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Fleet Size and Mix in the Norwegian Aquaculture Sector

A stochastic fleet renewal problem with an uncertain future

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Preface

This project thesis was written as fulfilment of the course TMR4930 – Marine Technology, Master`s Thesis. The report was written in its entirety by Adrian Stenvik during the spring of 2017.

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Abstract

The aquaculture sector in Norway aims to increase the production five times by 2050. For this aim to be reached it is likely that new solutions relating to the future service needs of the sector need to be developed. To support such a development, it could be of value to have a decision-making support tