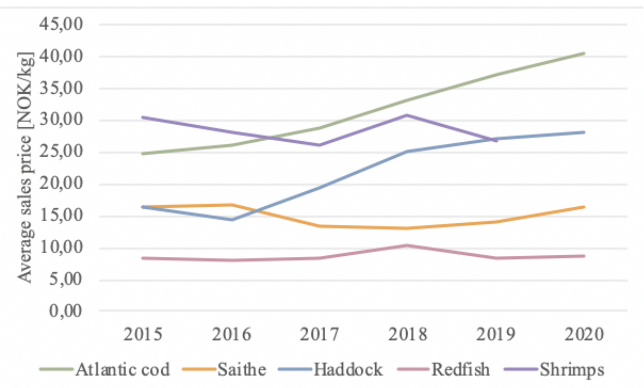
(a) Whitefish species



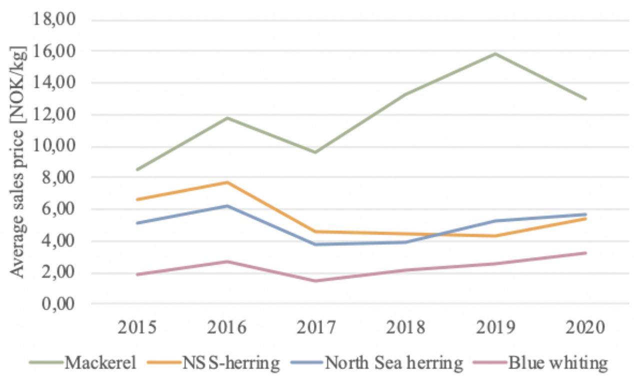
(b) Pelagic species

Figure 2.4: Development of the TAC for the most important fisheries in Norway. The graph on the left shows the development for whitefish species, while graph on the right shows the development of the pelagic species.

Most pelagic species are found in schools. The high density of fish leads to large catch rates when a school is located. In such schools there can be several millions of individuals, making the total biomass extremely high. This is the reason for the quotas being so much larger for pelagic species than they are for whitefish species. The sales price of the fish is varying based on the equipment used and when the fish is caught. Figure 2.5 shows the average sales price for different fish species. Here, it is worth noting that these prices are averages for all fish landed, not taking into account the type of equipment used. The prices have been varying over the last six years, some more than others. Especially the price of haddock and cod has seen a large increase, while the saithe has been somewhat stable. Regarding the sales price of the pelagic species it is mostly the mackerel that have seen large variations.



(a) Whitefish species

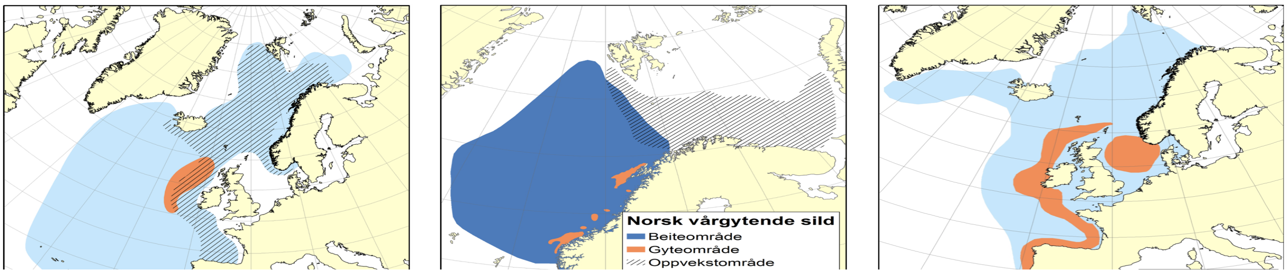


(b) Pelagic species

Figure 2.5: The graphs show the average sales price during the last six years for different species, regardless of gear type. The price is given in NOK per kilo fish delivered from the vessel.

Geographical Distribution and Seasonal Variations

Lilleng et al. have conducted a quite extensive research on when and where the most common fish species occur. Figure 2.6 shows the prevalence of the three most important pelagic species, as previously discussed. The NSS-herring is located in most of the Norwegian Sea, and at the edges of the Barents Sea, thus being quite important for the ecosystem here. The NSS-herring fishery takes place at three different stages of during a year; in the winter during spawning along the Norwegian coast, in the summer during their feeding migration, or in the fall when the fish returns to the coast for overwintering. However, the quality of the fish is low during the summer months, and Norwegian vessels do not not participate in this stage of the fishery. The North Sea herring is only located in the North Sea, thus it is not illustrated. It can be targeted year-round, but the best quality is obtained towards the end of the year. The blue whiting can be found in most of the North East Atlantic, but the fishery takes place to the west of the British Islands, and in the waters around the Faroe Islands, denoted the EU-zone, during the spawning season in the spring. The mackerel is one of Norway's most important and valuable stocks, and can be found all the way from the Spanish coast in the south, to Svalbard in the north. The main part of the fishery takes place during the autumn months, however, catches are reported from outside the Norwegian zone in January and February as well.

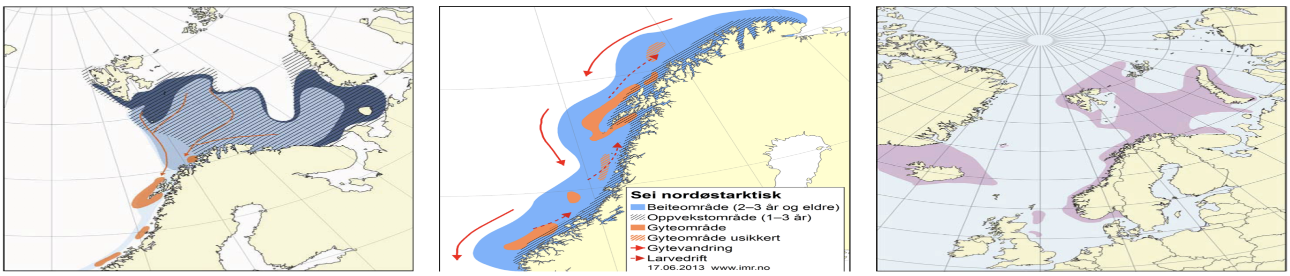


(a) Blue whiting **(b)** NSS-herring **(c)** Mackerel

Figure 2.6: The prevalence of the three pelagic species blue whiting, NSS-herring and mackerel (Havforskningsinstituttet, 2020).

The Atlantic cod is a migrating fish, with most of the commercial fishery going on far north, or outside of Lofoten from January to April. Because the stock migrates so much, a large part of the quota is divided equally between Norwegian and Russian vessels. The Northeast Arctic haddock can be found both along the Norwegian coast and the Barents Sea, or even in the North Sea. There is no specific fishery going specifically towards haddock, but it is an important species to include as most vessels will have a small by-catch quota on the fish. Because of this, there are no other regulations on when and where the fish can be caught. Another important whitefish species is the Northeast Atlantic saithe, which is roaming much of the same waters as the Atlantic cod and haddock. In addition to the Northeast Atlantic saithe, stocks of saithe in the North Sea are also fished, thus the quotas are divided between saithe north and south of 62°. Most vessels operating within Norwegian waters have a quota on saithe due to the prevalence of the fish.

The Atlantic shrimp is also included here, as it is a possible combinatorial operation for many fisheries. Most of today's catch is retrieved in the Barents Sea on the boarder to Russia, often by large stern trawlers or shrimp trawlers. The shrimps are mainly caught after the main cod season is over, meaning from early May until approximately the start of September. Shrimp fishing is also being carried out in the North Sea and Skagerak, but the amounts available here are not that high, averaging at 8000 tonnes the last years. The licenses for shrimp in these areas are divided between several countries, and almost exclusively targeted by small shrimp vessels. Thus, it will not be relevant to consider this fishery in the thesis.



(a) Atlantic cod **(b)** Northeast Atlantic saithe **(c)** Atlantic shrimp

Figure 2.7: The prevalence of the three demersal species Atlantic cod, Northeast Atlantic saithe and Atlantic shrimp (Havforskningsinstituttet, 2020).

The seasonal variations are important to consider, both in a regulatory matter and when looking into which fisheries that may be combined. In Figure 2.8, seasonal variations in catch rates has been illustrated using landing declarations from Fiskeridirektoratet (2019). However, none of these fisheries are closed outside their main season, but the highest quality and quantity can be expected to achieve during these months.

The number of different species that could be targeted is of course much higher than the ones presented here. Several demersal and deep-water species have not been mentioned, such as the Greenland halibut and redfish, although they are important species for the Norwegian fishing industry. This is because the quotas offered are often small, and given as by-catch quotas. The Greenland halibut fishery is only open for two months during the year, with one total quota for the two months. Thus, it is hard to predict how much one vessel can catch. In the computational study, the fishery of redfish and Greenland halibut will be included to showcase how small fisheries like these can impact the overall routing of the vessel.

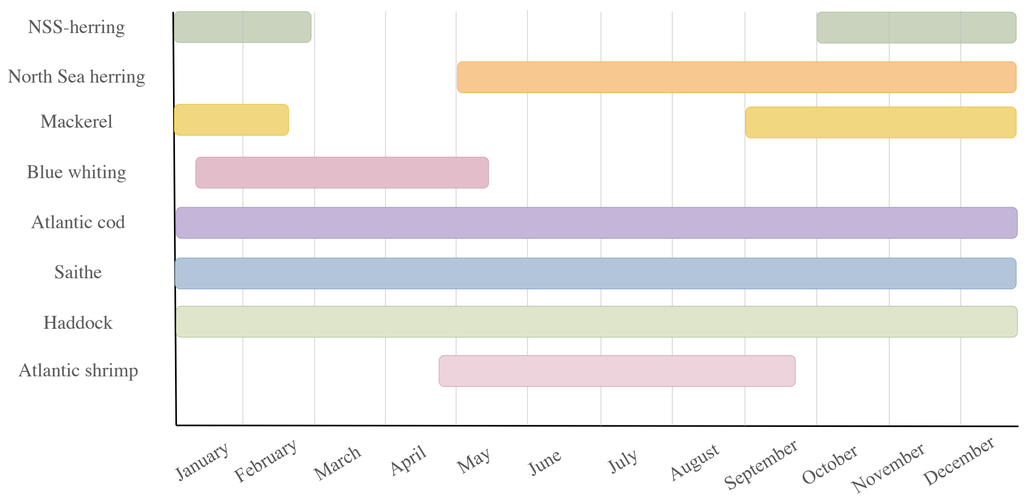


Figure 2.8: Diagram showing the main seasons of selected fisheries to consider in this thesis. None of these fisheries have restrictions on when they are allowed to be caught, however the quality and price of the fish is considerable higher during these time periods.

The table below summarizes the information given above, including the quotas relevant for this thesis. This means that out of the total quota of 2020, which is to be divided between small, privately owned vessels, the coastal fleet, and the ocean-going fleet, only the latter is displayed in the table. Because the dividing of quotas are quite complex, especially in the Barents Sea and on the border to Russia, it has been chosen to use approximate numbers on the quotas for the whitefish.

Table 2.1: Overview of characteristics of different species, including the main season and where to fish, and the total quota size for 2020. The vessel quota is dependent on the quota factor held by the vessel, and will only be given for the computational study.

Species	Location	Season	Quota [tonnes]
Atlantic cod	Barents Sea & off the coast of northern Norway	All year	130.222
Atlantic shrimp	Barents Sea	May-September	28.000
Northeast Atlantic haddock	Norwegian coast, the North Sea & in the Barents Sea	All year	50.643
Northeast Atlantic saithe	North of 62° South of 62°	All year	62.800
Blue whiting	EU-zone around the British islands	January-May	330.283
	Faroese fishing zone		30.000
North Sea herring	North Sea	May-December	112.340
NSS-herring	Norwegian Coast Barents Sea	October-January October	223.049
Mackerel	North Sea and along the coast	September-November & January	157.349

2.3 Fishing Vessels

As showed earlier, the Norwegian ocean-going fishing fleet consists of approximately 270 vessels. However, by going through the Register of Norwegian Fishing Vessels and removing vessels that either have a LOA below 30 meters or doesn't operate in Norwegian waters, the number of vessels is narrowed down to about 135. Out of these, three main groups of vessel types have been identified based on their main operating mode. When identifying the vessels main operating mode, the Register of Norwegian Fishing Vessels has been used in combination with the Register of Landings for each vessel. Then the gear type used for the largest part of their operation is defined as their vessel type group. The pie chart in Figure 2.9 illustrates the distribution of vessels within each main group, given as trawlers, purse seiners and conventional vessels respectively.

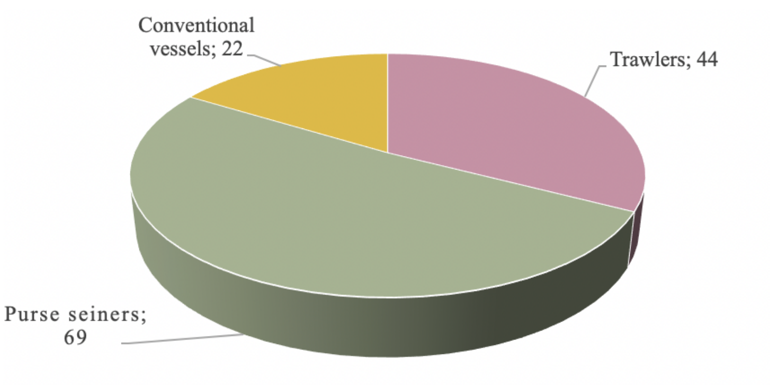


Figure 2.9: Distribution of the type of vessels in the Norwegian ocean-going fleet.

As shown in Figure 2.9, the majority of vessels fall within the purse seiners category. In the pelagic industry, which is were purse seiners operate, it is normal to have a combined gear operation. Hence, many vessel will have a purse seine installed as their main gear, but also have a pelagic trawl onboard for catching when the purse seine is not suitable. Out of the 69 vessels belonging to the purse seine-group, 54 of them can operate such a combination. When we talk about vessels belonging to the group of trawlers, we distinguish between pelagic and white fish trawlers. This is due to the difference in both how the catch is handled onboard, and how the different types of trawls operate. Pelagic trawlers make up about 12 of the 44 vessels, while the whitefish trawlers make up the rest. Within the conventional vessels group there are about 22 vessels. Vessels belonging to this group are using conventional fishing gears, meaning gears such as longlines or nets. As illustrated in Figure 2.3, conventional vessels are given quotas based on different criteria than the trawlers and purse seiners. The size of the cargo hold and the vessel itself are the most important factors considered when deciding the quota size.

Figure 2.10: Illustration of three typical fishing vessels. Bømmelfjord, a pelagic trawler on the left, the autoliner Geir II, and the purse seiner Fiskebas (Eidesvik Havfiske, 2020; Baltic Shipping, 2019; Fiskebas, 2019).

To give the reader a better understanding of what type of vessels that are being discussed here, an illustration of the three main groups are given in Figure 2.10 above. Although the vessels have quite similar appearances, there are some major differences between them. Different gears will have different requirements to deck space and configurations, while the species caught will have different needs in regards of handling and processing. For a conventional vessel such as a autoliner, most of the operation is carried out inside the vessel, hence not requiring an open deck space. On purse seiners, on the other hand, power blocks and fish pumps are required, meaning that an open deck space with a lot of equipment must be available. For vessels targeting whitefish species, large freezers are needed along with some processing equipment. Pelagic species are rarely processed at sea. Instead, they are stored on RSW-tanks and pumped directly from the vessel to the landing site.

2.3.1 Design Characteristic of Different Fishing Gears

Within the Norwegian ocean-going fleet, there are several different types of gears being used, although some are more popular than others. The pie chart in Figure 2.11 shows the distribution of catch between the different gears, while Table 2.2 shows the total amount caught by each gear respectively. In the following section, a brief explanation of the working principles of different gear types are given.

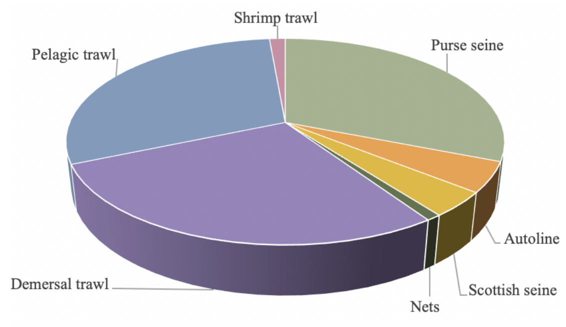


Figure 2.11: Chart showing the distribution of catch between different gears.

Gear type	Tonnes caught
Purse seine	523.131
Pelagic trawl	506.681
Demersal trawl	473.995
Autoline	79.698
Scottish seine	65.878
Shrimp trawl	23.489
Nets	15.757

Table 2.2: Tonnes caught in 2019 divided between the different gear types.

Purse seine

Purse seining is an important fishery in Norway, and is also on of the most effective gears in use today. The working principle of the gear is illustrated Figure 2.12. The operation start by deploying one end of the seine, then proceeds to encircle the school of fish with the seine until it reaches its starting point. The seine is then *pursed*, meaning that the bottom of the seines is closed so the fish cannot escape. Next, the hauling of the seine starts, before the fish is brought onboard the vessel.

When purse seines are being used, there are some required equipment that must be in place. Firstly, a type of power block to haul the seine must be installed. Today, the so-called Triplex-system is often used on vessels. This system will aid the hauling process of the seine in a safe and effective matter, and also prepare the seine so it is ready for the next haul. Next, a fish pump is used to move the fish from the ocean onto the vessel.

Due to the nature of the gear, purse seines are used on species that swims in schools. The most important species are the NSS-herring, the North Sea herring, and mackerel. The fish if usually stored in RSW-tanks on the vessel.

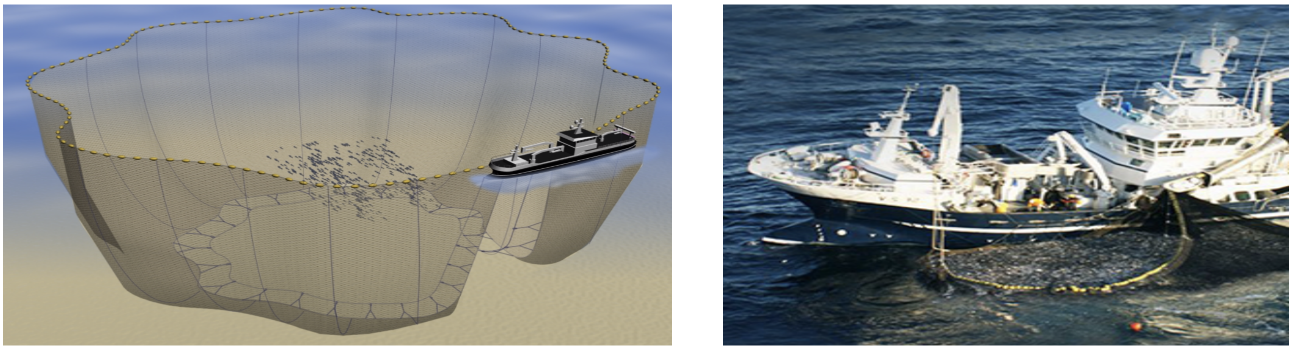


Figure 2.12: Illustration of the layout of a purse seine and the hauling process (Seafish, 2019).

Trawl

Trawls are probably the most versatile fishing gear, and out of the almost 2.5 million tonnes of fish caught in 2019, trawls contributed with about 1 million tonnes as given by Table 2.2 (Fiskeridirektoratet, 2019). The working principle is quite simple, with a cone-shaped bag being trawled through the water by a vessel. As mentioned in the previous section, we divide the group of trawlers into to sub-groups, mainly pelagic trawlers and white fish trawlers. These types of trawls have different characteristics regarding size, area demand, and also the targeted species, and will be further explained below.

Pelagic trawl

The pelagic trawl is by far the largest fishing gear used today, with a total area of up to 40.000 m^2 at the trawl opening. An illustration of a typical pelagic trawl can be seen in Figure 2.13 below. A pelagic trawl is towed in mid-waters by a vessel, and is spread horizontally by a set of trawl doors. The trawl has a square shape, made up of a panel above and below, and two side panels.

Like the purse seine, a pelagic trawl is extremely effective due to its size. As mentioned, these two gears are often used in combination with each other, as they target most of the same species. In addition to mackerel and herring, a pelagic trawl is used to catch blue whiting as well, since the trawl can operate at greater depths than a purse seine. When used in combination, the hauling process is basically the same as for the purse seine: the trawl is hauled at the side of the vessel by the use of a triplex system, and then the fish is pumped onboard. The trawl bag is then gathered on the net drum, and made ready for the next trip.

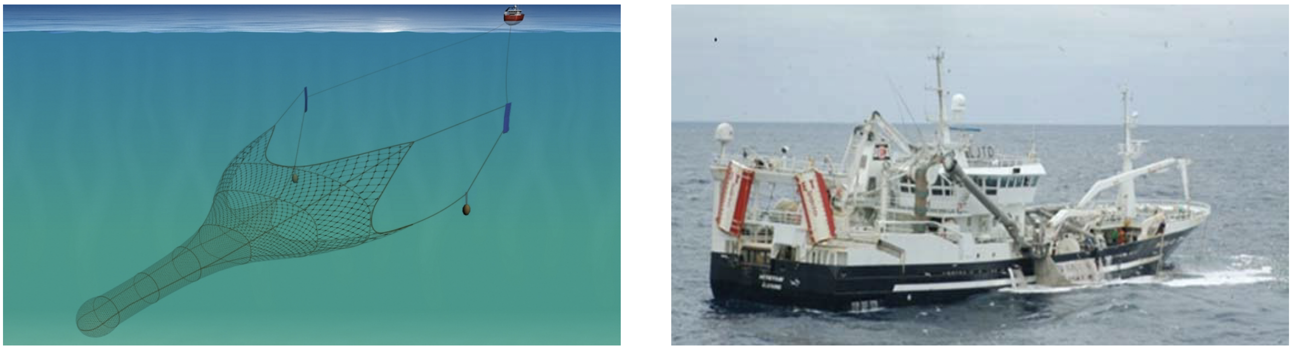


Figure 2.13: Illustration of the layout of a pelagic trawl, and the hauling process (Seafish, 2019; Lilleng et al., 2010).

Demersal trawl

The demersal trawl, often referred to as a white fish trawl or bottom trawl, is towed along the sea bottom. As a result, the layout of the trawl is quite different from a pelagic trawl. The demersal trawl consists of two net panels, one on the top and one on the bottom, and is opened by the use of floaters attached to the headline, and two trawl doors attached to the sweeps at each side. On the bottom net panel, steel bobbins are used to keep the trawl towards the bottom, while the ground gear is used to keep the trawl elevated from the sea bottom.

Today, demersal trawls are mostly used onboard stern trawlers, meaning that the trawl is both hauled and deployed from the stern of the vessel. The entire trawl is hauled onboard the vessel and then emptied into the processing facilities directly. To do this, an extensive amount of winches is needed. The most common species caught using a demersal trawl are the Atlantic cod, haddock, saithe, and Atlantic halibut.

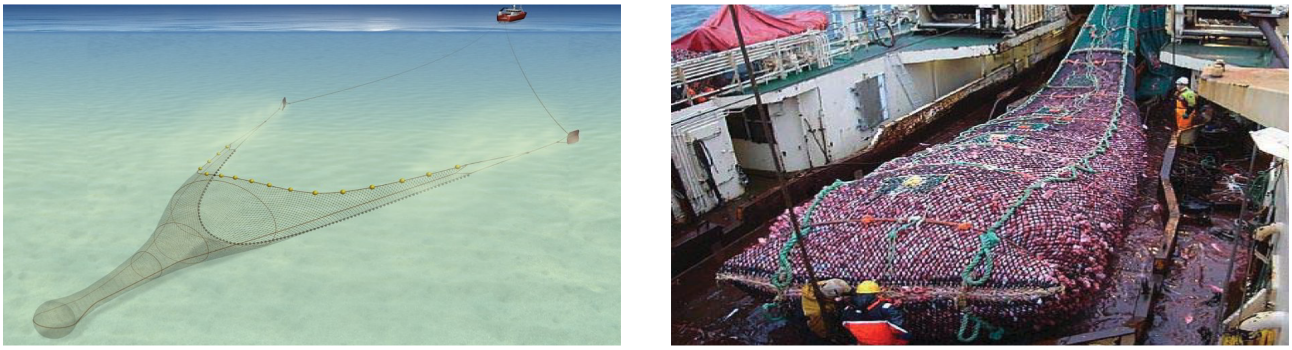


Figure 2.14: Illustration of the layout of a demersal trawl with otter boards on the left, and the hauling process on the right (Seafish, 2019; Lilleng et al., 2010).

Shrimp trawl

Many of the white fish trawlers also have licenses to attend the shrimp fishery, having a combined operation with the use of shrimp trawls as well. These trawls are quite small in size, and the mesh size of the net is very fine. For vessels that have a quota on shrimps, many will have a boiler installed in its factory to maintain a high quality of the shrimps. Shrimps that are not boiled are sold as *industrial shrimp*. In these cases, the shrimps are frozen directly after they are brought onboard. The shrimp trawl is handled in the same matter as a typical demersal trawl, thus being well-suited for combined operations.

Scottish seine

In Norway, the Scottish seine is the most widely used demersal seine, and is best described as a combination of a purse seine and a trawl. The layout of the gear is given in Figure 2.15, and resembles the look of a trawl. However, the Scottish seine has large wings on either side of the trawl opening to better trap the fish within the trawl bag. The deployment of the gear is similar to the method described for a purse seine: the vessel will encircle an area where the targeted fish is located by shooting one of the buoy and starboard arm (rope), before setting the seine and the port arm. When the vessel has returned to its starting position, the towing of the gear begins, lasting for about 30-45 minutes. Then the ropes are retrieved by the use of winches, and the catch is often pumped onboard the vessel.

The Scottish seine is mostly used on the same species as the demersal trawl, meaning the Atlantic cod, saithe, haddock, and the Atlantic halibut. The gear is only used in combination with other gear types, especially with autoline. However, due to its similarities with both trawls and purse seines, new combinations can be suitable in the future.

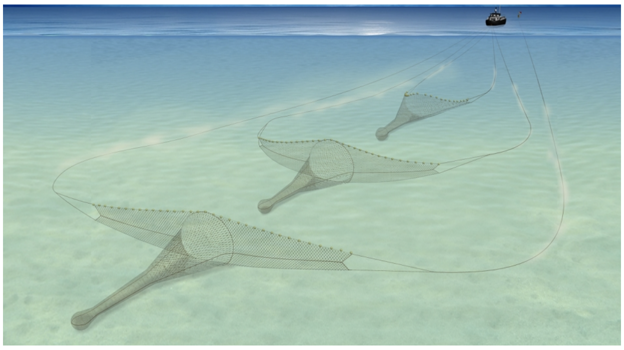



Figure 2.15: Illustration of the layout of a Scottish seine and the hauling process, here illustrated by a coastal vessel (Seafish, 2019; Scanfishphoto, 2015).

Autoline

The use of longlines has long traditions within the fishing industry, and can provide the highest quality of caught fish. Over the years, this fishing method has gone from being quite labor intensive, to highly automatized by the extensive use of technological equipment. The necessary equipment is illustrated in Figure 2.16. Concerning the vessel's design, some important features must be included. When shooting the line, an opening in the hull is needed. Here, the linesetter, which will drag the line from the magazine holding the lines through the bait machine and then into the sea, is located. A buoy with a weight attached will help the line deploy from the vessel. When all of the line is shot, the hauling process begins. The hauling of the line is conducted by the hauling unit and line retriever. The line is dragged through a system of pipes inside the vessel, before being attached to the magazines again, cleaned and separated, ready for the next shooting. Modern vessels will have a moon-pool in the hull where the line is retrieved, which has increased the safety of the crew and reduced the loss of fish, especially in bad weather (Hallenstvedt and Dybdahl, 2018).

Within the ocean-going fleet, the type of line used is called a *bankline*, and the fishing will mostly be conducted towards the sea floor. The species targeted are mostly the demersal ones, and with the gear being a so-called active fishing gear it is well-suited for larger fish or species distributed over bigger areas, thus not typical shoals. Atlantic cod, haddock, Greenland halibut, and the common ling are species that are caught using autolines.

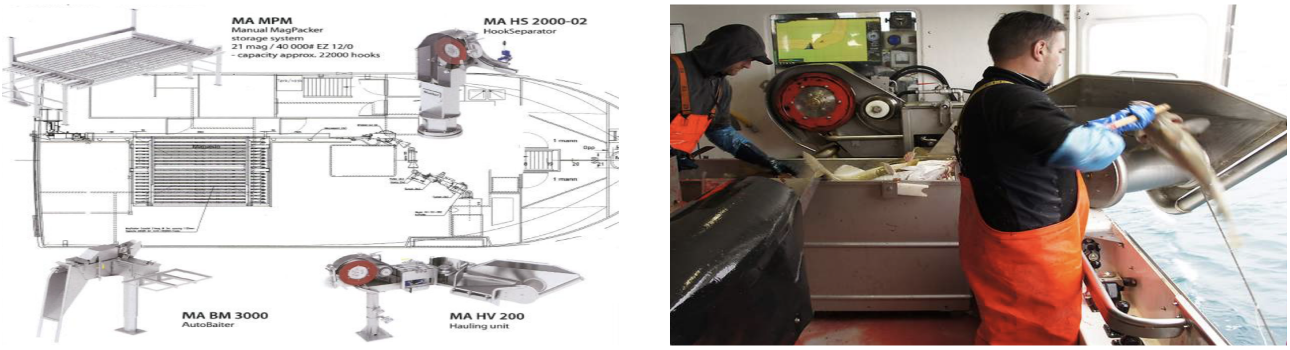


Figure 2.16: Illustration of the deck arrangement and the hauling process on a autoliner (Mustad Autoline, 2019).

Nets

As showed, fishing with nets are rarely done in the ocean-going fishing fleet, and is more widespread within the coastal fleet. On some autoline vessels, nets are used in combination with the lines, as the deployment of the gear is quite similar. The principle of a net is simple: it is deployed using buoys and weights at an area where the fish is migrating. The nets are made to fit the fish targeted by varying the mesh size, the thickness of the thread, and also the colour of the thread used. The soaking time of the net, meaning how long the net is active in the sea, is very important to consider with respect to the quality of the fish. With the quality already being lower than with use of other gear, as the fish can further damage itself trying to get free of the net, fish can start to rot if the soaking time becomes to high.

The use of nets is almost exclusively used on saithe in ocean-going fishing, but most species can be caught using this gear. With nets being a passive fishing gear, the by-catch rate can become high if the gear is not used right.

Figure 2.17: Illustration of the working principle of a net, and Vestliner, a vessel with combined net and lining operations (Lilleng et al., 2010; Redaksjonen, 2018).

2.4 Operation of a Fishing Vessel

The operation's of a fishing vessel is a continuous process, as shown in Figure 2.18. This cycle represent a single trip, meaning that the vessel will start and finish in the same operation mode, being a port facility or at sea. Assuming that the vessel's starting point is at a port facility, the vessel will begin preparing for its trip here. This will include filling up fuel tanks, making sure that the water tanks and provisions are fully stocked up, and that the gears to be used on the following trip are onboard. Every four to six weeks there will be a crew change which will take place when the vessel is at shore, however the exact place is not important to consider.

When the vessel is ready, it will sail to a fishing ground chosen based on the fishery it is going to target. The time spent sailing is highly dependent on where the vessel is heading, and the weather conditions at the time. At the desired fishing ground, the captain will initiate fish searches. Depending on the targeted species, this can be done by the use of either echo sounders, sonars, information acquired from other vessels, or other tools. When a school of fish is located, the crew on deck will deploy the fishing gear. The vessel will continue the fishing operations until the capacity of the vessel is reached. How fast a vessel can reach its capacity will of course depend on the size of the vessel, as well as the effectiveness of the gear type in use and the density of fish in the area. If the captain is not satisfied with the catching, the vessel will move around and sail to other areas searching for more fish. With a full cargo hold, the vessel will sail to the nearest port facility for unloading. These port facilities are known as fish landing sites, and a certain vessel will often make use of a handful of such desired ports. At the landing site, the vessel will unload its fish and start to prepare for its next trip, hence completing the cycle.

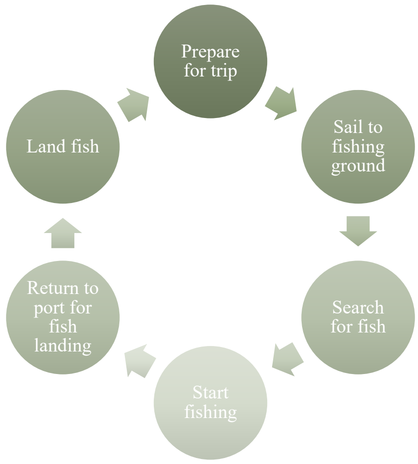


Figure 2.18: Operation cycle of a typical fishing vessel.

For a vessel that is able to shift its operating mode from one gear type to another, the operation cycle is somewhat different. Below, Figure 2.18 has been slightly altered in order to show where these differences occur. For a vessel that have been designed for a change in operation mode, the blue circle in Figure 2.19 is used. This is the case for the vessel *M/S Atlantic* which was mentioned in the introduction of the thesis (Lindbæk, 2020). This vessel has been designed in such a way that all equipment needed are either installed or stored onboard at all times. When the vessel needs to go from one operating mode to the other, it can perform the gear change at sea in approximately 15 minutes.

The pink circles in the figure is meant to illustrate a vessel conducting a more complicated and time consuming equipment change. For example, this may occur if the vessel must pick up equipment on land, or if the vessel must undergo alterations which require a visit to a shipyard. The latter is is course more time consuming, and more costly, and there aren't many vessels who conducts such changes today. For a combined pelagic trawler and purse seiner, the pick-up alternative is relevant. When operating, the vessel will only carry the equipment needed for one of the gear types, meaning it must sail to its depot port to pick up new equipment, and unload the excess equipment. This leads to a higher sailing cost due to the extra time spent on sailing between the port and the fishing ground.

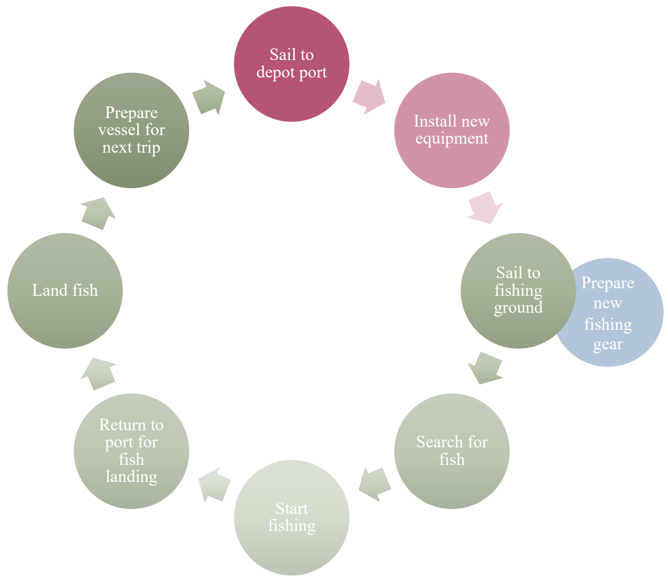


Figure 2.19: Operation cycle illustrating a vessel that can shift its operation mode. The pink circles are applicable when the change in gear requires more effort, i.e. if equipment modules needs to be placed onboard. The blue circle indicates a simple switch, which can be done while the vessel is sailing.

Chapter 3

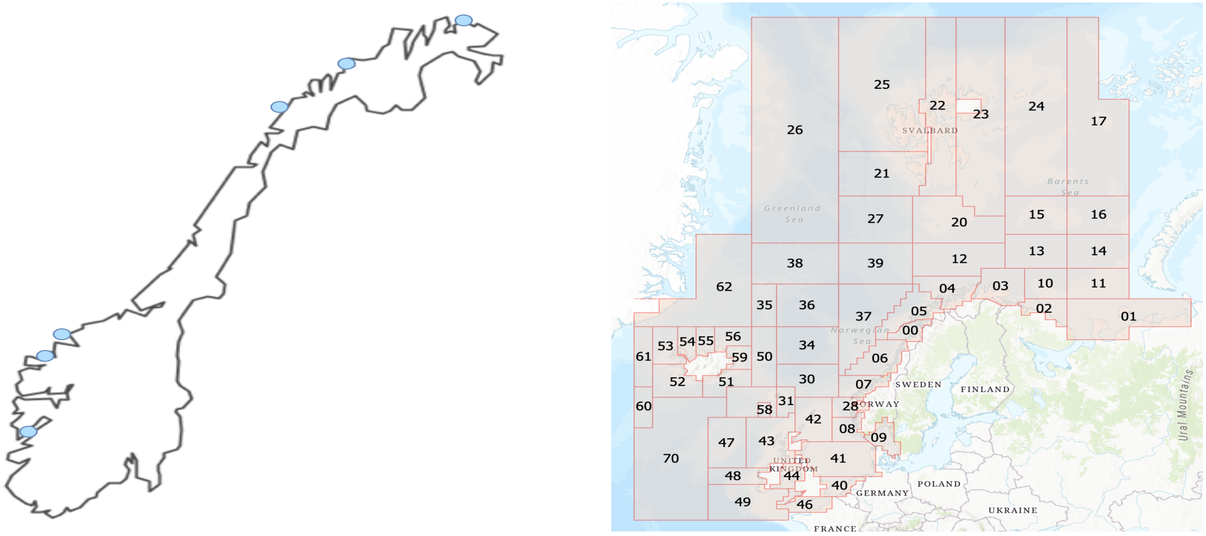
Problem Description

This chapter will describe the simplified problem regarding routing of fishing vessels, and is based on the introduction into fishing vessels and fisheries given in Chapter 2. The problem description will give the reader the necessary information required to understand the mathematical problem which is created in Chapter 6. Firstly, the geographical domain of the problem will be described in Section 3.1, including how the different nodes are defined. This section will mainly be focused on the fishing locations, as the landing sites are of lesser importance due to their density along the Norwegian coast. In Section 3.2, the significance of the vessel characteristics will be described, together with an illustration of how the routing model should operate.

3.1 Geographical Domain

The geographical domain is important to define at an early stage, otherwise, the problem can become quite complex and less accurate due to the amount of information that is needed. The complexity of a optimisation model will increase with the problem size, implying that a geographical constraint on the problem is important. This is further described in Chapter 4. As in every vehicle routing problem, a set of nodes is needed to create the model. In this case, there will be a total of four node types to consider, where the landing sites and the fishing grounds are the main ones. As given in Chapter 2, the operations will take place in the waters surrounding Norway, and in landing sites along the Norwegian coastline. In addition, an initial starting node and a dummy end node is needed for programming purposes.

The landing sites and fishing grounds in the problem are illustrated in Figure 3.1. With Norway having long traditions within the fishing industry, there is a huge number of available landing sites along the coastline. A loaded fishing vessel will choose which site it unloads its cargo based on two criteria: where the vessel is located at the time, and who has bought the fish onboard. Thus, a vessel will often have a handful of possible landing sites to choose from, and it is assumed that it will choose the nearest one. A simple sketch showing some available landing sites is given in Figure 3.1a. When it comes to the fishing grounds, which are scattered all over the ocean, a more in-depth division is needed. This thesis will use the division set by ICES and the Directorate of Fisheries, as illustrated in Figure 3.1b. Thus, one node will correspond to one of these individual areas. What is worth noting, is that when a vessel is unloading its catch at a landing site, it has to report the area of catching to Norwegian authorities. These catch areas are a further division of the ICES areas, and can be seen on the website belonging to the Norwegian Fishermen's Sales Organization for Pelagic Fish. It has been chosen not to use these catch areas in this thesis due to the complexity that would be obtained.



(a) **(b)**

Figure 3.1: Figure 3.1a illustrates the different landing sites used to unload the fish, while Figure 3.1b gives a simple overview of the different locations for fishing (ArcGIS, 2018).

Furthermore, the type of fisheries available and the fishing gears that are allowed to use within each fishing ground must be included. As described in Chapter 2, some areas are more prone to certain species of fish, and also to the fishing gears that are allowed to use due to vulnerable ecosystems. Thus, a given node may have restrictions on when it is allowed to fish there, what type of fish that can be caught, and the type of gear that is allowed to use. This is taken into consideration by feeding the model with information about the node, as illustrated in Figure 3.2. However, it is only the fishing ground nodes that require this type of information as the landing sites will be independent of all these factors. In some cases, there might be restrictions on the type of fish that can be offloaded at a landing site, but this will not be taken into account here. A parameter that explains the node type is included in the model to account for the difference between the two types.

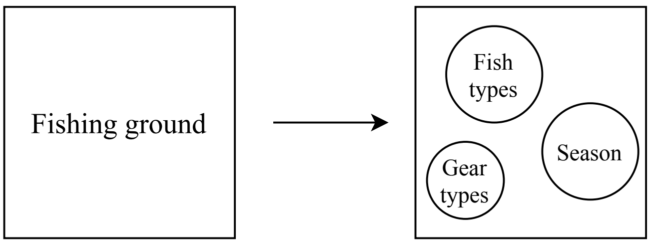


Figure 3.2: Illustration of the information contained in a fishing ground node.

As discussed in the previous chapter, different species are targeted in different time periods during a year. Thus, information about seasonal variation in the fisheries is also included in the fishing ground node. Some species don't have distinctive seasons, and are targeted when other, more profitable species, are hard to come by.

3.2 Fishing Vessels

The fleet of fishing vessels is heterogeneous, as very few fishing vessels are exactly alike. The type of vessel, as described in Section 2.3, is an important factor that gives different constraints on cargo capacity, which type of gears it can operate, and also on the type of licenses it can hold. The cargo capacity, and also the type of cargo hold, will determine when the vessel has to return to a port. Further, the licenses held by each vessel will indicate which fisheries it can participate in, thus constraining the possible locations and gears that can be used. Since the quotas are independent of the number of vessels a ship owner has, it is decided to not route a fleet of vessels, but instead only consider a single vessel. This will simplify the modeling process and decrease the complexity of the problem.

A simplification of the operation cycle given in Section 2.4 is shown in Figure 3.3. Here, *D1* illustrates the depot node, while *F1* and *P1* denotes a fishing ground and a landing site respectively. When leaving the depot node, the vessel must sail to a suitable fishing location following the vessel's equipment fittings. If the fishery at the location is good, it will keep fishing until the capacity of the vessel is reached before returning to a suitable port for unloading. If the fishery is poor, on the other hand, the vessel can sail to a new area and continue fishing here, as illustrated by the second part of the figure, denoted *Trip n+1*. When the vessel has returned and unloaded its cargo, it can either travel out at sea again, or it can travel to the depot for a change of equipment.

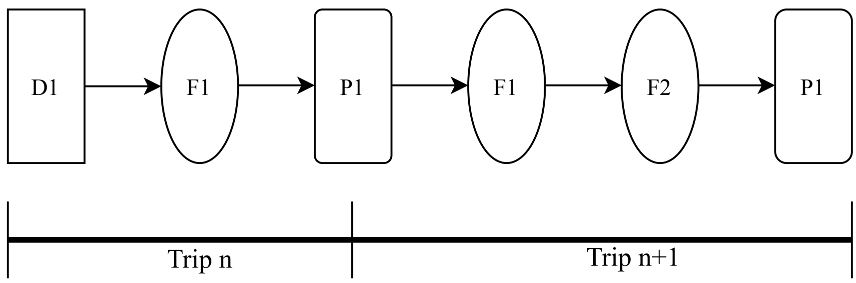


Figure 3.3: A 2-trip route for a fishing vessel, starting at a depot node for provisioning. The vessel then travels to the fishing ground F1 before returning to a port for unloading. The next trip starts by sailing back to the same fishing ground, and then finding a new location to fish before returning. Illustration made by author, inspired by Millar and Gunn (1991).

Furthermore, there are some logical constraints that must be upheld for the model to be somewhat realistic. In Figure 3.4, it has been attempted to show one of these logical constraints when it comes to which fishing grounds the vessel can visit. In the illustration, three different fishing grounds are given that each require a different gear type in order for the vessel to operate here. The vessels is denoted $Vessel1.n$ based on the gear type installed at the time. The vessel starts from *fishing ground 1* and is sailing towards a landing site. When the fish is unloaded, the vessel can either choose to travel back to the previous fishing ground, or it can change its gear to suit another fishing ground or species. Here, the change of gear is illustrated by a circular node. It should be noted, however, that some gear changes can be done swiftly, and it is not required to conduct this change at the home port unless it is stated. The cost associated with the change of equipment will depend on how simple the change can be done; if the equipment is already onboard the vessel, it can conduct the change when sailing from one location to another. But if the operation requires a stay in port for some time, the cost will increase rapidly.

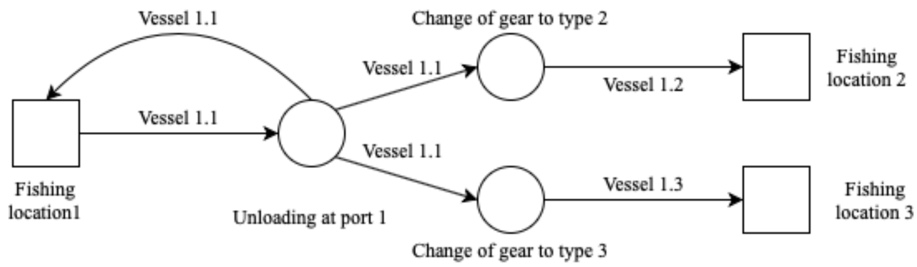


Figure 3.4: Illustration of the logical constraints regarding the vessel's choice of fishing ground.

The type of equipment that is in use on the vessel will not only restrict the type of fishery the vessel can target, but also the effectiveness of the fishing operation. A vessel using a trawl or a purse seine will fill up their cargo holds quicker than a vessel using Scottish seines or autolines, given that the external characteristics are equal. Moreover, the gear type in use will also affect the quality of the fish, which ultimately will influence sales prices. These relations must be taken into consideration in the optimisation model.

Chapter 4

Literature Review

This literature review has been conducted to fully understand the problem at hand, and to get an overview of the previous work that has been done on similar problem types. The main objective of this thesis is to find an optimal routing plan for a fishing vessel while taking into consideration different gear configurations, meaning that the problem is two-sided. Previous literature regarding fishing vessels and general design theory must be discussed in order to create effective and realistic solutions for the gear configurations on the vessel. A deeper understanding of routing problems is important when designing the model which will be used later in this thesis. In short, the literature review will form the foundation for the methodology and modeling to come.

In Section 4.1, studies and theories about the design process of fishing vessels and the concept of modularisation is introduced and explained. Next, problems with similarities to the fishing vessel routing problem are described in Section 4.2, together with some support literature on classical routing problems. Although there is little work that has been done where the design of a vessel has been combined with operations research, it will be attempted to fuse these two fields together in Section 4.3.

4.1 Ship Design and Modularisation

The design process and methodology is an important part of the solution of problem at hand. In 1959, Evans (2009) introduced the *design spiral* which captures the iterative nature of the design process. Over the years, the spiral has been subject to many changes and extensions, as well as some criticism that the spiral locks naval architects to their first assumptions (Levander, 2012; Dudin and Gaspar, 2016). The classical design spiral is described as a point-based design spiral approach, meaning that the design process begins with initial characteristics already being determined by a client. Thus, the iterative process has already been narrowed down, and the optimal solution may be lost, even before the process has started.

To combat this, Levander (2012) introduced the system based design spiral, a method which aims to find an initial starting point rather than the optimal solution. An illustration of the spiral introduced by Levander can be seen in Figure 4.1. The method relies heavily on developing a breakdown of both the payload and ship systems in a functional structure. By identifying the important systems onboard, the main features, or the nature of the vessel if you will, can be captured. According to Levander, *the functional design of the vessel can be developed to a high degree of detail without premature commitment to specific overall dimensions, layout and arrangements.* He also argues that the approach can contribute to both reducing the time spent and the investments made at an early stage of the process, making the process more effective. The SBSD is in someways referred to as a checklist of requirements that all contribute to several suitable solutions, which then can be subject to further analysis to find the optimal one.

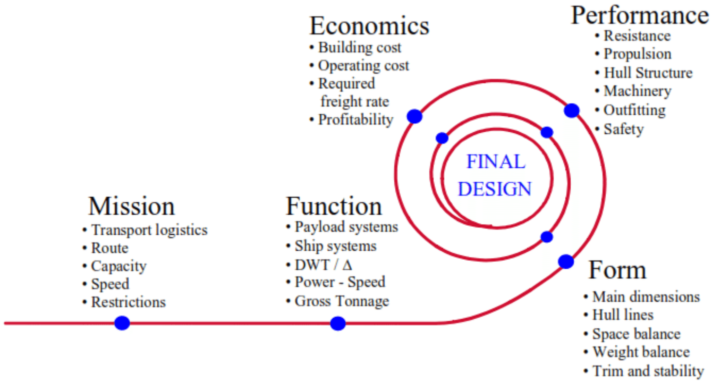


Figure 4.1: Illustration of System Based Ship Design (Levander, 2012).

The system based ship design method converted the systematic design theories introduced by Pahl et al. into the ship design universe. The systematic design approach was first intended for land constructions, but the systematic way of working and the implementation of design catalogues is well-suited for ship design as well. The approach consists of four main steps: 1) the functional interrelationships, 2) the working interrelationships, 3) the constructional interrelationship, and 4) the system interrelationship. The first step aims to identify the main function of the design, while the second step introduces design catalogues as a solution to how the functions can be fulfilled within the design. Pahl et al. defines these as *a collection of known and proven solutions to design problems*, with the purpose of connecting physical effects to the chosen working principle. Design catalogues are of great help within ship design, as they can help transform functions, or equipment, onboard into forms with associated volumes and areas. The design can therefore be better visualized at an early stage, and simple calculations can be performed. The third and fourth step aims to present sketches of the proposed designs and connect these to the larger plan (Pahl et al., 2007).

The SBSD method is a well-known and established design method, and have been implemented when designing offshore vessels, cruise ships, ferries and cargo vessels with great success. Some research has been conducted towards the design of special vessels, including fishing boats. As described by Dudin and Gaspar (2016), the design of fishing vessels have traditionally been heavily relying on empirical methods and local preferences in a region. Thus, the industry have a history of being resistant towards innovative design and state of the art technology. However, times are shifting and innovative designs are emerging. Dudin and Gaspar investigates the possibility of applying the system based design method to the design process of fishing vessels, but also states that the method is suitable for the modernisation process of already existing vessels. By making use of the SBSD step-by-step method, a case study on a stern trawler is described at the end of their paper. The results presented give quite a good understanding of the complexity that goes into the design of fishing vessels, as a lot of the onboard equipment is dependent on each other. By assigning each system a given area, a simple layout of the final design is given.

Dudin and Gaspar (2016) has conducted an extensive breakdown of the steps within the SBSD process, highlighting important features specific to fishing vessels. Such features are, for example, the importance of sufficient cargo holds, the outfitting in regards of equipment, and the distinction between different types of fishing vessels. A functional breakdown structure represents a product architecture for the vessel, which can be used to create a modular design platform. The concept *product architecture* can be described as a way of categorising a system's main functions and how they are related to each other (Erikstad, 2009). Ulrich defined it as *the scheme by which the function of a product is allocated to physical components* (1995). Each of these modules can be scaled to an appropriate size, thus making them suitable for different vessel types. By making use of a modular approach, the complexity and uncertainties relating to the design process of fishing vessels can be handled in a simplified matter.

In his master's thesis, Kristiansen (2014) looks at the possibility of introducing the concept of modularisation into the design of fishing vessels in the Norwegian coastal fleet. He proposes five main aspects that must be considered when designing a fishing vessel: 1) which licenses are available, 2) which fishery to target, 3) where the fishing should be carried out, 4) preferred fishing gear, and 5) the ship owner's personal preferences. The findings are similar to the ones presented by Dudin and Gaspar, especially with regards to many features being determined by the regional affiliation. As implied earlier, this has lead to very little innovation within the industry. However, with climate change and stricter regulations on the biomass available, new and better solutions should be implemented. By introducing modularisation in the fishing industry, one can achieve a much more sustainable fleet, which is more flexible with regards to the fisheries it can target, and the operation modes it can carry out. A more flexible fleet can withstand uncertainties if done right, and still be competitive compared to more specialized vessels (Choi et al., 2018). By creating a common platform, a single ship can perform multiple missions by simply switching out different modules, as illustrated in Figure 4.2.

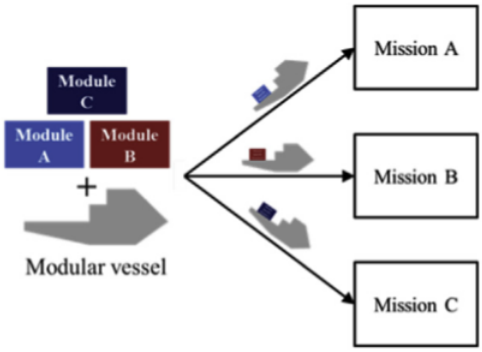
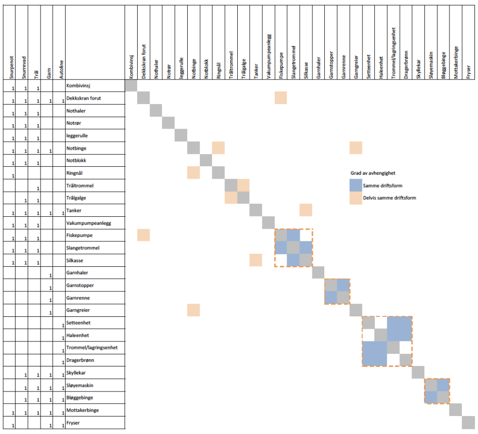
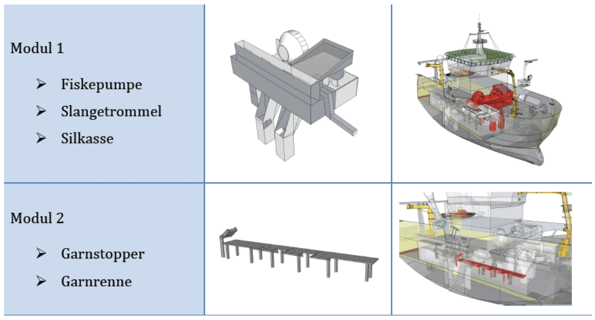


Figure 4.2: Operational flexibility provided by a modular adaptable ship. A modular vessel can be reconfigured with different modules, which each can meet a different mission (Choi et al., 2018).

Kristiansen (2014) creates his modules by first constructing a functional structure of all tasks the vessel should perform, before relating these to different gears and equipment. The relations are created by the use of a method called *House of Quality*, which is described as *a kind of conceptual map that provides the means for interfunctional planning and communication* (Hauser and Clausing, 1988). When the relations have been created, Kristiansen uses a *Design Structure Matrix* to find suitable modules, as well as defining which equipment that have dependencies on others. The DSM is defined as *"a network modeling tool used to represent the elements comprising a system and their interactions, thereby highlighting the system's architecture (or designed structure)"* (Eppinger and Browning, 2012). Since vessels belonging to the coastal fleet in Norway are subject to length restrictions, the vessels have been carefully equipped with as much equipment and gear that is possible. This has lead to highly dependant relations between different equipment, which makes the creation of possible modules quite hard. However, Kristiansen was able to create four possible modules, where three of them were suitable for several different operation modes. Furthermore, he presents some basic requirements related to the vessel's form and configuration so that the different modules easily can be fitted onto the vessel. Figure 4.3 shows the DSM created by Kristiansen next to two of his proposed solutions.



(a) Design structure matrix



(b) Two of the four modules he created

Figure 4.3: The two illustrations show the results obtained by Kristiansen. Figure 4.3a shows the final DSM with respect to the operation mode, equipment and how strong the dependency is between the different design parameters. Figure 4.3b illustrates two possible modules that he created (Kristiansen, 2014).

In the late 1970s, Suh introduced the theory of *axiomatic design*, where he formed two axioms as a basis for more effective engineering design (Suh, 1990). The two axioms, the independence axiom and the information axiom, can be used to decide the complexity of a design. By utilizing the independence axiom, the independence between the functional requirements of the vessel should be maintained. This means that the design should be made in such a way that no functions, i.e. systems, depend on each other. Suh used the *design mapping matrix* to illustrate this matter. This matrix is illustrated in Figure 4.4 below. Here, the functional requirements are given by FR_n, the design parameters that answer to the requirements are denoted DP_n, and the B_{nm} matrix in the middle connects each requirement with the design parameters. Figure 4.4a illustrates how the desired design should be, with no dependencies between functions. This means that if there are changes to one design parameter, it will only affect one requirement. However, if the shape of the *B-matrix* is similar to the one in Figure 4.4b, a change in one design parameter may alter several requirements. The second design axiom, the information axiom, seeks to minimise the complexity of the design. Farid and Suh states that *if it is more difficult to describe the design, it is more difficult to predict the performance of the design* (Farid and Suh, 2016). By calculating the probability of meeting the functional requirements based on the range of each design parameter, the complexity of the design can be calculated. The aim is to minimise this value, as a lower value indicates a less complex design.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} B_{11} & 0 & 0 \\ 0 & B_{22} & 0 \\ 0 & 0 & B_{33} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix}$$

(a) Uncoupled design

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix}$$

(b) Coupled design

Figure 4.4: Illustration of the design mapping matrix given by the independence axiom. The desired shape of the *B-matrix* is given in Figure 4.4a, where the design meets the independence axiom perfectly. In Figure 4.4b the same design parameter answers to several functional requirements, making the design coupled and more complex (Suh, 1990).

As most systems will be coupled to some extent, the aim is to *decouple* these in a way that facilitates the creation of subsystems. The goal of creating these subsystems is to ensure that a change in a functional requirement only will affect the given subsystem. Figure 4.5 shows how the design mapping matrix looks when the design is decoupled (Suh, 1990). To use the axiomatic design in practise is hard. However, they can help the designer move in the correct direction. It is a great tool to determine the complexity of the design, and the link between axiomatic design and the use of the design structure matrix (DSM) is strong. The DSM can be said to be a more visual representation of the independence axiom, where all the design parameters, i.e. the equipment onboard, are listed and grouped based on their dependency. An example of how the DSM can look like for a given design is shown in Table 4.1. Like Kristiansen experienced, there are many dependencies between the equipment and systems onboard a fishing vessel, and the use of a modular approach may prove to be more time consuming and costly than the overall reward.

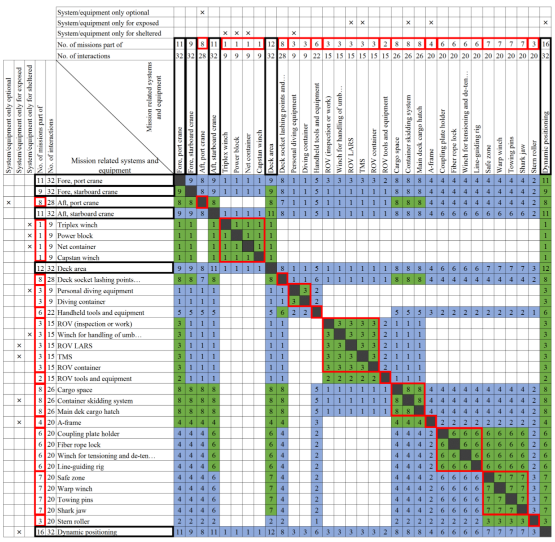
$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} B_{11} & 0 & 0 \\ B_{21} & B_{22} & 0 \\ B_{31} & B_{32} & B_{33} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix}$$

Figure 4.5: Decoupled design (Suh, 1990).

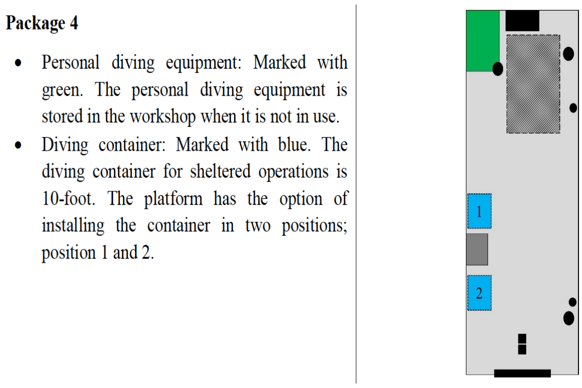
	DP_1	DP_2	DP_3
DP_1	1	0	0
DP_2	1	1	0
DP_3	1	1	1

Table 4.1: Related design structure matrix.

In his thesis, Nekstad (2017) continues some of the work from Kristiansen, with emphasis on the aquaculture service vessel industry. Nekstad puts a lot of work into highlighting the importance of including uncertainty and flexibility in the design of aquaculture vessels, as these are especially exposed to continuously changing environments and working contexts. In his thesis, a framework for the design of a vessel platform and a set of system and equipment packages are presented. He also makes good use of the DSM and is able to present which systems and equipment that must be permanently installed on the vessel, and which that can be installed when needed. The DSM can be seen in Figure 4.6a. The thesis also presents extensive work on different deck configurations, making it easy to understand the solutions available and the flexibility that the different modules may provide for the vessel. Figure 4.6b illustrates one of these configurations. The grey areas indicate permanently placed equipment, while the green and blue are modules that can be taken on and off when needed. By dividing the modules into different packages and specifying the type of location they can be used on, his master's thesis is a great tool for the industry to use.



(a) Design structure matrix



(b) Illustration of one of the modules created in his thesis

Figure 4.6: The two illustrations show the results obtained by Nekstad. Figure 4.6a shows the *form DSM*, meaning how the mission related systems and equipment are coupled. Figure 4.3b illustrates one of the configurations he developed (Kristiansen, 2014).

This thesis will use some of the results obtained by Kristiansen and Nekstad as a foundation for developing possible configurations in the computational study in Chapter 7.

4.2 Vehicle Routing and Scheduling Problems

Maritime transportation planning problems are traditionally classified into three planning levels based on the planning period of the problem, namely strategic, tactical, and operational problems (Christiansen et al., 2007). It is always desirable to maintain these distinctions between the three planning levels. However, they will often depend on each other, making maritime transportation planning problems quite complex. In this thesis, the main focus will be on the routing and scheduling of a fishing vessel, which falls under the tactical problems category. However, ship design and fleet decisions are classified as a strategic problem, complicating the problem at hand. In this section, articles treating routing problems which can be translated to this project will be presented, and their findings and conclusions will be discussed.

The vehicle routing problem (VRP) is a hard and well-known combinatorial optimisation problem which calls for the determination of optimal routes for a fleet of vehicles with given capacities that are to serve a set of customers with given demands (Laporte, 2007). The problem was first introduced by Dantzig and Ramser in 1959, and is considered to be a generalization of the traveling salesman problem, which first appeared at the start of the 20th century (Cummings, 2000). Whereas the travelling salesman problem considers a salesman travelling between cities and returning to the initial starting point for the lowest possible cost, the vehicle routing problem allows for multiple returns to the starting point. The simple structure of the problem makes it suitable for several different applications, such as delivery of newspapers, collection of dairy products from farms, as well as vessel routing and cargo allocation within the maritime industry (Laporte, 2007). However, this has lead to quite specialized problems, meaning that it exists few accurate solution algorithms for distinctive VRPs. Consequently, the use of heuristics has become more popular, and has also shown to provide quite good results.

The VRP can be described as follows: given a set of customers with different demands, a vehicle, with a given capacity, is to be routed so that the total traveling time, or cost, is minimised. An illustration of a typical layout and possible solution of a VRP is given in Figure 4.7. Although the problem may seem easy, it has been shown that the computational time increases rapidly by introducing a large number of customers (Laporte, 2007).

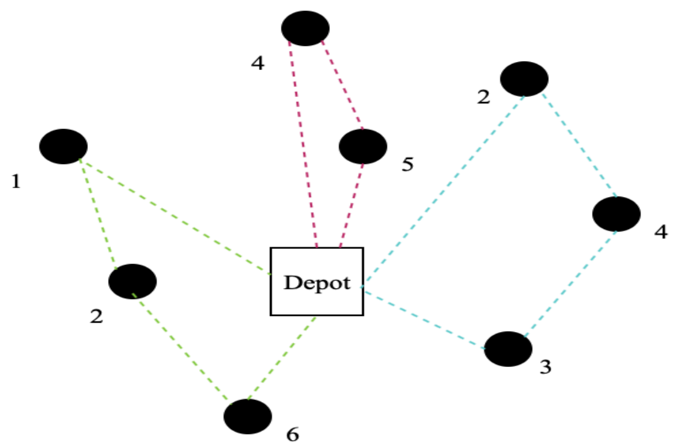


Figure 4.7: Illustration of a possible solution of a VRP, where the vehicle has a capacity of 9. Eight customers are to be served, each with a given demand as illustrated by the number. To serve all eight customers, the vehicle must conduct three routes, as given by the colored lines.

Due to the vast variety in problem types where a VRP approach is suitable, a more in-depth review of previous articles and literature has been conducted below. In Table 4.2, characteristics of the problem at hand is given, along with the same characteristics for different articles.

Table 4.2: Overview of the characteristics of relevant articles.

Article	Maritime VRP	Application	Modelling Time	Fleet size
This thesis	Yes	Fishing vessels	Discrete	Single
Christiansen et al. (2017)	Yes	Supply vessels	Discrete	Multiple
Floudas and Lin (2004)	No, MI(N)LP	Chemical processes	Discrete & continuous	-
Wen et al. (2010)	No, DMPVRP	Distribution of goods	Discrete	Multiple
Millar and Gunn (1991)	Yes	Fishing vessels	-	Multiple

In their paper, Christiansen et al. (2017) investigates a real operational problem of routing and scheduling a fleet of supply vessels used to service customer ships anchored outside a major port. The problem is considered a *rich* multi-trip vehicle routing problem, including time windows, tank allocation and stowage constraints, and time-dependent travel times. The problem is solved by using both an arc-flow model and a path-flow model, and the paper aims to compare the two well-known methods. Although the path-flow model requires a path generation algorithm, the results show that it is superior over the arc-flow model, thus being best suited to be used in real planning situations.

The key take away from this paper is the use of a time discrete modeling approach to model a continuous problem. A discrete-time formulation divides the planning period into a number of time intervals of uniform duration, which is well suited when the problem in question has time dependent parameter values. In this paper, the sailing time is time dependent due to sailing restrictions during the night. Christiansen et al. found that a discrete-time approach in a continuous problem gave quite exact results, as well as making the problem easier to compute.

Floudas and Lin (2004) dived further into the importance of different time approaches, and demonstrated the differences of using a continuous-time and discrete-time approaches within the scheduling of chemical processes. The problem at hand can be described as a multi-product scheduling problem, which creates a mixed-integer non-linear programming (MINLP) problem when exposed to a continuous-time environment, and a mixed-integer linear programming (MILP) problem in cases with discrete-time. Compared to a continuous-time model, the discrete-time models will contain more variables due to the introduction of a time index in each variable. Thus, discrete-time models are defined as large combinatorial problems, and the computational time can increase rapidly as the problem expands. Continuous-time models will have fewer variables, but the formulation of the problem is more complex due to the fact that these problems can create non-linear formulations. Hence, the solution algorithms available are more complex, and the benefits of having fewer variables are nulled out. By keeping models linear with a discrete-time approach, it is possible to find satisfying solutions to complicated problems, with a reasonable computational time.

Another benefit of using a discrete-time modeling approach, is the possibility of illustrating the problem in a time-space network. For vehicle routing problems, this means that the flow of the vehicle can be visualised. This can lead to an easier modelling process, as possible errors in the model and the thought process can be found. Figure 4.8 gives an illustration of a time-space network, as illustrated in the paper by Christiansen et al. (2017).

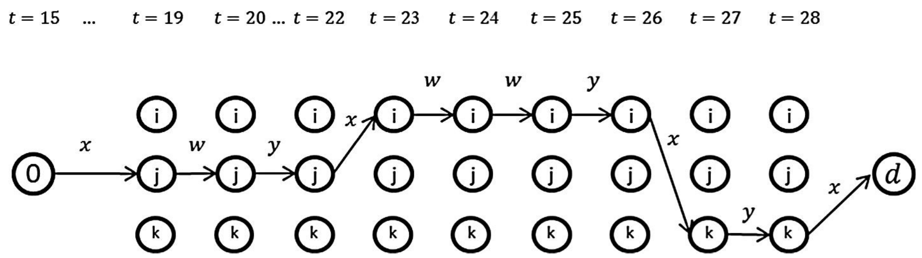


Figure 4.8: Example of how a vessel may travel in a time-space network. The vessel starts in a depot node in time period $t = 15$ before sailing to node j with arrival in time period $t = 19$. The vessel is then located at the same node for two consecutive time periods, before sailing to node i in time period $t = 23$, etc. (Christiansen et al., 2017).

In their report on dynamic multi-period routing problems (DMPVRP), Wen et al. (2010) makes use of a three-phase heuristic over a rolling horizon in order to obtain a solution for a problem with multiple objectives. This heuristic is well suited for complex problems with a large number of variables, such as time-discrete models. By dividing the planning horizon into smaller parts, the problem can be solved in phases. Here, the results obtained in one phase can be used to solve the sub-problem in the following phase, until the entire planning horizon has been covered. This approach may lead to a more solvable problem, without reducing the integrity of the initial problem (Wen et al., 2010).

When it comes to literature which combines operations research with fishing vessels, the selection is rather sparse. However, in 1991, Millar and Gunn created a routing model for Canadian trawlers. The objective of their article was to find a minimum-cost fleet-dispatching plan in order to satisfy demand for various species from processing plants, within a set planning horizon. Millar and Gunn have a special focus on creating specific solution algorithms for their trawler routing problem, making it quite attached to their specific problem. However, the main take away points are related to the model formulation. For many VRPs, the demand and supply of cargoes are known in advance. This is not necessarily the case when dealing with a living biomass. To overcome this issue, Millar and Gunn uses historical catch rates and stock estimations to estimate the amount of fish that can be caught in the future. In the end, Millar and Gunn concludes that the routing of trawlers is in fact quite complex. However, simplifications and estimations of dynamic parameters are possible to implement in order to obtain satisfying results. The article is quite old, and both the solution methods and the modelling itself has come a long way since it was written. Thus, their approach, rather than the results, is of more interest for this thesis.

4.3 Problems Concerning both the Routing and Design of Vessels

As this thesis investigates the possibility of routing a vessel based on a shifting design, it would be beneficial to investigate already existing research conducted on the field. However, as with the routing of fishing vessels, little research has been done on combining a routing problem with a design optimisation problem. Most routing problems conducted today have been towards supply and demand problems, where a vessel is required to fulfill a request. The vessel will in most cases already have a predetermined layout, meaning that the main issue will be related to how much the vessel can load and unload at given locations, or where and when the vessel should sail to keep costs down.

The problem at hand will be quite different as the configuration of the vessel is included, as well as the cargo being a natural biomass. Thus, the problem will not be a classic pickup and delivery problem, nor a classic design issue. The equipment configurations on the vessel must be decided simultaneously as the optimal route is generated, and the approach can best be explained through an iterative process as illustrated in Figure 4.9. This figure is a simplified version of the needs, function, and form mapping model - a model which shows the iterative nature of the design process. Compared to a classic fishing vessel operation, this thesis aims to extend the borders of how and where the vessel can operate by implementing the possibility of changing the vessel's operating conditions. By changing how the vessel can operate, the optimal route is hard to find, and iterations may be helpful to find an optimal solution that can satisfy both sides of the problem.

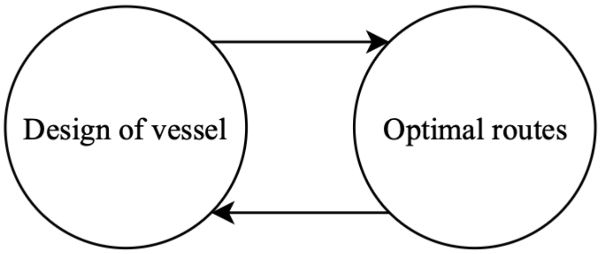


Figure 4.9: Iteration process between design and routing. By going back and forth, the optimal design and routing plan can be found.

Chapter 5

Methodology

This chapter will present the methodologies and approaches applied to solve the problem at hand. As stated earlier, the main objective of this thesis is to investigate the possibility of combining different equipment configurations on a vessel with a routing model to obtain a more competitive vessel in a continuously changing industry. Thus, the methods used in this thesis are twofold: firstly, the design aspect of the problem must be investigated, and secondly, basic information on the optimisation process must be provided.

Section 5.1 will introduce the design methodologies relevant for this thesis, with a special focus on modular approaches. In Section 5.2, the process of creating an optimisation model is presented. These two sections are mainly used as a theory base for the methodology created in Section 5.3, where a more in-detail description of the methodology used for this problem is presented.

5.1 Design Methodology

Design is a widely used term that applies to everything around us. Thus, it can be hard to understand exactly what the essence of the word means. Many people have tried to explain the term and why we use design on a daily basis. For example, Herbert Simon once described design as:

> *"To design is to devise courses of action aimed at changing existing situations into preferred ones"*

This means that people use design as a way of obtaining their desired reality, in various magnitudes. In many ways, the end-goal is often known, but the way of getting there is the real problem and where new insight is gathered. The needs-function-form mapping model is often used to illustrate the design process, and is illustrated in Figure 5.1. The mapping model can be used to describe both the axiomatic design approach presented by Suh (1990), with mapping between the functional and physical domain, and the systematic design approach by Pahl et al. (2007).

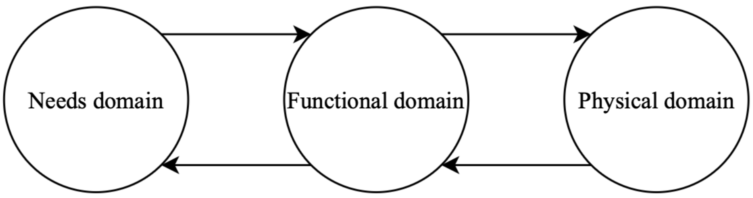


Figure 5.1: The needs, function and form mapping model.

Systematic design is an approach consisting of four main phases that can be illustrated using the mapping model above (Pahl et al., 2007). The first phase, *task clarification*, aims to describe the mission and main objective of the design. Next, the *conceptual design* phase seeks to define the main and secondary functions. By using design catalogues, connections between possible solutions and functions can be made. The process of breaking down the main objective of the design into functions can be of great value, especially when it comes to special vessels. On these vessels, systems may be quite dependent on each other, and a functional breakdown can make it possible to identify which systems that are of great importance, and which systems than can be denoted secondary ones. The independence axiom presented by Suh can then be used to decide the complexity of the design (Suh, 1990; Farid and Suh, 2016). Complex vessels will have intertwined functions, thus making it hard to do adjustments at a later stage. Since most special vessels operate in highly shifting markets, such as the offshore oil and gas industry, or within fisheries and aquaculture, their design should be as flexible as possible.

One approach to increase the degree of flexibility is to investigate whether or not the vessel can be designed to fit into a modular approach. By identifying the main functions following the methodology introduced by Pahl et al., and making use of both the independence and information axiom defined by Suh, a great starting point for a modular approach is created. Furthermore, the design structure matrix is a great tool to implement in order to visualize the functions of a system, as illustrated in Figure 5.2. At an early stage, these steps can be used to minimize the number of interactions outside a given system, thus minimizing the propagation of changes outside that given system (Eppinger and Browning, 2012).

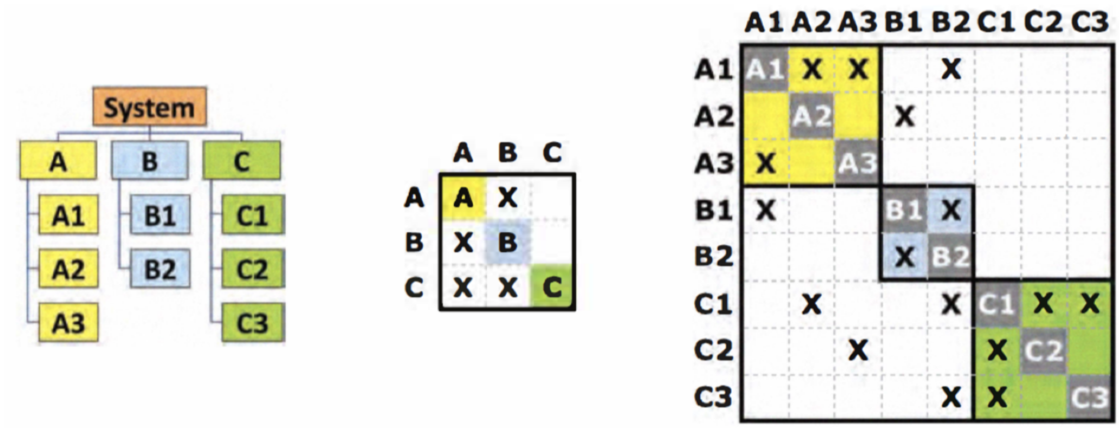


Figure 5.2: The relationship between the functional hierarchy of a system, and the design structure matrix (Eppinger and Browning, 2012).

In his thesis, Kristiansen (2014) uses the design structure matrix to obtain insights into the dependencies between different equipment. By clustering equipment that rely on each other together, he was able to create four independent modules, given that the platform they belong too are designed in such a way that the modules can be easily fitted. In sum, his results clearly indicates that a fishing vessel has a lot of dependant subsystems, implying that the implementation of modules should be thought of when creating the vessel's form.

5.2 The Optimisation Process

As defined by Lundgren et al. (2010), a special working approach is used when optimisation models are employed to analyse and solve decision problems. This is often referred to as the *optimisation process*, and consist of four phases: identify, formulate, solve, and evaluate. An illustration of the optimisation process is shown in Figure 5.3.

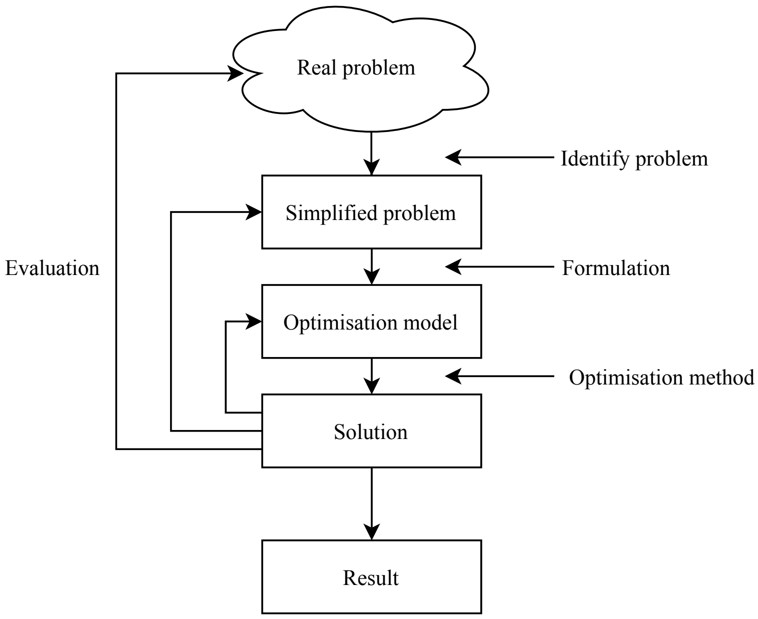


Figure 5.3: Illustration of the optimisation process (Lundgren et al., 2010).

The first step of the process is to define the real problem that is to be analysed and solved, meaning the boundaries and characteristics that are of importance to the modeling process. However, the real problem is often quite complex, and to include everything in an optimisation model is not always feasible. The key components of the problem must be identified and grouped based on which components that are of great importance and which that may be discarded. One should also investigate whether or not it is possible to solve the problem using an optimisation model, or if it is better to use other methods instead. When this is done, you are left with a simplified problem that can be formulated mathematically as an optimisation model.

An optimisation model describes the problem at hand using decision variables, an objective function, and several constraints and parameters. The objective function defines the problem type as either a *maximum* or *minimum* problem, depending on the end goal and problem structure. For instance, the goal of a vehicle routing problem can either be to maximize the profits, or to minimize travel time. The solvability of the problem will be affected by the number of variables in the model, and by the model structure itself. Depending on the structure of the problem, a general commercial solver can be used.

When the complete model is ready to run, data needs to be gathered. The results of the model will only be as good as the input, meaning that this is an important step of the process. If exact values are hard to find, the modelers should seek to find estimates that are in the same magnitude as the real ones. Once the optimisation model has provided a solution, the results must be evaluated. This is, on paper, the last phase of the optimisation process. However, as with the design process, the iterative nature of the problem leads to a back-and-forth process, as illustrated by the arrows on the left hand side of Figure 5.3. The evaluation phase makes sure that the optimisation model actually describes the desired problem accurately enough.

5.3 Methodology Developed for this Problem

The methodology created for this problem is illustrated in Figure 5.4. This figure aims to explain how the problem requires a two-sided approach, with the field of operations research on one side, and the aspects related to design and modularisation on the other. The methodology follows the steps of the optimisation process by first identifying the real problem. This is done by conducting a thorough background study on the fishing industry and how vessels are being operated today. Existing theories about vessel design and routing problems will also affect the formulation of the model. Combined, the identified problem and background material, existing design and modularisation topics, and theories from operations research form the basis for the creation of the mathematical model used in this thesis.

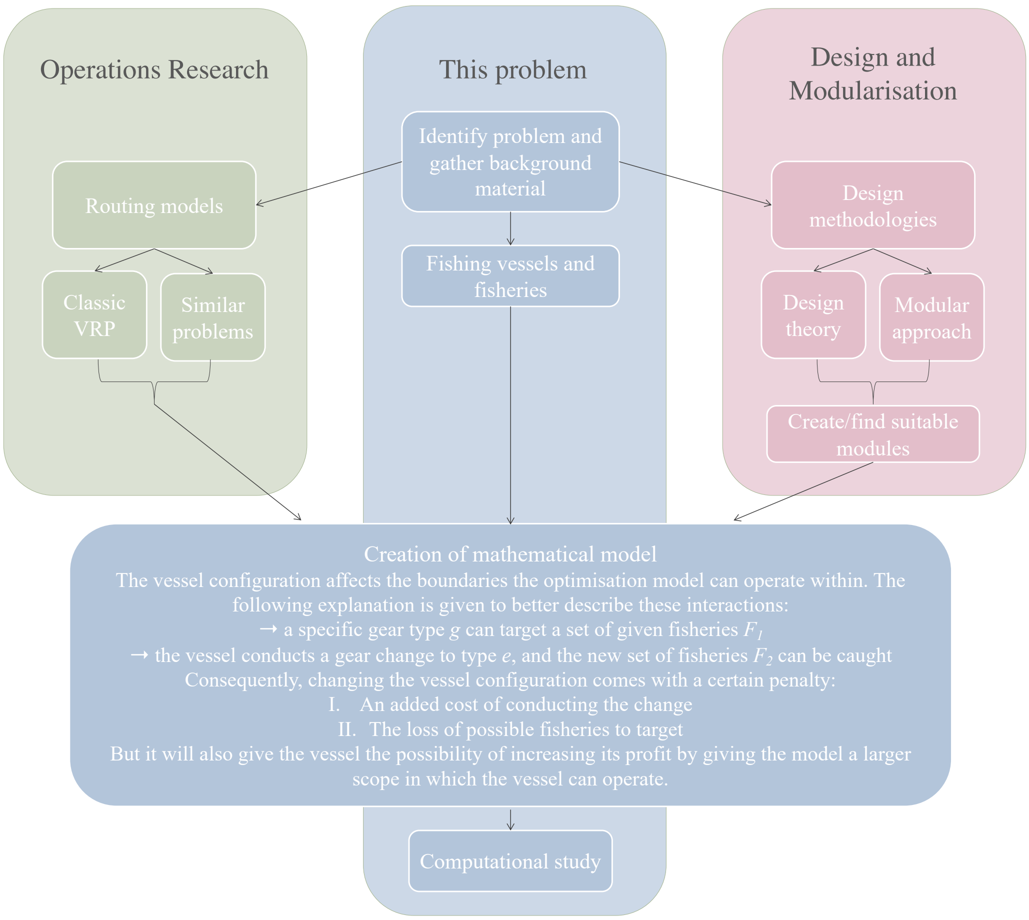


Figure 5.4: Illustration showing the methodology for this thesis. As mentioned, the main topics of the problem are two-folded; the design and modular aspect on one side, and the operation research aspect on the other. The figure is meant to create an overview of how the different parts are connected.

As described by the optimisation process by Lundgren et al. (2010), the problem must be simplified before it can be translated into an optimisation model. This has been done in Chapter 3, where the problem description restricts the problem's magnitude in both a geographical and operational matter. The creation of suitable equipment modules takes place in parallel with the model formulation. The connection between the design aspect and the optimisation model is what separates this problem from other classical design problems and routing models, hence much time has gone into understanding how this interaction should be captured in the model. In the figure above, the interaction between the design aspect of the problem and the creation of the optimisation model is explained.

The main focus of this thesis has not been on the design aspect. Hence, the work conducted by Kristiansen (2014) plays a huge role when defining possible equipment configurations. Although Kristiansen's focus was towards the coastal fleet, the similarities between the fishing gears make it possible to up-scale some of the modules created, with some minor changes. However, in contrast to Kristiansen's work, this thesis aims to find modules which don't require a retrofitting of the vessel.

When all aspects of the problem are known and simplified, the next step is to convert the problem to an optimisation model using a mathematical model. The base of the model is created according to the main principles of classical vehicle routing problems, as presented by Christiansen et al. (2007). The problem will be modeled as a mixed integer linear programming problem (MILP). A MILP-problem is easily recognizable by its mix of binary and integer variables, linear objective functions and constraints, and most commercial solvers are suitable for solving such problems (Lundgren et al., 2010). In this thesis, the Xpress-IVE software is used to solve the problem. By keeping the model linear the computational time can be decreased in comparison with a non-linear one, as illustrated by Floudas and Lin (2004). Additionally, a MILP structure is a great way of easily describe the problem at hand.

Lastly, the model will be verified and tested using a computational study, which is described in Chapter 7. The case study is created as realistically as possible so that the optimisation model can be used as a decision support tool for real-life operations. As described in the optimisation process, the importance of high-quality data can not be emphasized enough, and much work has been put into data gathering. To verify input values, direct contact with several industry actors have been made. In cases where data verification has not been possible, estimates have been made.

Chapter 6

Mathematical Model

Based on the problem description given in Chapter 3, a mathematical model of the fishing vessel routing problem has been developed. Section 6.1 will introduce the modelling approach chosen for this problem, while the model itself will be given in Section 6.2. The implementation of the model in the Xpress-IVE solver software is presented in Section 6.3.

6.1 Modelling Approach

For both computational reasons and simplicity, the model should be formulated as a multi-integer linear programming (MIP) problem. By keeping the problem linear, the problem can be solved by the use of most solvers available. However, as stated by Floudas and Lin (2004), it can increase the time spent on creating the model, as most realistic problems are not linear.

Although the operations of a fishing vessel will take place in a continuous time environment, it has been chosen to develop a discrete-time model to keep the model linear. As stated by Christiansen et al. (2017) and Floudas and Lin (2004), a discrete-time formulation is well-suited when the problem in question has time dependent parameter values. Here, the sailing time and the time it takes to fill up the capacity of the vessel will be time dependent due to varying weather conditions and uncertain fisheries. By implementing a time-discrete model, the planning horizon is divided into time increments of equal length. The time increments should be sufficiently small so that the model is as realistic as possible, but not to small so that the computational time becomes to large. It is assumed that a normal unloading process will take approximately a day, including refueling. Based on this, the size of the time increment is set to a day. The sailing times will be rounded up to the nearest integer, so that they correspond to a number of time periods.

By using a time-space network, the vessel's flow through the system can be illustrated. Such a network has been created following the same approach as Christiansen et al. (2017) presented in their article, and can be seen in Figure 6.1 below. During the modelling phase, this network is used to make sure that the model is capturing all aspects of the flow of the vessel, thus being of large value during the formulation of the model.

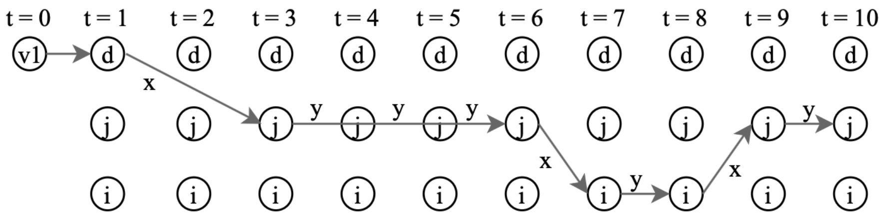


Figure 6.1: Example of the operations of a vessel $v1$. The nodes denoted d are depot nodes, j are fishing locations, and i the unloading nodes. The vessel will sail along the edges with the index x, while the y indicate that the vessel will be operating in that node for multiple time periods.

6.2 Mathematical Model

In this subsection, the mathematical formulation of the problem is presented. Section 6.2.1 will introduce the relevant notation used in the model, including sets, indices, parameters and variables. In Section 6.2.2 the full mathematical model is given, which consists of the objective function, numerous constraints, and the definition of the variables. Explanation of each constraint is also provided here. For the compressed mathematical model, see Appendix A.

6.2.1 Notation

The following section will present the notation used in the mathematical model. Capital letters will be used for sets and parameters, while decision variables and indices will be represented by lower-case letters.

Each node in the model is represented by two indices, (i, g), where i denotes the node number while g denotes the gear type carried by the vessel. The indices are contained in the set $\mathcal{M}$, which only hold the allowed combinations of the two. The initial position for the vessel is represented by the index o, while the index d denotes the dummy end node, i.e. the artificial destination port for the vessel. The two nodes are modeled as the same node in the implementation of the model, and are contained in the set $\mathcal{N}^T$. The set $\mathcal{N}$ holds all nodes except o and d. All nodes contained in this set are defined as either a fishing location or a landing site, and are held in the subsets $\mathcal{N}^F$ and $\mathcal{N}^P$, respectively.

As given by the problem description in Chapter 3, certain areas can have restrictions regarding the gear types that are allowed to use. The number of total available gear types are given by the set $\mathcal{G}$, and both g and e are used as indices. The terms *gear type* and *equipment type* are used as the same term throughout the thesis. The set of fisheries are denoted $\mathcal{F}$, indexed by f. The time horizon of the problem is given by the set $\mathcal{T}$, indexed by t. The parameters are mostly given in terms of *tonnes*, *days* and *NOK*, if nothing else is stated.

The model is built up by four decision variables: x_{igjet}, y_{igt}, l_{gft} and q_{igft}. x_{igjet} and y_{igt} are defined as binary variables, meaning that they will take the value $1\, or\, 0$ depending on if the variable is included in the solution. x_{igjet} will be 1 if the vessel sails from node (i, g) to node (j, e) in time period t, where the gear types $g\, and\, e$ can be the same. y_{igt} is defined as the *task variable* and if this is active, i.e. equal to 1, the vessel is operating. The term *operating* can mean one of two things, namely the vessel is fishing or the vessel is unloading its cargo. The vessel is only allowed to carry out its respective tasks at a suitable node, which is given by the type of node in question; $\mathcal{N}^F$ allows for fishing, while $\mathcal{N}^P$ allows the vessel to unload at a port.

The variable q_{igft} illustrates how much fish that is either caught or delivered to a land site in a given time period, while l_{gft} keeps track of the amount of fish onboard the vessel at all times. Both variables should be non-negative, as a negative load is not feasible.

Sets

$\mathcal{N}^T$	Set of all nodes, including o and d
$\mathcal{N}$	Set of locations in the problem
$\mathcal{N}^F$	Set of fishing grounds, subset of $\mathcal{N}$
$\mathcal{N}^P$	Set of landing sites in the problem, subset of $\mathcal{N}$
$\mathcal{T}$	Set of time periods within the planning horizon
$\mathcal{G}$	Set of fishing gears
$\mathcal{F}$	Set of fisheries
$\mathcal{M}$	Set of allowed nodes (i,g) where $i \in \mathcal{N}$ and $g \in \mathcal{G}$

Indices

i, j	Nodes, $i, j \in \mathcal{N}$
o	Initial starting node
d	Dummy end node
t	Time period, $t \in \mathcal{T}$
g, e	Type of fishing gear, $g, e \in \mathcal{G}$
f	Type of fishery, $f \in \mathcal{F}$

Parameters

C^S	The cost per time period of sailing
C^G_g	The cost of operating gear g
C^C_{ge}	The cost of switching from gear type g to gear type e
P_{gft}	Sales price obtained for fish species f caught using gear g in time period t
Q^{CAP}	The cargo capacity of the vessel
Q^{QUOTA}_{gf}	The vessel's quota for fishery f using gear type g
T^S_{igjet}	Sailing time between nodes i and j in time period t
L_{ig}	The effectiveness/unloading rate of gear g if located at location i
I_{ig}	Explains the node type, and equals 1 if the node belong to the set $\mathcal{N}^F$, i.e. is a fishing ground, and -1 if the node is a landing site, thus belonging to the set $\mathcal{N}^P$.

Decision Variables

x_{igjet}	A binary variable which takes the value 1 if the vessel sail between nodes i, g and j, e in time period t, 0 otherwise
y_{igt}	A binary variable which takes the value 1 if the vessel is fishing/unloading fish using gear type g at location i in time period t, 0 otherwise
l_{gft}	The amount of catch f onboard the vessel at the end of time period t caught using fishing gear g
q_{igft}	The amount of fish f caught/offloaded at location i using gear g in time period t

6.2.2 Model Formulation

Objective Function

The objective in this model is to maximize profits. For this problem, the revenue earned is based on how much fish the vessel is able to deliver, while to costs are related to the operation of the vessel. The objective function consists of several terms, and can be seen below:

$$
\begin{aligned}
max\ z = & \sum_{\substack{(i,g)\in\mathcal{M} \\ |i\in\mathcal{N}^{\mathcal{P}}}} \sum_{g\in\mathcal{G}} \sum_{f\in\mathcal{F}} \sum_{t\in\mathcal{T}} P_{gft} q_{igft} \\
& - \sum_{(i,g)\in\mathcal{M}} \sum_{(j,e)\in\mathcal{M}} \sum_{t\in\mathcal{T}} C^S T^S_{igjet} x_{igjet} \\
& - \sum_{(i,g)\in\mathcal{M}} \sum_{g\in\mathcal{G}} \sum_{t\in\mathcal{T}} C^G_g y_{igt} \\
& - \sum_{(i,g)\in\mathcal{M}} \sum_{(j,e)\in\mathcal{M}} \sum_{t\in\mathcal{T}} C^C_{ge} x_{igjet}
\end{aligned} \tag{6.1}
$$

The first term in the objective function decides the overall revenues that the vessel is able to obtain. P_{gft} represents the the sales price for a given fish species that is caught using a specific gear type and delivered to a landing site at a given time. The decision variable q_{igft} will only contribute to this term when it is located in node (i, g), given that $i \in \mathcal{N}^{\mathcal{P}}$. The second term calculates the sailing costs. C^S is defined as $[NOK/day]$, while the time it takes to sail between two nodes are given by T^S_{ijt}. The third term denotes the costs of operating a certain gear type, while the last term defines the cost related to conducting an equipment change. C^C_{ge} denotes the cost of switching from equipment g to e, and the term will only be active when a change is carried out.

Routing Constraints

To capture the routing aspect of the model, the two binary variables x_{igjet} and y_{igt} are constructed. x_{igjet} is equal to 1 if the vessel sails from node (i, g) to node (j, e) in time period t, and 0 otherwise. The variable is only created for selected combinations of (i, g) and (j, e). The decision variable y_{igt} is equal to 1 of the vessel is conducting a task at node (i, g) in time period t. A task is defined as either a fishing operation or an unloading operation. The task conducted is decided by the type of node. The routing constraints are as follows:

$$\sum_{(g)\in\mathcal{G}} \sum_{\substack{(j,e)\in\mathcal{M} \\ |j\in\mathcal{N}^{\mathcal{F}}}} x_{ogje1} = 1 \tag{6.2}$$

$$\sum_{\substack{(i,g)\in\mathcal{M} \\ |i\in\mathcal{N}^{\mathcal{P}}}} \sum_{(e)\in\mathcal{G}} \sum_{t\in\mathcal{T}} x_{igdet} = 1 \tag{6.3}$$

$$y_{ig,t-1} + \sum_{(j,e)\in\mathcal{M}} x_{jeig,t-T^S_{igjet}} = y_{igt} + \sum_{(j,e)\in\mathcal{M}} x_{igjet} \qquad (i,g)\in\mathcal{M},\ t\in\mathcal{T} \mid t>1 \tag{6.4}$$

$$\sum_{(j,e)\in\mathcal{M}} x_{igje,t-T^S_{igjet}} \leq y_{igt} \qquad (i,g,)\in\mathcal{M},\ t\in\mathcal{T} \tag{6.5}$$

$$\sum_{(i,g)\in\mathcal{M}} y_{igt} + \sum_{(i,g)\in\mathcal{M}} \sum_{(j,e)\in\mathcal{M}} \sum_{t'=t}^{T^S_{igjet}} x_{igjet'} \leq 1 \qquad t\in\mathcal{T}, i\neq j \tag{6.6}$$

$$\sum_{(i,g)\in\mathcal{M}} \sum_{(j,e)\in\mathcal{M}} x_{igjet} \leq 1 \qquad t\in\mathcal{T} \tag{6.7}$$

Constraints 6.2 ensures that the vessel leaves its initial position, and that it sails directly to a fishing location, while Constraints 6.3 ensures that the vessel's voyage ends in the dummy end node. The vessel is only allowed to sail to the dummy end node if the cargo hold is empty, meaning that it can only travel to such a node after being unloaded at a landing site. Constraints 6.4 describes the flow through a node, and can be explained as follows: the only way the vessel can enter a node in the current time period, i.e. the right side of the constraints, is by either fishing at the given node or by sailing to the given node in the previous time period. Constraints 6.5 ensures that if the vessel sails to a node (i, g), it will carry out an operation there, meaning it will not sail to a node only to sail away again in the next time period. Constraints 6.6 ensures that the vessel is either sailing or operating, unless the vessel is changing its gear at the same location (i.e. going from (i, g) to (i, e)). Constraints 6.7 says that the sailing variable can only be true once within a time period t.

Cargo Constraints

As described in the problem description in Chapter 3, a vessel will have certain restrictions related to the fish it can target, the equipment it can carry, and on the quantity of catch. The variable q_{igft} represents the quantity caught or unloaded at location (i, g), while l_{gft} represents the total load onboard the vessel. The capacity of the vessel is given by the parameter Q^{CAP}, while the quotas assigned to the vessel are given by Q^{QUOTA}_{gf}. The effectiveness, or capability, of a given gear type is defined as L_{ig}, which denotes how many tonnes of fish the gear is capable of catching during a day of operation. The following cargo constraints are added to the model:

$$\sum_{g\in\mathcal{G}} \sum_{f\in\mathcal{F}} l_{gf1} = 0 \tag{6.8}$$

$$\sum_{g\in\mathcal{G}} \sum_{f\in\mathcal{F}} l_{gft} \leq Q^{CAP} \qquad t\in\mathcal{T} \tag{6.9}$$

$$\sum_{g\in\mathcal{G}} \sum_{f\in\mathcal{F}} l_{gft} = \sum_{g\in\mathcal{G}} \sum_{f\in\mathcal{F}} l_{gf,t-1} + \sum_{(i,g)\in\mathcal{M}} \sum_{f\in\mathcal{F}} I_i q_{igft} \qquad t\in\mathcal{T} \mid t>1 \tag{6.10}$$

$$\sum_{f\in\mathcal{F}} q_{igft} \leq L_{ig} y_{igt} \qquad (i,g)\in\mathcal{M}, t\in\mathcal{T} \tag{6.11}$$

$$\sum_{i\in\mathcal{N}^{\mathcal{F}}}\sum_{t\in\mathcal{T}} q_{igft} \leq Q_{gf}^{QUOTA} \qquad g\in\mathcal{G}, f\in\mathcal{F} \tag{6.12}$$

$$\sum_{i\in\mathcal{N}^{\mathcal{F}}}\sum_{t\in\mathcal{T}} q_{igft} \geq 0.1\cdot Q_{gf}^{QUOTA} \qquad g\in\mathcal{G}, f\in\mathcal{F} \tag{6.13}$$

Constraints 6.8 ensures that the cargo hold of the vessel is empty at the start of the planning period, while Constraints 6.9 states that the amount of fish onboard never can exceed the capacity of the vessel. Constraints 6.10 makes sure that the amount of fish onboard equals the amount of fish caught, based on the amount of fish onboard in the previous time period. By implementing the parameter I_i, which defines the node type, the constraints will hold for all locations $(i,g)\in\mathcal{M}$. Constraints 6.11 states that the vessel will not catch any fish unless the y_{igt}-variable is active. At the same time it ensures that the vessel is not fishing more than what the installed equipment is capable of. Constraints 6.12 and 6.13 ensures that the quota restrictions are upheld. The amount of fish caught should not exceed the allowable quota, and is captured through Constraints 6.12. To force the model to target all species that it holds a quota on, Constraints 6.13 are added.

Variable Constraints

Lastly, the variables must be defined and constrained. Constraints 6.14 and 6.15 are the binary requirements for the sailing variable and the task variable, respectively. Constraints 6.16 and 6.17 define the variables l_{gft} and q_{igft} as continuous variables, and will only take values larger or equal to zero.

$$x_{igjet}\in\{0,1\} \qquad (i,g)\in\mathcal{M}, (j,e)\in\mathcal{M}, t\in\mathcal{T} \tag{6.14}$$

$$y_{igt}\in\{0,1\} \qquad (i,g)\in\mathcal{M}, t\in\mathcal{T} \tag{6.15}$$

$$l_{gft}\geq 0 \qquad g\in\mathcal{G}, f\in\mathcal{F}, t\in\mathcal{T} \tag{6.16}$$

$$q_{igft}\geq 0 \qquad (i,g)\in\mathcal{M}, f\in\mathcal{F}, t\in\mathcal{T} \tag{6.17}$$

6.3 Implementation and Adjustments

The mathematical model has been implemented in Mosel, and solved using the optimisation software Xpress-IVE Version 8.5 64-bit. The mathematical model is created in a single Mosel file, and all constraints and variables are declared and created in this file. The parameters are stored in a separate text file, making it easier to run the model for different cases. The implemented model can be seen in Appendix B.

The extent of the problem is highly dependant on the number of constraints and variables that are created, implying that these should only be created if necessary. In this section, some adjustments made to the formulation of the model above are shown. Section 6.3.1 gives a brief explanation on how some of the sets have been defined, while the creation of the decision variables are described in Section 6.3.2. When creating the input file, it was decided to calculate parameters depending on three indices, instead of writing them out. The reasoning behind this decision, and how it was done, is included in Section 6.3.3. Here, the calculation of the sailing time and the sales price are also illustrated.

6.3.1 Definition of Sets

In the mathematical model above, each node were given two specific attributes; the location i and the current installed equipment g, and is defined as a part of the set $\mathcal{M}$. The set is defined in such manner that only allowed combinations of (i, g) are included. When the model was implemented, it was decided to define the possible combinations when creating the variables rather than creating an additional set. Hence, the set $\mathcal{M}$ is not included in the implementation of the model.

Next, the nodes belonging to the subsets N^P and N^F must be defined. The parameter I_i is used to denote the node type by taking the value 1 if the node in question is a fishing location, or the value -1 if it is a landing site. The parameter is only defined for nodes contained in the set N, meaning that the initial start node and dummy end node are not included.

6.3.2 Creating the Decision Variables

Since the sailing variable is dependant on five indices, the amount of variables created will increase exponentially if the problem size is increased. To avoid the model using time and memory on creating unnecessary variables, a set of constraints have been applied to the creation of x_{igjet}. These will be further explained in this section.

The sailing variable x_{igjet} will be equal to 1 if the given variable is active in the solution, meaning that the vessel sails from node (i, g) to (j, e) in time period t. As mentioned above, the variable should only be created if the combination of indices are allowed, hence the parameter B_{ge} is created. The parameter will only take the values $[0, 1]$, and will be equal to 1 if the vessel can change its equipment configuration from type g to e while it is located at sea. If $B_{ge} = 0$ it means that the vessel can't conduct the gear change at sea, however it may be possible at a suitable port. In addition, the vessel can only sail from the depot node if its destination is a fishing ground. This is captured in the first *if-loop* in the pseudo code below. When the vessel is ending its trip, i.e. sailing back to the dummy end node, it must empty its cargo hold first. Hence, the second *if-loop* is created, which states that the vessel can only sail to node 0 from a landing site.

Algorithm 1 Pseudo code for creation of the sailing variable, x_{igjet}

for all $i \in \mathcal{N}^{\mathcal{T}}, g \in \mathcal{G}, j \in \mathcal{N}^{\mathcal{T}}, e \in \mathcal{G}, t \in \mathcal{T}$ **do**
    if $ii = 0$ and $jj \in \mathcal{N}^{\mathcal{F}}$ **then**
        create x_{igjet}
    end if

    if $jj = 0$ and $ii \in \mathcal{N}^{\mathcal{P}}$ **then**
        create x_{igjet}
    end if

    if $ii \in \mathcal{N}$ and $jj \in \mathcal{N}$ **then**
        if $B_{ge} = 1$ or $gg = ee$ **then**
            create x_{igjet}
        end if
    end if

    if $ii = jj$ and $gg \neq ee$ **then**
        create x_{igjet}
    end if
end for

The operating variable y_{igt} is created for all combinations of indices, unless a given area has restrictions on the equipment that can be used. The decision variable q_{igft} is only created for combinations of f and g that are allowed, meaning that it is possible to catch a given fish species f using gear g. To account for this the parameter A_{gf} is created, which equals 1 if the gear type and fishery is compatible, and 0 if it is not. The variables l_{gft} and q_{igft} are created as continuous variables. By not creating the variables which have incompatible combinations of g, f the computational work required by the model is reduced. However, as there are limits on both the amount of gear and species in question, it is believed that this is not necessary.

6.3.3 Calculating Parameter Values

Sailing Time Parameter

The time it takes to sail from one node to another is an important aspect to consider, as it will affect how large the overall sailing cost will be. Because the sailing time depends both on the speed of the vessel, the distance between the areas, and the weather conditions, the creation of the parameter appeared to be quite challenging. To combat this, the parameter is calculated based on the distance and speed of the vessel, which will vary from one time period to another to simulate changing weather conditions.

The following pseudo code is created and used in the implementation of the model. Here, D_{ij} denotes the distance between the nodes i and j, while V_t is defined as the vessel's speed in time period t. To ensure that the time period counter does not get affected by these calculations, the sailing time is rounded up to the nearest integer, i.e. the nearest day. In reality, the sailing time can vary from a few hours to several days, thus such an approach can lead to a loss of time used on the fishing operation. This will be further discussed later in the thesis. As stated by the first *if-loop*, the vessel will experience a sailing time of 1 day if the vessel is conducting a gear change within the same node. In reality, this might take a couple of hours or even just a few minutes. But with the amount of uncertainties within the problem, it is decided that a conservative estimate of the time best suited.

Algorithm 2 Pseudo code for creation of the sailing time parameter

for all $i \in \mathcal{N}^{\mathcal{T}}, j \in \mathcal{N}^{\mathcal{T}}, t \in \mathcal{T}$ **do**
  if $D_{ij} = 0$ **or** $V_t = 0$ **and** $B_{ge} = 1$ **then**
    $T^S_{igjet} = 1$
  else
    $T^S_{igjet} = \left(\frac{D_{ij}}{V_t}\right) \cdot \frac{1}{24}$
  end if
end for

Sales Price Parameter

To better capture the variation in sales prices, a similar approach to the one described above is used. The sales price varies based on the type of species, what time of year the fish is caught, and in some cases also with the type of equipment that is used. To best incorporate all these factors, two parameters have been created. P_{gf} denotes the sales price of species f caught with equipment g, while P_{ft} denotes the seasonal variations in the sales price of species f. The latter is given values ranging from $0 - 1$, where a value of 1 indicates that the species is in-season. If the fish is caught out of its *normal* season, the sales price is set to be somewhat lower by giving P_{ft} values below 1. To avoid creating unnecessary parameters, P_{gft} will only be created if the fishery and gear type is compatible, which is defined by the parameter A_{gf}.

Algorithm 3 Pseudo code for creation of the sales price parameter

for all $g \in \mathcal{G}, f \in \mathcal{F}, t \in \mathcal{T}$ **do**
  if $A_{gf} \geq 1$ **then**
    $P_{gft} = P_{gf} \cdot P_{ft}$
  end if
end for

Chapter 7

Computational Study

This chapter will describe a computational study of the routing model introduced in Chapter 6, using as realistic values as possible. The purpose of the computational study is to investigate the model's capabilities, hence, the problem size will be somewhat constrained compared to a real-size problem.

Two separate test cases have been created. The first case, presented in Section 7.1, is made to simply showcase how the model works. The second test case aims to capture how the larger, and more challenging gear changes, impact the vessel's optimal route and is presented in Section 7.2. The results obtained are shown in Section 7.3.

7.1 Test Case I: The Stern Trawler

The first test case is created based on a common equipment configuration used today, namely a stern trawler with the capability of shrimp trawling. These types of vessels have the ability to perform rapid gear changes on their trips, hence the type of change is referred to as *simple*, and can be performed while the vessel is sailing. Although the shift can be done while at sea, a cost related to a change is included so that the optimisation model doesn't conduct a change every other day. The costs are of minor significance, and can be seen in Table 7.1 below. Given that the main operation of the vessel is to use its whitefish trawl, it is assumed that the cost of switching to the shrimp trawl is higher than going the other way around.

The capability of the gear, i.e. the effectiveness, is defined as how much the vessel is able to catch during one day of fishing. The value of the parameter is set based on conversations with different people in the industry, and it should be noted that these values are highly varying based on several factors, being the weather conditions at the time or the density of fish in the area. Certain areas may be closed for a given fishery or gear type. This is accounted for through the parameter L_{ig}, by lowering the value to zero. This has been done to restrict the areas where the vessel can trawl for shrimps. The cost of operating the different gear types are based on the efforts needed by the vessel, and to some extent also the crew. When trawling for whitefish, the resistance caused by the trawl is much higher than it is when using the shrimp trawl, hence the vessel should use more power. The whitefish that is caught also needs more processing time compared to the shrimps, resulting in a higher cost related to the whitefish operation.

Table 7.1: Parameters related to the gear types of the vessel. The parameter name is included in the header.

	Cost of change [C^C_{ge}]	Effectiveness [L_{ig}]	Cost of operating [C^G_g]
Whitefish trawl	NOK 19.000	40-60 tonnes/day	NOK 45.000/day
Shrimp trawl	NOK 25.000	30-40 tonnes/day	NOK 30.000/day

The characteristics related to the vessel itself are presented in Table 7.2. The capacity of the vessel is decided based on stern trawlers operating today. The optimisation model given in Chapter 6, defined the vessel speed as a function of time. However, it has been chosen to keep the sailing speed at a constant level. The cost related to sailing is given as NOK/day, and is calculated based on the average fuel consumption of similar vessels after discussing with industry actors.

Table 7.2: Parameters related to the vessel's characteristics. The parameter name is included in the header.

Vessel capacity [Q^{CAP}]	**Vessel speed [V]**	**Cost of sailing [C^S]**
500 tonnes	15 knots	NOK 75.000/day

As stated in Chapter 2, the amount of fish a vessel is allowed to catch is decided by the vessel's quotas. Most stern trawlers will have a combination of structural quotas and quotas directly linked to their desired operation. The size of the quotas are based on the quota factor, which depends on the vessel size. For instance, the factory stern trawler *Granit* has three structural quotas for *cod trawl*, a license for shrimp trawling and an additional cod trawl license. The quotas owned by the vessel in this study are based on the average quotas obtained by other stern trawlers.

For the vessel used in this study, Table 7.3 presents relevant parameters for different fish species to be caught. In total, six different species are included: the Atlantic cod, haddock, saithe, Greenland halibut, redfish, and the Atlantic shrimp. The planning period is set to 30 days, which is approximately the length of one trip. The overall quotas have been scaled to fit the planning period, meaning that a overall quota of 3000 tonnes of cod corresponds to a monthly quota of 300 tonnes. The sales prices are based on the graphs presented in Figure 2.5. Variation of the sales price are accounted for by creating a range in which the parameter can vary in.

Table 7.3: Fisheries included in the computational study with the associated sales price and quota size. The sales price is given in ranges to account for the variations in price over time. The parameter name is included in the header.

	Sales price [P_{gft}]	**Quota [Q_{gf}^{QUOTA}]**
Atlantic cod	NOK 30-40/kg	300 tonnes
Atlantic shrimp	NOK 25-30/kg	150 tonnes
Greenland halibut	NOK 25-35/kg	40 tonnes
Haddock	NOK 20-30/kg	140 tonnes
Redfish	NOK 5-10/kg	250 tonnes
Saithe	NOK 12-16/kg	150 tonnes

Furthermore, the geographical extent of the problem has been limited to only consider fishing grounds north of $62°N$, which is roughly shown in Figure 7.1. The areas are based on the ICES fishery zones presented in Figure 3.1, where a node corresponds to a certain zone. To simplify the problem further, the fishing grounds nearest to the coastline has been excluded. Very few stern trawlers operate within these areas, hence it is assumed that the simplification not will remove any realistic solutions. Five landing sites are included in the problem, as illustrated by the figure. The landing site in Ålesund has been chosen as the vessel's depot node, hence it is denoted as *Node 0,1*.

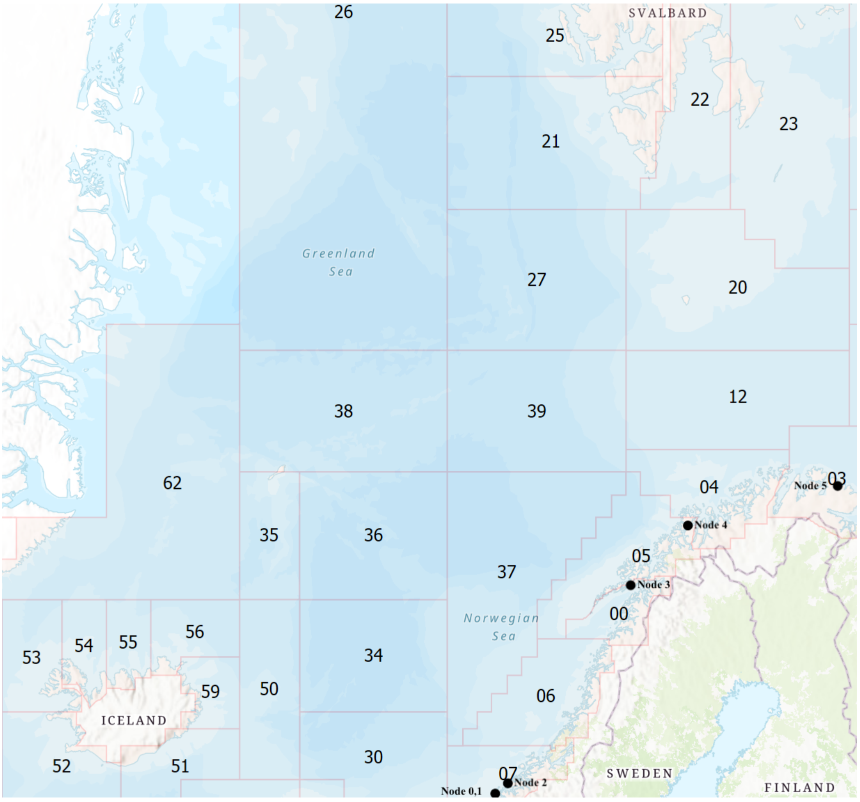


Figure 7.1: Geographical domain of Test Case I.

The distances between each landing site can be seen in Table 7.4, while the entire distance matrix can be seen in Appendix C.3. Since the ICES zones are quite big a simplification on how the distances are measured has been done. The vessel is forced to sail to the middle of each zone and the distance is measured here. Hence, a vessel traveling just over the border between two zones in reality, are forced to travel to the middle. This will lead to uncertainty regarding the sailing time, however the extra work related to creating a full range of distances for each node was considered too much. However, the sailing distance between each port is assumed to be fairly accurate.

Table 7.4: Matrix showing the sailing distance between the different landing sites. The matrix is symmetric, meaning that there are no difference going from 1 to 2, and 2 to 1. The distances are given in nautical miles.

	0 - Ålesund	**1 - Ålesund**	**2 - Bud**	**3 - Svolvær**	**4 - Tromsø**	**5 - Båtsfjord**
0	0	0	33	405	540	805
1	-	0	33	405	540	805
2	-	-	0	372	505	775
3	-	-	-	0	133	403
4	-	-	-	-	0	270
5	-	-	-	-	-	0

To restrict the problem even further, constraints on where the Greenland halibut can be caught is included. These can be seen in Constraints 7.1. This is due to the complicated quota regulations on the species, which states that the fishery is only open during certain time periods, or in the waters surrounding Greenland. For this study, the vessel can only catch Greenland halibut in the ICES zones 26 and 62. In addition, the vessel must catch at least 50% of the total quota for Greenland halibut during the 30 days. In the input file, the Greenland halibut is defined as $f = 4$ while the two fishing zones are defined as $i = 15$ and $i = 17$, respectively.

$$\sum_{t \in \mathcal{T}} q_{ig4t} \geq 0.5 \cdot Q_{g4}^{QUOTA} \qquad i = [15, 17], g \in \mathcal{G} \tag{7.1}$$

The full input file explaining all parameters used in for this case study is given in Appendix C.1. The results obtained from the optimisation model are presented in Section 7.3.1.

7.2 Test Case II: The Combined Vessel

The second test case aims to incorporate different equipment configurations that needs to be conducted while the vessel is located at port. It is decided that the best way of showcasing this is through a study based on an autoline vessel, which also have the capability of using nets without any big changes. This combination is fairly common in today' industry. This means that all equipment needed for both the autoline and net operation is installed on the vessel. If the captain decides to shift gears this can be done quick, and it is assumed that it can be carried out while the vessel is at sea. Parameters related to the vessel itself are given in Table 7.5. Compared to the stern trawler, the capacity of the vessel is lower. This is due to the size differences between stern trawlers and autoline vessels; the length of stern trawlers ranges from 60-80 meters, while autoline vessel are rarely built above 60 meters.

Table 7.5: Parameters related to the vessel's characteristics. The parameter name is included in the header.

Vessel capacity [Q^{CAP}]	**Vessel speed [V]**	**Cost of sailing [C^S]**
400 tonnes	15 knots	NOK 75.000/day

In addition to the combined operation above, the vessel can go through some changes to also support fishing using a Scottish seine or a shrimp trawl. The extent of the change depends on the gear choice, and the details are given in Section 7.2. The choice of not including demersal trawl, purse seine or the pelagic trawl was done intentionally. The demersal trawl is quite area demanding, requiring an open deck through the length of the vessel for its trawl bags. Because the design of the combined vessel differs from a typical stern trawler it will require huge alterations to the construction of the vessel, thus it is not relevant for this study. The pelagic trawl and purse seine are used for other fish species than what a classic line vessel is targeting. The cargo holds onboard are thus not compatible, making these gear types unnecessary to include.

Table 7.6: Possible changes of the operation mode for the vessel.

Operation mode	**Explanation of change**
Nets	Simple change that can be conducted while the vessel is at sea
Scottish seine	The vessel must sail to its depot port and install the gear here. It is assumed that the installation can be carried out at the port by certified personnel
Shrimp trawl	The vessel must sail to its depot port and pick up and install the gear here.

The geographical domain of the test case is chosen to be the same as for the previous case, i.e. the ICES fishing zones north of $62°N$. The vessel can conduct the large changes in its equipment configuration at its home port in Ålesund, hence constraints ensuring this must be created.

Each fishing gear will have different capabilities regarding how much they can fish during a day, and also on what fisheries they can be applied. The capability has been found after correspondence with people in the industry. Table 7.7 illustrates the different gear parameters, while Figure 7.2 defines the compatibility between the fisheries and gear types. It is assumed that the cost of changing the operation mode of the vessel is independent of of the previous operation mode. However, if the vessel is to conduct a simple change when one of the more complex equipment configurations are installed, the vessel must sail to a port to do so.

Table 7.7: Parameters related to the gear types of the vessel. The parameter name is included in the header.

	Cost of change [C^C_{ge}]	**Effectiveness [L_{ig}]**	**Cost of operating [C^G_g]**
Autoline	NOK 10.000	20-40 tonnes/day	NOK 50.000/day
Nets	NOK 13.000	25-35 tonnes/day	NOK 45.000/day
Scottish seine	NOK 30.000	30-50 tonnes/day	NOK 55.000/day
Shrimp trawl	NOK 25.000	30-40 tonnes/day	NOK 30.000/day

Figure 7.2: The compatibility between the gear types and fisheries. The X illustrates that the species and gear are compatible, and corresponds to the parameter A_{gf} in the mathematical model.

	Autoline	**Nets**	**Scottish seine**	**Shrimp trawl**
Atlantic cod	X	X	X	-
Atlantic shrimp	-	-	-	X
Greenland halibut	X	-	-	-
Haddock	X	X	X	-

As for the fisheries included in this test case, an overview can be seen in Table 7.8. Stern trawlers and autoline vessels target many of the same species, hence the same fisheries are included here, except for the redfish and saithe. Due to the extent of the problem these have been chosen to be left out to ease the computational work needed to be done by the solver. As previously mentioned, the sales price depend on the type of gear used due to the quality of the fish. The quality of fish caught using an autoline is high as the fish will experience little to none impact when its being hauled. On the other hand, the use of nets can cause the fish to injure itself when it is caught, thus lowering the quality of the product. These factors are captured within the sales price given below. The total quotas for each fishery are decided based on autoline vessels operating today, while the distribution between the possible gear types are based on assumptions.

Table 7.8: Fisheries included in the computational study with the associated sales price and quota size. The sales price is given in ranges to both account for the different gears that can be used and the seasonal variation. The parameter name is included in the header.

		Sales price [P_{gft}]	**Quota** [Q_{gf}^{QUOTA}]
	Autoline	NOK 40-45/kg	100 tonnes
Atlantic cod	Nets	NOK 20-30/kg	40 tonnes
	Scottish seine	NOK 35-45/kg	40 tonnes
Atlantic shrimp	Shrimp trawl	NOK 25-30/kg	90 tonnes
Greenland halibut	Autoline	NOK 30-40/kg	40 tonnes
	Autoline	NOK 25-35/kg	80 tonnes
Haddock	Nets	NOK 15-20/kg	20 tonnes
	Scottish seine	NOK 20-30/kg	30 tonnes

7.2.1 Adjustments Needed for Implementation of Test Case II

In order for the mathematical model presented in Chapter 6 to also consider a more complicated and costly equipment changes, some alterations must be done. Firstly, the sailing variable x_{igjet} must be created for combinations where the change of gear can happen. As given in the description of the test case the vessel can only carry out a larger change at its home port. This means that x_{1g1et} is an allowed index combination, and will be true if the vessel changes its equipment configuration from g to e in time period t.

Next, constraints stating that the vessel is only allowed to conduct specific changes at its home port is needed. It is assumed that constraints are independent of the order of the change, meaning that a change from (i, g) to (j, e) is no different from conducting the opposite change. The following constraints where added to the model in hopes of capturing these features of the problem:

$$\sum_{g \in \mathcal{G}} \sum_{e \in \mathcal{G}} x_{igiet} \leq 1 \qquad i = 1, t \in \mathcal{T} \tag{7.2}$$

If the location node $i \neq 1$ then the corresponding x_{igjet}-variable should not be active, i.e. the value should be 0.

7.3 Results of the Computational Study

The results from the computational study is presented in this chapter. The solution obtained for the first test case, the stern trawler, is illustrated in Section 7.3.1, while the result from the second test case is given Section 7.3.2.

7.3.1 Test Case I: The Stern Trawler

The results from running the model can be seen in Table 7.9. The amount of fish caught in each visited fishing location is given in the third column, while the total catch of each species is given in the second to last column. As illustrated, the vessel fills up its quotas for all species except for the Atlantic cod and shrimp. The vessel delivers its catch at two different landing sites; 490 tonnes are delivered to

Tromsø in time period 17, while 500 tonnes are delivered to Svolvær in time period 29. The overall profit is found to be NOK 39.9 million, and the model reached the optimal solution in 2650 seconds.

Table 7.9: Overview of the obtained results from running the model for Test Case I. *Node no.* corresponds to fishing location, and can be found in Appendix C.3. The table illustrates how much the vessel has caught in each node, as well as the total quantity of each species that are delivered. To compare the results, the overall quota has been added as well.

	Node no.	Quantity caught	Total quantity delivered	Overall quota
Atlantic cod	13	235 tonnes	290 tonnes	300 tonnes
	17	55 tonnes		
Haddock	15	20 tonnes	140 tonnes	140 tonnes
	17	120 tonnes		
Saithe	13	120 tonnes	150 tonnes	150 tonnes
	17	30 tonnes		
Greenland halibut	15	20 tonnes	40 tonnes	40 tonnes
	17	20 tonnes		
Redfish	13	145 tonnes	250 tonnes	250 tonnes
	17	105 tonnes		
Atlantic shrimp	12	120 tonnes	120 tonnes	150 tonnes

With this test case being quite simple, we know that all species, except the Atlantic shrimp, is caught using the whitefish trawl. Hence, a further investigation of the gear types in use is not necessary. However, the time periods for when the vessel changes from the whitefish trawl to the shrimp trawl is of interest. Table 7.10 summarises all combination of indices where the x_{igjet} variable equals 1. As one can see, the vessel conducts a total of four equipment changes; to and from the depot node, and in time periods 16 and 18 when the vessel is targeting shrimps. Although the vessel is allowed to change its gear while staying within the same location, it has chosen not to do this.

Table 7.10: The table gives an overview of which x_{igjet}-variables that are active in the optimised solution.

Time Period	From (i,g)	To (j,e)
1	(0,2)	(17,1)
9	(17,1)	(15,1)
12	(15,1)	(12,2)
16	(12,2)	(4,1)
18	(4,1)	(13,1)
28	(13,1)	(3,1)
30	(3,1)	(0,2)

To better illustrate the solution obtained, the optimised route of the vessel is drawn in Figure 7.3. Here, one can also see the corresponding ICES zones with the node numbers. The vessel start its journey in Ålesund, before traveling to ICES zone 62 (i.e. node 17). Here it is trawling for whitefish species for five consecutive days before sailing to zone 26 (i.e. node 15). After three days the vessel sails towards location 27 (node 12), and is also conducting a gear change on the way. The next three days the vessel trawls for shrimp, before sailing to Tromsø (i.e. node 4) to unload the fish. On its way the vessel changes back to its whitefish trawl. The last fishing trip for the vessel is carried out in fishing zone 39 (i.e. node 13), and the vessel delivers the fish caught here in Svolvær. As given by the mathematical model, the vessel ends its trip in Ålesund.

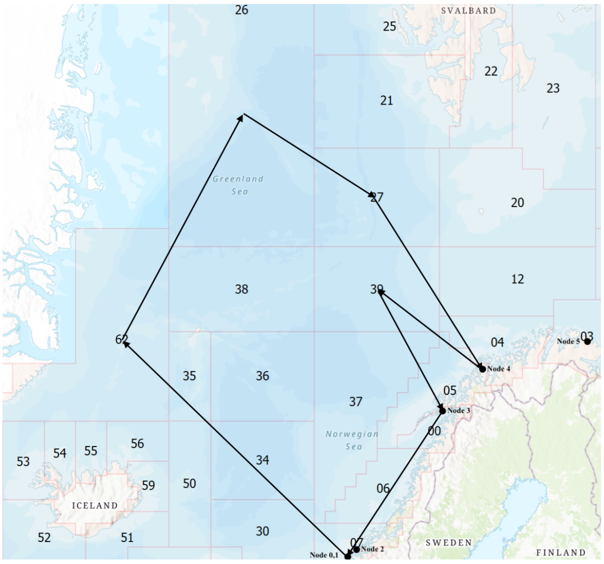


Figure 7.3: Optimised route obtained for Test Case I.

7.3.2 Test Case II: The Combined Vessel

When Test Case II was tested, several modeling issues appeared. To get the model to run properly, Constraints 6.13 had to be removed. The added constraints in the previous test case regarding the Greenland halibut were also causing problems, hence it was not included for this case.

When running the model after implementing Constraints 7.2 and conducting the adjustments mentioned above, the results in Tables 7.11 and 7.12 were obtained. Table 7.11 illustrates the amount of fish caught with the specific gear types, and compares the catch with the overall quotas. The result yields that the vessel delivers a total of 280 tonnes at landing site 1, while the objective value was NOK 15.9 million. The model reached this solution after 950 seconds, less than half of the time used by Test Case II. The results show that the vessel is not fulfilling its quotas, with the reason being that the vessel is either unable or unwilling to conduct the necessary equipment change. An attempt was made to force the vessel to conduct at least one of these equipment changes, however this was not successful.

Table 7.11: Fisheries included in the computational study with the associated sales price and quota size. The sales price is given in ranges to both account for the different gears that can be used and the seasonal variation. The parameter name is included in the header.

		Node no.	Quantity caught	Quota
Atlantic cod	Autoline	20	100 tonnes	100 tonnes
	Nets	20	40 tonnes	40 tonnes
	Scottish seine	-	-	40 tonnes
Atlantic shrimp	Shrimp trawl	-	-	90 tonnes
Greenland halibut	Autoline	20	40 tonnes	40 tonnes
Haddock	Autoline	20	80 tonnes	80 tonnes
	Nets	20	20 tonnes	20 tonnes
	Scottish seine	-	-	30 tonnes

In addition to the amount of fish caught, the vessel generate the route displayed in Table 7.12. As clearly stated here, the vessel is only sailing between three of the nodes, namely the depot node, node 20 and node 1. In reality, the depot node and node 1 are the same location, hence the vessel is going back and forth between the start node and the nearest fishing ground. There were no constraints on how much the vessel could catch in a given location, hence the lowest sailing costs are obtained by only operating within one node. To combat this, a minimum requirement on the quantity caught of a given species in a certain area could've been implemented. However, as the model has several errors related to the gear changes, the results would've been unrealistic anyway.

Table 7.12: The table gives an overview of which x_{igjet}-variables that were active in the optimised solution.

Time Period	**From (i,g)**	**To (j,e)**
1	(0,2)	(20,1)
12	(20,1)	(20,2)
16	(20,2)	(1,1)
18	(1,1)	(20,2)
20	(20,2)	(20,1)
28	(20,1)	(20,2)
30	(1,2)	(0,1)

The results that were obtained in the second test case, implies that there exists some errors within the definition of the sailing variable. An attempt of removing the restrictions regarding the creation of the variable was made, but the solver then states that the problem were infeasible. This leads to the conclusion that the implemented Constraints 7.2 are causing other constraints to be broken.

Chapter 8

Discussion

This chapter will discuss the work that has been done throughout this thesis. First, a discussion regarding the assumptions that were made during the creation of the mathematical model is given, and the impact these pose on the obtained results. Next, a discussion regarding the results from the computational study is given. The steps conducted in order to get a fully working optimisation model will be briefly explained.

When creating the mathematical model, a handful of assumptions had to be made so that the model could find a solution within a reasonable time frame. Since the model is created based on a discrete-time approach, some information can get lost if the time steps are to large. With time steps of one day, transits that in reality are completed in a matter of hours are forced to last at least 1 day. Consequently, valuable time that could've been used at generating profits is lost in the model. By decreasing the time steps, the solution obtained may have been more realistic. However, this would've increased the computational time significantly. An attempt was done at running Test Case I with a planning horizon of 60 days instead of 30, but the model was stopped after running for six hours. At this point, the model had used the last three hours decreasing the optimality gap from 20% down to 19.59%. The computational time is also dependant on the computer in which the solver is installed. This implies that a solution may have been obtained faster by using a different device. The model is only able to capture varying weather conditions through the vessel's speed parameter. In order to get realistic results when weather conditions are included, historical weather data and a stochastic approach should have been used.

Furthermore, some assumptions and simplifications regarding how a vessel is operated are made in the model. For instance, it is assumed that the vessel will be operating continuously throughout the planning period, meaning that scheduled maintenance, longer stays in port, etc., are not taken into consideration when creating the model. This could be achieved by introducing time windows, but with the model being as complex as it is, this possibility has not been investigated. The crew is a part of the reason why the planning of the vessel's route is so important to have in place at an early stage. A single vessel typically have to separate shifts working at the vessel for a period of four to six weeks at a time. Hence, the model should be created so that the vessel visits a port for the crew change to happen. In addition, different fisheries have different demands to the type of handling and processing necessary, hence the model should account for additional port visits if it plans to target such a fishery. These aspects have not been included during the modeling of the problem. For the test cases, a planning horizon of 30 days have been chosen, thus it is assumed that it is not not necessary to account for the change of crew.

In a real fishing operation, a vessel can go for days without finding and catching any fish. This is due to fish species constantly being on the move, and predictions and historical data can only give approximate areas where the fish may be located. In the model, the quantity of fish is modeled deterministically, meaning that the location and distribution of fish is known in advance. In reality, the amount of fish caught in an area, also referred to as the density of fish, is unknown and highly variable. An attempt of capturing some of this uncertainty has been done through the gear capability parameter. The results showed, however, that the vessel will capture the maximum allowed quantity during a day of fishing. To get a more accurate result, the parameter should be modeled as a stochastic variable. This will introduce a whole new topic to investigate, and has not been touched upon in this thesis.

The importance of feeding the model with realistic and correct input data is high, but may be difficult to achieve in practise. By contacting fishermen, ship owners, ship designers and operating managers, the parameter values in the model have been set. However, these values are highly dependent on the different vessel's characteristics. The fuel consumption of the engine during transit and fishing depend on the size of the vessel and the engine type, and will decide the majority of the costs related to sailing and operation. Regarding the cost of making changes to the equipment configuration, little information has been acquired as this is not something that is commonly done in the industry today. Estimations have been used to decide the cost parameters, meaning that the attributes mentioned above has not been accounted for. The sales price of the different species will depend on a number of factors, as described previously. In addition, the price will depend on the size of the fish, as well as how the fish has been processed. The model does not look at the size distribution of the fish caught, meaning that it is not possible to incorporate these distinctions in the model. Overall, the parameter values are mainly based on estimations and assumptions, hence the results should be further investigated before any large decisions are made based on the model's output. With that being said, the objective value obtained when running Test Case I showed to be close to a realistic result. On a good trip, a stern trawler can have an income ranging from NOK 30-50 million, depending on the type of fish it has caught. A profit of NOK 39.9 million is high, but realistic, especially when considering that the model doesn't account for all real life aspects surrounding the problem.

As briefly mentioned in the previous chapter, the implementation of large equipment changes have not been successful. Much time was used on troubleshooting the model, though without any luck. The constraints illustrated in Constraints 7.2, aimed to secure that the sailing variable was allowed to take the value 1 when the conditions are met, i.e. the vessel can only conduct a complicated change at its home port. The creation of the variable, which was explained in great detail in Section 6.3, was also altered so that this combination of indices were allowed. The solution of Test Case II did not include any of the large changes, which could've been a valid solution. However, when an attempt was made to force the vessel to conduct a large gear change, the model gave the optimal solution of *not doing anything* despite of breaking several constraints. Multiple attempts on solving this matter was conducted, but none of these attempts provided satisfying results.

The main focus of this thesis has been on the creation of an optimisation model, meaning that the creation of suitable modules and equipment configurations have not been prioritised. Hence, the work presented by Kristiansen (2014) was used as a base for possible gear configurations. If the model is to be used as a decision tool for a ship owner considering a combined vessel, more details regarding the possibilities should be investigated. A similar study to the one conducted by Kristiansen should be applied to ocean-going vessels, so that the requirements regarding the vessel's form are described in more detail. In this thesis, it is assumed that a *large and complicated* change can be conducted on the vessel without any special alterations to the design. This will in most cases not be accurate. For instance, the combined vessel *M/S Atlantic* was built so that the operating mode could quickly change from using an autoline to a Scottish seine. In order to fit all equipment needed and to meet stability requirements, the vessel is both longer and wider than other autoline vessels. This leads to the conclusion that combining different equipment configurations is far more complex than to place an equipment module on deck of a vessel.

In sum, several extensions and improvements should be made in order to conclude that the optimisation model can provide any guidance during the planning process. Firstly, the model should be able to account for large gear changes. Secondly, the process of creating possible equipment configurations should be devoted more time, both in terms of the equipment's attributes and the requirements for altered vessel characteristics. A more thorough analysis regarding the related costs of these processes should also be conducted.

Chapter 9

Conclusion

This thesis aimed to develop an optimisation model that combined the expanded operating environment with the operational planning of the vessel, intending to create a tool that can be used during the decision process. With a more regulated industry in terms of admissions and the quantity of biomass that are allowed to gather from the sea, the potential of incorporating new equipment configurations on a vessel is large and can help increase the flexibility of the vessel.

The problem described in this thesis has not been investigated before, hence a thorough understanding of the problem was needed. To achieve this an extensive background study has been conducted on the fishing industry and related literature. The optimisation model developed tracks the vessel's operation cycle through the planning period and ensures that the vessel aims to fulfill its assigned quotas. The results of the first case study yield that the vessel almost can deliver its assigned quotas within the time frame, which is set to 30 days. However, the vessel goes through unnecessary equipment changes that are not realistic in the real operation of the vessel. It is assumed that the solution emerges from the fact that the cost of operating, as well as changing from the shrimp trawl is lower than the costs related to the whitefish trawl.

Although a fully working optimisation model was not obtained, the partial model provides insight into how a changing operation context can influence the routing of a vessel. The attempt of combining a shifting operating environment for the fishing vessel with the routing model is something that has not been done before, hence little support literature exists.

Further work on the topic should be done for the model to work as an aid in the industry. Firstly, the possibility of conducting large equipment changes should be implemented. The cost associated with this, as well as the time frame of the operation, should be found and included. Furthermore, a more in-depth study on the equipment configurations and the requirements these pose on the vessel should be carried out. As mentioned, the main focus of this thesis was on the development of the model and assumptions regarding the equipment changes that have been used.

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Appendix

A Mathematical Model

Sets

$\mathcal{N}^T$	Set of all nodes, including o and d
$\mathcal{N}$	Set of locations in the problem
$\mathcal{N}^F$	Set of fishing grounds, subset of $\mathcal{N}$
$\mathcal{N}^P$	Set of landing sites in the problem, subset of $\mathcal{N}$
$\mathcal{T}$	Set of time periods within the planning horizon
$\mathcal{G}$	Set of fishing gears
$\mathcal{F}$	Set of fisheries
$\mathcal{M}$	Set of allowed nodes (i,g) where $i \in \mathcal{N}$ and $g \in \mathcal{G}$

Indices

i, j	Nodes, $i, j \in \mathcal{N}$
o	Initial starting node
d	Dummy end node
t	Time period, $t \in \mathcal{T}$
g, e	Type of fishing gear, $g \in \mathcal{G}$
f	Type of fishery, $f \in \mathcal{F}$

Parameters

C^S	The cost per time period of sailing
C^G_g	The cost of operating gear g
C^C_{ge}	The cost of switching from gear type g to gear type e
P_{gft}	Sales price obtained for fish species f caught using gear g in time period t
Q^{CAP}	The cargo capacity of the vessel
Q^{QUOTA}_{gf}	The vessel's quota for fishery f using gear type g
T^S_{igjet}	Sailing time between nodes i and j in time period t
L_{ig}	The effectiveness/unloading rate of gear g if located at location i
I_{ig}	Explains the node type, and equals 1 if the node belong to the set $\mathcal{N}^F$, i.e. is a fishing ground, and -1 if the node is a landing site, thus belonging to the set $\mathcal{N}^P$.

Decision Variables

x_{igjet}	A binary variable which takes the value 1 if the vessel sail between nodes i, g and j, e in time period t, 0 otherwise
y_{igt}	A binary variable which takes the value 1 if the vessel is fishing/unloading fish using gear type g at location i in time period t, 0 otherwise
l_{gft}	The amount of catch f onboard the vessel at the end of time period t which was caught using fishing gear g
q_{igft}	The amount of fish f caught/offloaded at location i using gear g in time period t

Model Formulation

$$
\begin{aligned}
max\ z = & \sum_{\substack{(i,g)\in\mathcal{M}\\|i\in\mathcal{N}^{\mathcal{P}}}} \sum_{g\in\mathcal{G}} \sum_{f\in\mathcal{F}} \sum_{t\in\mathcal{T}} P_{gft} q_{igft} \\
& - \sum_{(i,g)\in\mathcal{M}} \sum_{(j,e)\in\mathcal{M}} \sum_{t\in\mathcal{T}} C^S T^S_{igjet} x_{igjet} \\
& - \sum_{(i,g)\in\mathcal{M}} \sum_{g\in\mathcal{G}} \sum_{t\in\mathcal{T}} C^G_g y_{igt} \\
& - \sum_{(i,g)\in\mathcal{M}} \sum_{(j,e)\in\mathcal{M}} \sum_{t\in\mathcal{T}} C^C_{ge} x_{igjet}
\end{aligned}
\tag{A.1}
$$

$$
\sum_{(g)\in\mathcal{G}} \sum_{\substack{(j,e)\in\mathcal{M}\\|j\in\mathcal{N}^{\mathcal{F}}}} x_{ogje1} = 1 \tag{A.2}
$$

$$\sum_{\substack{(i,g)\in\mathcal{M}\\|i\in\mathcal{N}^{\mathcal{P}}}}\sum_{(e)\in\mathcal{G}}\sum_{t\in\mathcal{T}} x_{igdet} = 1 \tag{A.3}$$

$$y_{ig,t-1} + \sum_{(j,e)\in\mathcal{M}} x_{jeig,t-T^S_{igjet}} = y_{igt} + \sum_{(j,e)\in\mathcal{M}} x_{igjet} \qquad (i,g)\in\mathcal{M},\ t\in\mathcal{T} \mid t>1 \tag{A.4}$$

$$\sum_{(j,e)\in\mathcal{M}} x_{igje,t-T^S_{igjet}} \leq y_{igt} \qquad (i,g,)\in\mathcal{M},\ t\in\mathcal{T} \tag{A.5}$$

$$\sum_{(i,g)\in\mathcal{M}} y_{igt} + \sum_{(i,g)\in\mathcal{M}}\sum_{(j,e)\in\mathcal{M}}\sum_{t'=t}^{T^S_{igjet}} x_{igjet'} \leq 1 \qquad t\in\mathcal{T}, i\neq j \tag{A.6}$$

$$\sum_{(i,g)\in\mathcal{M}}\sum_{(j,e)\in\mathcal{M}} x_{igjet} \leq 1 \qquad t\in\mathcal{T} \tag{A.7}$$

$$\sum_{g\in\mathcal{G}}\sum_{f\in\mathcal{F}} l_{gf1} = 0 \tag{A.8}$$

$$\sum_{g\in\mathcal{G}}\sum_{f\in\mathcal{F}} l_{gft} \leq Q^{CAP} \qquad t\in\mathcal{T} \tag{A.9}$$

$$\sum_{g\in\mathcal{G}}\sum_{f\in\mathcal{F}} l_{gft} = \sum_{g\in\mathcal{G}}\sum_{f\in\mathcal{F}} l_{gf,t-1} + \sum_{(i,g)\in\mathcal{M}}\sum_{f\in\mathcal{F}} I_i q_{igft} \qquad t\in\mathcal{T} \mid t>1 \tag{A.10}$$

$$\sum_{f\in\mathcal{F}} q_{igft} \leq L_{ig} y_{igt} \qquad (i,g)\in\mathcal{M}, t\in\mathcal{T} \tag{A.11}$$

$$\sum_{i\in\mathcal{N}^{\mathcal{F}}}\sum_{t\in\mathcal{T}} q_{igft} \leq Q^{QUOTA}_{gf} \qquad g\in\mathcal{G}, f\in\mathcal{F} \tag{A.12}$$

$$\sum_{i\in\mathcal{N}^{\mathcal{F}}}\sum_{t\in\mathcal{T}} q_{igft} \geq 0.1\cdot Q^{QUOTA}_{gf} \qquad g\in\mathcal{G}, f\in\mathcal{F} \tag{A.13}$$

$$x_{igjet}\in\{0,1\} \qquad (i,g)\in\mathcal{M}, (j,e)\in\mathcal{M}, t\in\mathcal{T} \tag{A.14}$$

$$y_{igt}\in\{0,1\} \qquad (i,g)\in\mathcal{M}, t\in\mathcal{T} \tag{A.15}$$

$$l_{gft}\geq 0 \qquad g\in\mathcal{G}, f\in\mathcal{F}, t\in\mathcal{T} \tag{A.16}$$

$$q_{igft}\geq 0 \qquad (i,g)\in\mathcal{M}, f\in\mathcal{F}, t\in\mathcal{T} \tag{A.17}$$

B Source Code

```
model FishingVesselRoutingModel

options explterm        !Each expression must end with ;
options noimplicit      !Everything except indices must be declared

uses "mmxprs"           !Use Xpress Optimizer

parameters
  TestCase = "InputTestCaseI.txt";
  !TestCase = "InputTestCaseII.txt";
end-parameters

setparam("XPRS_verbose",true);


!--------------------------------------------------------------------------!
                  !Declaration of indices and sets
!--------------------------------------------------------------------------!

declarations
    !Sets
    AllLocations:       set of integer;
    Locations:          set of integer;
    TimePeriods:        set of integer;
    FishingGears:       set of integer;
    Fisheries:          set of integer;


    !Indices
    nLocations:         integer;            ! i,j
    PlanningHorizon:    integer;            ! t
    nFishingGears:      integer;            ! g,e
    nFisheries:         integer;            ! f
end-declarations

initializations from TestCase
  nLocations;
  PlanningHorizon;
  nFishingGears;
  nFisheries;
end-initializations

Locations := 1 .. nLocations;
AllLocations := 0 .. nLocations;
TimePeriods := 1 .. PlanningHorizon;
FishingGears := 1 .. nFishingGears;
Fisheries := 1 .. nFisheries;

finalize(Locations);
finalize(AllLocations);
finalize(TimePeriods);
finalize(FishingGears);
finalize(Fisheries);
```

```
!-----------------------------------------------------------------------!
                  !Declaration of parameters
!-----------------------------------------------------------------------!

declarations
  NodeType:         array(Locations)                          of integer;
  A:                array(FishingGears, Fisheries)            of integer;
  B:                array(FishingGears, FishingGears)         of integer;
  ! Only include when running Test Case II
  !C:               array(FishingGears)                       of integer;

  SailingCost:                                                real;
  OperationCost:    array(FishingGears)                       of integer;
  ChangeCost:       array(FishingGears, FishingGears)         of integer;

  Price:            array(FishingGears, Fisheries)            of real;
  PriceDevelopment: array(Fisheries, TimePeriods)             of real;

  VesselSpeed:                                                integer;
  SailingDistance:  array(AllLocations, AllLocations)         of real;

  VesselCapacity:                                             integer;
  Quota:            array(FishingGears, Fisheries)            of integer;
  GearCapability:   array(Locations, FishingGears)            of real;
end-declarations


initializations from TestCase
  NodeType;
  A;
  B;
  !C;

  SailingCost;
  OperationCost;
  ChangeCost;

  Price;
  PriceDevelopment;

  VesselSpeed;
  SailingDistance;

  VesselCapacity;
  Quota;
  GearCapability;
end-initializations


!-----------------------------------------------------------------------!
                  !Preprocessing of parameters
!-----------------------------------------------------------------------!

!Creation of the sailing time, T_{ijt}
declarations
SailingTime:   array(AllLocations, FishingGears, AllLocations,
FishingGears, TimePeriods)  of integer;
end-declarations

forall (ii in AllLocations, gg in FishingGears, jj in AllLocations, ee in
FishingGears, tt in TimePeriods) do
```

```
    if (SailingDistance(ii,jj) = 0 or VesselSpeed = 0 and B(gg,ee)=1) then
    SailingTime(ii,gg,jj,ee,tt) := 1;
    else
  SailingTime(ii,gg,jj,ee,tt) := ceil((SailingDistance(ii,jj) /
VesselSpeed) / 24);
    end-if
end-do


!Creation of the sales price, P_{gft}
declarations
    SalesPrice: array(FishingGears, Fisheries, TimePeriods) of real;
end-declarations

forall (gg in FishingGears, ff in Fisheries, tt in TimePeriods) do
    SalesPrice(gg,ff,tt) :=
        Price(gg,ff) * PriceDevelopment(ff,tt) * A(gg,ff);
end-do


!-------------------------------------------------------------------------!
                  !Declaration of variables
!-------------------------------------------------------------------------!

Declarations
x:          dynamic array(AllLocations, FishingGears, AllLocations,
                          FishingGears, TimePeriods)
of mpvar;

  y:          dynamic array(Locations, FishingGears, TimePeriods)
of mpvar;

  l:          dynamic array(FishingGears, Fisheries, TimePeriods)
of mpvar;

  q:          dynamic array(Locations, FishingGears, Fisheries,
                            TimePeriods)
of mpvar;
end-declarations


!-------------------------------------------------------------------------!
                  !Creating variables
!-------------------------------------------------------------------------!

!----- Creation of x_igjet
forall (ii in AllLocations, gg in FishingGears, jj in AllLocations, ee in
FishingGears, tt in TimePeriods) do

    if (ii = 0 and
        jj <> 0 and
        NodeType(jj)=1 ) then
                create(x(ii,gg,jj,ee,tt));
    end-if

    if (jj = 0 and
        ii <> 0 and
        NodeType(ii)=-1) then
            create(x(ii,gg,jj,ee,tt));
    end-if
```

```
    if (ii <> 0 and
        jj <> 0 ) then
            if (gg = ee) then
            create(x(ii,gg,jj,ee,tt));
            elif (B(gg,ee) = 1 and gg <> ee) then
            create(x(ii,gg,jj,ee,tt));
            end-if
    end-if

    x(ii,gg,jj,ee,tt) is_binary;
end-do


!----- Creation of y_igt
forall (ii in Locations, gg in FishingGears, tt in TimePeriods) do
    create(y(ii,gg,tt));
     y(ii,gg,tt) is_binary;
end-do

!----- Creation of l_gft
forall (gg in FishingGears, ff in Fisheries, tt in TimePeriods) do
    create(l(gg,ff,tt));
end-do

!----- Creation of q_igft
forall (ii in Locations, gg in FishingGears, ff in Fisheries, tt in
        TimePeriods)   do
    if (A(gg,ff)=1) then
        create(q(ii,gg,ff,tt));
    end-if
end-do






!-------------------------------------------------------------------------!
                  !Declaration of objective function and constraint
!-------------------------------------------------------------------------!

declarations
  TotalProfit:                                                      linctr;

  InitialCon:                                                       linctr;
  InitialCon2:                                                      linctr;
  TerminationCon:                                                   linctr;
  TerminationCon2:                                                  linctr;
  FlowCon:          array(Locations, FishingGears, TimePeriods)  of linctr;
  FlowCon2:         array(Locations, FishingGears, TimePeriods)  of linctr;
  FlowCon3:         array(TimePeriods)                           of linctr;
  OperationCon:     array(TimePeriods)                           of linctr;

  CargoCon:         array(TimePeriods)                           of linctr;
  CapCon:           array(TimePeriods)                           of linctr;
  AmountCon:        array(Locations, FishingGears, TimePeriods)  of linctr;
  QuotaCon:         array(FishingGears, Fisheries)               of linctr;
```

```
  !----- Only include when running Test Case I
  QuotaCon2:        array(FishingGears, Fisheries)              of linctr;
  HalibutCon:       array(Locations, FishingGears)              of linctr;

  !----- Only include when running Test Case II
  ChangeCon:        array(Locations, TimePeriods)               of linctr;

end-declarations



!-------------------------------------------------------------------------!
                  !Formulation of the objective function and constraints
!-------------------------------------------------------------------------!
!---- Objective function
TotalProfit :=
    sum(ii in Locations, gg in FishingGears, ff in Fisheries,
         tt in TimePeriods | NodeType(ii)=-1)
                -NodeType(ii)*SalesPrice(gg,ff,tt)*q(ii,gg,ff,tt)

 - (sum(ii in AllLocations, gg in FishingGears, jj in AllLocations,
         ee in FishingGears, tt in TimePeriods | ii <> jj) S
                SailingCost*SailingTime(ii,gg,jj,ee,tt)*x(ii,gg,jj,ee,tt))

 - (sum(ii in Locations, gg in FishingGears, tt in TimePeriods |
         NodeType(ii)=-1)
                y(ii,gg,tt)*OperationCost(gg))

 - (sum(ii in AllLocations, gg in FishingGears, jj in AllLocations,
        ee in FishingGears, tt in TimePeriods)
                x(ii,gg,jj,ee,tt)*ChangeCost(gg,ee));


!---- Routing Constraints


! 6.2
InitialCon :=
    sum(gg in FishingGears, jj in Locations, ee in FishingGears|
        NodeType(jj)=1) x(0,gg,jj,ee,1) = 1;

! Expansion of 6.2
InitialCon2 :=
    sum(gg in FishingGears, jj in Locations, ee in FishingGears,
         tt in TimePeriods | tt > 1) x(0,gg,jj,ee,tt) = 0;

! 6.3
TerminationCon :=
    sum (ii in Locations, gg in FishingGears, ee in FishingGears |
         NodeType(ii)=-1) x(ii,gg,0,ee,PlanningHorizon) = 1;

! Expansion of 6.3
TerminationCon2 :=
    sum(ii in Locations, gg in FishingGears, ee in FishingGears,
        tt in TimePeriods | NodeType(ii)=1) x(ii,gg,0,ee,tt) = 0;

! 6.4
forall (ii in Locations, gg in FishingGears, tt in TimePeriods | tt > 1) do
    FlowCon(ii,gg,tt) :=
        y(ii,gg,tt-1) + sum (jj in AllLocations, ee in FishingGears |
tt - SailingTime(jj,ee,ii,gg,tt) > 0)
```

```
x(jj,ee,ii,gg,tt-SailingTime(ii,gg,jj,ee,tt))
    = y(ii,gg,tt) +
        sum (jj in AllLocations, ee in FishingGears) x(ii,gg,jj,ee,tt);
end-do

! 6.5
forall (ii in Locations, gg in FishingGears, tt in TimePeriods) do
    FlowCon2(ii,gg,tt) :=
        sum (jj in Locations, ee in FishingGears |
        tt-SailingTime(jj,ee,ii,gg,tt)>0)
        x(jj,ee,ii,gg,tt-SailingTime(jj,ee,ii,gg,tt)) <= y(ii,gg,tt);
end-do

! 6.6
forall (tt in TimePeriods) do
    OperationCon(tt) :=
    sum (ii in Locations, gg in FishingGears) y(ii,gg,tt)
    + sum (ii in AllLocations, gg in FishingGears, jj in AllLocations,
           ee in FishingGears, t in tt..SailingTime(ii,gg,jj,ee,tt)
           | ii <> jj) x(ii,gg,jj,ee,t) <= 1;
end-do

! 6.7
forall ( tt in TimePeriods) do
    FlowCon3(tt) :=
 sum (ii in AllLocations, gg in FishingGears, jj in AllLocations,
      ee in FishingGears) x(ii,gg,jj,ee,tt) <= 1;
end-do


! 7.2, constraint implemented for Test Case II
(!forall (ii in Locations, tt in TimePeriods) do
    if (ii = 1) then
        ChangeCon(ii,tt) :=
            sum (gg in FishingGears, ee in FishingGears | B(gg,ee) = 0 and
C(ee) = 1) x(ii,gg,ii,ee,tt) <= 1;
    else
        ChangeCon(ii,tt) :=
            sum (gg in FishingGears, ee in FishingGears, jj in Locations |
B(gg,ee)=0) x(ii,gg,jj,ee,tt) = 0;
    end-if
end-do !)


!---- Cargo Constraints

! 6.8 and 6.10
forall (tt in TimePeriods) do
    if (tt = 1) then
        CargoCon(tt) :=
            sum (gg in FishingGears, ff in Fisheries) l(gg,ff,tt) = 0;
    elif (tt > 1) then
        CargoCon(tt) :=
            sum (gg in FishingGears, ff in Fisheries) l(gg,ff,tt) =
            sum (gg in FishingGears, ff in Fisheries) l(gg,ff,tt-1) +
            sum(ii in Locations, gg in FishingGears, ff in Fisheries)
               NodeType(ii)*q(ii,gg,ff,tt);
    end-if
end-do
```

```
! 6.9
forall (tt in TimePeriods) do
  CapCon(tt) :=
   sum (gg in FishingGears, ff in Fisheries) l(gg,ff,tt) <= VesselCapacity;
end-do


! 6.11
forall (ii in Locations, gg in FishingGears, tt in TimePeriods) do
   AmountCon(ii,gg,tt) :=
  sum(ff in Fisheries) q(ii,gg,ff,tt) <= GearCapability(ii,gg)*y(ii,gg,tt);
end-do


! 6.12
forall (gg in FishingGears, ff in Fisheries) do
    QuotaCon(gg,ff) :=
        sum (ii in Locations, tt in TimePeriods | NodeType(ii)=1)
               q(ii,gg,ff,tt) <=  Quota(gg,ff);
end-do

! 6.13
forall (gg in FishingGears, ff in Fisheries) do
    QuotaCon2(gg,ff) :=
        sum (ii in Locations, tt in TimePeriods | NodeType(ii)=1)
               q(ii,gg,ff,tt) >= 0.01*Quota(gg,ff);
end-do

! 7.2, constraint added for Test Case I
forall (ii in Locations, gg in FishingGears | NodeType(ii)=1) do
    if (ii = 15 or ii = 17) then
    HalibutCon(ii,gg) :=
        sum (tt in TimePeriods) q(ii,gg,4,tt) >= 0.5*Quota(gg,4);
    else
    HalibutCon(ii,gg) :=
        sum (tt in TimePeriods) q(ii,gg,4,tt) = 0;
    end-if
end-do



!-------------------------------------------------------------------------!
                  !Maximize the total profit
!-------------------------------------------------------------------------!

maximize(TotalProfit);

!-------------------------------------------------------------------------!
                  !Create output file
!-------------------------------------------------------------------------!

declarations
    Outputname: string;
end-declarations

Outputname := 'Output_' + TestCase + '.txt';
fopen(Outputname, F_OUTPUT);

writeln('The optimal solutions based on the given input data, as well as');
writeln(' the overall routing of the vessel is presented below: ');
```

```
writeln;
writeln('The total profit is: ' + getobjval +' NOK.' );
writeln;

writeln('-------------------------------------------------------------------
---------------------------------------');

writeln('The routing of the vessel is given below: ');
writeln;

forall(ii in AllLocations, gg in FishingGears, jj in AllLocations, ee in
FishingGears, tt in TimePeriods | getsol(x(ii,gg,jj,ee,tt)) = 1) do
    writeln('The vessel sails from node '+ii+' to ' +jj+' in time period '
+tt+'.');
end-do

writeln('-------------------------------------------------------------------
---------------------------------------');
writeln;

writeln('The following total catch is logged for the vessel: ');

forall( ii in Locations, gg in FishingGears, tt in TimePeriods) do
if( getsol(y(ii,gg,tt)) = 1 and
    NodeType(ii) = 1) then
writeln('At fishing ground ' +ii+' in time periods ' +tt+', the vessel
caught ' +getsol(sum(ff in Fisheries) q(ii,gg,ff,tt))+ ' tonnes of fish.');
end-if
end-do

writeln;
writeln('The disribtuion of fish species caught are:');

forall(ff in Fisheries) do
writeln('Fish species ' +ff+ ': '+getsol(sum(ii in Locations, gg in
FishingGears, tt in TimePeriods | NodeType(ii) = 1)q(ii,gg,ff,tt))+ '
tonnes caught.');
end-do

writeln('-------------------------------------------------------------------
---------------------------------------');
writeln;


forall(ii in Locations) do
if( NodeType(ii) = -1 ) then
    writeln('The vessel delievers ' +getsol(sum(gg in FishingGears, ff in
Fisheries, tt in TimePeriods) q(ii,gg,ff,tt))+ ' tonnes of fish to landing
site ' +ii+'.');
end-if
end-do



fclose(F_OUTPUT);

end-model
```

C Computational Study

C.1 Test Case I

```
!------ Input file for Test Case I


!------ Parameters linked to the creation of sets and indices
nLocations : 26
PlanningHorizon : 30
nFishingGears : 2
nFisheries : 6


!------ Parameters linked to the definition of sets/variables
NodeType : [-1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1]

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

B: [ 0 1
     1 0]


!------ Parameters linked to the objective function

SailingCost : [75000]

OperationCost : [45000 30000]

ChangeCost : [1000000 25000
              19000 1000000 ]


! The overall sales price is calculated using these two parameters
Price : [37000 27000 15000 29000 8000 0
         0 0 0 0 0 27000]

PriceDevelopment :
[1 1 1 1 1 1 1 1 1 1 1 1 1 1.2 1.2 1.3 1.4 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 1 1 1 1 1 1 1.1 1.2 1.4 1 1 1 1 1.1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.7 0.75 0.8 0.8 0.9 1 1 1 1…
 1 1 1 1 1 1 1 1 1 1 1
 1 1.1 1.2 1.2 1 1 1 1 1 1 1 1 1 1 1 1 1 0.5 0.55 0.6 0.7 0.7 0.7 0.6…
 0.6 0.6 0.4 0.4 0.4 0.3
 1 1.1 1.1 1.2 1.2 1 1 1 1 1 0.8 0.8 0.9 0.9 0.9 0.1 0.1 0.1 0.1 0.1…
 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1]


! The sailing time is calculated using these two parameters
VesselSpeed : 15

SailingDistance :[  0 0 33 405 540 805 715 820 950 925 990 875 760 615 372
885 650 705 575 473 320 580 435 520 580 650 740
                    0 0 33 405 540 805 715 820 950 925 990 875 760 615 372
885 650 705 575 473 320 580 435 520 580 650 740
                    33 33 0 372 505 775 665 775 920 900 960 840 735 572 340
850 610 675 535 440 285 595 430 534 595 685 755
                    405 405 372 0 133 403 305 415 575 565 690 540 410 265
165 590 440 635 500 360 390 750 570 645 630 740 795
                    540 540 505 133 0 270 190 300 470 465 595 474 350 250
260 560 470 700 570 440 490 875 665 740 720 830 895
```

```
                    805 805 775 403 270 0 170 270 390 430 575 490 440 400
500 640 650 910 790 650 750 1100 900 990 940 1035 1110
                    715 715 665 305 190 170 0 115 315 317 441 322 256 237
387 450 471 715 620 511 620 990 766 855 800 891 956
                    820 820 775 415 300 270 115 0 210 190 195 235 215 280
471 415 470 710 643 551 691 1035 822 895 842 920 970
                    950 950 920 575 470 390 315 210 0 80 215 215 300 420
631 403 561 768 737 678 840 1144 958 1007 938 1007 1040
                    925 925 900 565 465 430 317 190 80 0 133 145 248 397
614 324 507 700 694 623 795 1090 916 955 858 956 980
                    990 990 960 690 595 575 441 195 215 133 0 151 285 442
656 261 480 692 675 625 812 1060 890 926 830 890 923
                    875 875 840 540 474 490 322 235 215 145 151 0 137 292
513 191 357 562 555 485 675 947 770 810 727 800 844
                    760 760 735 410 350 440 256 215 300 248 285 137 0 146
377 210 261 491 456 380 542 850 650 702 634 704 749
                    615 615 572 265 250 400 237 280 420 397 442 292 146 0
227 326 240 473 392 271 418 750 549 624 576 651 696
                    372 372 340 165 260 500 387 471 631 614 656 513 377 227
0 498 291 484 338 197 245 616 420 494 480 585 653
                    885 885 850 590 560 640 450 415 403 324 261 191 210 326
498 0 255 398 421 430 592 800 645 680 596 640 673
                    650 650 610 440 470 650 471 470 561 507 480 357 261 240
291 255 0 240 203 176 355 584 420 440 370 457 475
                    705 705 675 635 700 910 715 710 768 700 692 562 491 473
484 398 240 0 150 282 384 437 339 309 214 239 270
                    575 575 535 500 570 790 620 643 737 694 675 555 456 392
338 421 203 150 0 148 251 414 244 267 184 271 330
                    473 473 440 360 440 650 511 551 678 623 625 485 380 271
197 430 176 282 148 0 178 463 287 345 280 400 471
                    320 320 285 390 490 750 620 691 840 795 812 675 542 418
245 592 355 384 251 178 0 388 170 265 168 379 446
                    580 580 595 750 875 1100 990 1035 1144 1090 1060 947
850 750 616 800 584 437 414 463 388 0 220 143 240 312 366
                    435 435 430 570 665 900 766 822 958 916 890 770 650 549
420 645 420 339 244 287 170 220 0 100 149 250 311
                    520 520 534 645 740 990 855 895 1007 955 926 810 702
624 494 680 440 309 267 345 265 143 100 0 97 168 235
                    580 580 595 630 720 940 800 842 938 858 830 727 634 576
480 596 370 214 184 280 168 240 149 97 0 105 184
                    650 650 685 740 830 1035 891 920 1007 956 890 800 704
651 585 640 457 239 271 400 379 312 250 168 105 0 83
                    740 740 755 795 895 1110 956 970 1040 980 923 844 749
696 653 673 475 270 330 471 446 366 311 235 184 83 0]


!------ The characteristics related to the vessel
VesselCapacity : [500]

Quota : [300 140 150 40 250 0
               0 0 0 0 0 150]


GearCapability : [500 500      50 40          55 0            50 35
                  500 500      50 40          40 0            45 35]
                  500 500      50 40          60 0
                  500 500      50 40          55 0
                  500 500      60 0           40 0
                  60 0         55 0           55 0
                  50 40        40 0           55 35
                  50 40 ...    40 0 ...       60 35 ...
```

C.2 Test Case II

```
!------ Input file for Test Case II
! When running the model for Test Case II, remember to add constraints 7.2
and remove constraints 6.13 and 7.1
! The parameter C must also be included, see declarations


!------ Parameters linked to the creaton of sets and indices
nLocations : 26
PlanningHorizon : 30
nFishingGears : 4
nFisheries : 4


!------ Parameters linked to the definition of sets/variables
NodeType : [-1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1]

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

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

C: [0 0 1 1]


!------ Parameters linked to the objective function

SailingCost : [75000]

OperationCost : [45000 35000 40000 30000]

ChangeCost : [1000000 10000 50000 50000
              10000 1000000 60000 50000
              50000 60000 1000000 70000
              50000 50000 70000 1000000]


! The overall sales price is calculated using these two parameters
Price : [42000 0 35000 27000
         25000 0 0 16000
         40000 0 0 25000
         0 27000 0 0]

PriceDevelopment : [
1 1 1 1 1 1 1 1 1 1 1 1 1.2 1.2 1.3 1.4 1 1 1 1 1 1 1 1 1 1 1 1 1

1 1.1 1.1 1.2 1.2 1 1 1 1 1 0.8 0.8 0.9 0.9 0.9 0.1 0.1 0.1 0.1 0.1 0.1 0.1
0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1

1 1 1 1 1 1 1 1 1.1 1.2 1.4 0.9 0.9 0.9 1 1.1 1 1 1 1 1 1 1 1 1 1 1 1 1

0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.7 0.75 0.8 0.8 0.9 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 ]
```

```
! The sailing time is calculated using these two parameters
VesselSpeed : 15

SailingDistance :[  0 0 33 405 540 805 715 820 950 925 990 875 760 615 372
885 650 705 575 473 320 580 435 520 580 650 740
                    0 0 33 405 540 805 715 820 950 925 990 875 760 615 372
885 650 705 575 473 320 580 435 520 580 650 740
                    33 33 0 372 505 775 665 775 920 900 960 840 735 572 340
850 610 675 535 440 285 595 430 534 595 685 755
                    405 405 372 0 133 403 305 415 575 565 690 540 410 265
165 590 440 635 500 360 390 750 570 645 630 740 795
                    540 540 505 133 0 270 190 300 470 465 595 474 350 250
260 560 470 700 570 440 490 875 665 740 720 830 895
                    805 805 775 403 270 0 170 270 390 430 575 490 440 400
500 640 650 910 790 650 750 1100 900 990 940 1035 1110
                    715 715 665 305 190 170 0 115 315 317 441 322 256 237
387 450 471 715 620 511 620 990 766 855 800 891 956
                    820 820 775 415 300 270 115 0 210 190 195 235 215 280
471 415 470 710 643 551 691 1035 822 895 842 920 970
                    950 950 920 575 470 390 315 210 0 80 215 215 300 420
631 403 561 768 737 678 840 1144 958 1007 938 1007 1040
                    925 925 900 565 465 430 317 190 80 0 133 145 248 397
614 324 507 700 694 623 795 1090 916 955 858 956 980
                    990 990 960 690 595 575 441 195 215 133 0 151 285 442
656 261 480 692 675 625 812 1060 890 926 830 890 923
                    875 875 840 540 474 490 322 235 215 145 151 0 137 292
513 191 357 562 555 485 675 947 770 810 727 800 844
                    760 760 735 410 350 440 256 215 300 248 285 137 0 146
377 210 261 491 456 380 542 850 650 702 634 704 749
                    615 615 572 265 250 400 237 280 420 397 442 292 146 0
227 326 240 473 392 271 418 750 549 624 576 651 696
                    372 372 340 165 260 500 387 471 631 614 656 513 377 227
0 498 291 484 338 197 245 616 420 494 480 585 653
                    885 885 850 590 560 640 450 415 403 324 261 191 210 326
498 0 255 398 421 430 592 800 645 680 596 640 673
                    650 650 610 440 470 650 471 470 561 507 480 357 261 240
291 255 0 240 203 176 355 584 420 440 370 457 475
                    705 705 675 635 700 910 715 710 768 700 692 562 491 473
484 398 240 0 150 282 384 437 339 309 214 239 270
                    575 575 535 500 570 790 620 643 737 694 675 555 456 392
338 421 203 150 0 148 251 414 244 267 184 271 330
                    473 473 440 360 440 650 511 551 678 623 625 485 380 271
197 430 176 282 148 0 178 463 287 345 280 400 471
                    320 320 285 390 490 750 620 691 840 795 812 675 542 418
245 592 355 384 251 178 0 388 170 265 168 379 446
                    580 580 595 750 875 1100 990 1035 1144 1090 1060 947
850 750 616 800 584 437 414 463 388 0 220 143 240 312 366
                    435 435 430 570 665 900 766 822 958 916 890 770 650 549
420 645 420 339 244 287 170 220 0 100 149 250 311
                    520 520 534 645 740 990 855 895 1007 955 926 810 702
624 494 680 440 309 267 345 265 143 100 0 97 168 235
                    580 580 595 630 720 940 800 842 938 858 830 727 634 576
480 596 370 214 184 280 168 240 149 97 0 105 184
                    650 650 685 740 830 1035 891 920 1007 956 890 800 704
651 585 640 457 239 271 400 379 312 250 168 105 0 83
                    740 740 755 795 895 1110 956 970 1040 980 923 844 749
696 653 673 475 270 330 471 446 366 311 235 184 83 0]


!------ The characteristics related to the vessel
VesselCapacity : [500]
```

```
Quota : [100 0 40 80
         40 0 0 20
         40 0 0 30
         0 90 0 0]


GearCapability : [500 500 500 500
                  500 500 500 500
                  500 500 500 500
                  500 500 500 500
                  500 500 500 500
                  30 25 40 0
                  30 25 45 35
                  40 30 45 35
                  40 30 40 30
                  35 30 45 30
                  35 35 50 40
                  50 25 40 40
                  60 25 30 0
                  55 30 30 0
                  40 30 45 0
                  40 30 50 0
                  55 25 50 0
                  40 30 45 0
                  60 25 40 0
                  55 25 35 0
                  40 0 35 0
                  55 0 40 0
                  55 0 35 30
                  60 0 30 30
                  50 0 30 35
                  45 0 30 40]
```

C.3 Distance Matrix

	0 Ålesund	1 Ålesund	2 Bud	3 Svolvær	4 Tromsø	5 Båtsfjord	6 (12)	7 (20)	8 (23)	9 (22)	10 (25)	11 (21)	12 (27)	13 (39)	14 (37)	15 (26)	16 (38)	17 (62)	18 (35)	19 (36)	20 (34)	21 (51)	22 (50)	23 (59)	24 (56)	25 (55)	26 (54)
0 Ålesund	0	0	33	405	540	805	715	820	950	925	990	875	760	615	372	885	650	705	575	473	320	580	435	520	580	650	740
1 Ålesund	0	0	33	405	540	805	715	820	950	925	990	875	760	615	372	885	650	705	575	473	320	580	435	520	580	650	740
2 Bud	33	33	0	372	505	775	665	775	920	900	960	840	735	572	340	850	610	675	535	440	285	595	430	534	595	685	755
3 Svolvær	405	405	372	0	133	403	305	415	575	565	690	540	410	265	165	590	440	635	500	360	390	750	570	645	630	740	795
4 Tromsø	540	540	505	133	0	270	190	300	470	465	595	474	350	250	260	560	470	700	570	440	490	875	665	740	720	830	895
5 Båtsfjord	805	805	775	403	270	0	170	270	390	430	575	490	440	400	500	640	650	910	790	650	750	1100	900	990	940	1035	1110
6 (12)	715	715	665	305	190	170	0	115	315	317	441	322	256	237	387	450	471	715	620	511	620	990	766	855	800	891	956
7 (20)	820	820	775	415	300	270	115	0	210	190	195	235	215	280	471	415	470	710	643	551	691	1035	822	895	842	920	970
8 (23)	950	950	920	575	470	390	315	210	0	80	215	215	300	420	631	403	561	768	737	678	840	1144	958	1007	938	1007	1040
9 (22)	925	925	900	565	465	430	317	190	80	0	133	145	248	397	614	324	507	700	694	623	795	1090	916	955	858	956	980
10 (25)	990	990	960	690	595	575	441	195	215	133	0	151	285	442	656	261	480	692	675	625	812	1060	890	926	830	890	923
11 (21)	875	875	840	540	474	490	322	235	215	145	151	0	137	292	513	191	357	562	555	485	675	947	770	810	727	800	844
12 (27)	760	760	735	410	350	440	256	215	300	248	285	137	0	146	377	210	261	491	456	380	542	850	650	702	634	704	749
13 (39)	615	615	572	265	250	400	237	280	420	397	442	292	146	0	227	326	240	473	392	271	418	750	549	624	576	651	696
14 (37)	372	372	340	165	260	500	387	471	631	614	656	513	377	227	0	498	291	484	338	197	245	616	420	494	480	585	653
15 (26)	885	885	850	590	560	640	450	415	403	324	261	191	210	326	498	0	255	398	421	430	592	800	645	680	596	640	673
16 (38)	650	650	610	440	470	650	471	470	561	507	480	357	261	240	291	255	0	240	203	176	355	584	420	440	370	457	475
17 (62)	705	705	675	635	700	910	715	710	768	700	692	562	491	473	484	398	240	0	150	282	384	437	339	309	214	239	270
18 (35)	575	575	535	500	570	790	620	643	737	694	675	555	456	392	338	421	203	150	0	148	251	414	244	267	184	271	330
19 (36)	473	473	440	360	440	650	511	551	678	623	625	485	380	271	197	430	176	282	148	0	178	463	287	345	280	400	471
20 (34)	320	320	285	390	490	750	620	691	840	795	812	675	542	418	245	592	355	384	251	178	0	388	170	265	168	379	446
21 (51)	580	580	595	750	875	1100	990	1035	1144	1090	1060	947	850	750	616	800	584	437	414	463	388	0	220	143	240	312	366
22 (50)	435	435	430	570	665	900	766	822	958	916	890	770	650	549	420	645	420	339	244	287	170	220	0	100	149	250	311
23 (59)	520	520	534	645	740	990	855	895	1007	955	926	810	702	624	494	680	440	309	267	345	265	143	100	0	97	168	235
24 (56)	580	580	595	630	720	940	800	842	938	858	830	727	634	576	480	596	370	214	184	280	168	240	149	97	0	105	184
25 (55)	650	650	685	740	830	1035	891	920	1007	956	890	800	704	651	585	640	457	239	271	400	379	312	250	168	105	0	83
26 (54)	740	740	755	795	895	1110	956	970	1040	980	923	844	749	696	653	673	475	270	330	471	446	366	311	235	184	83	0

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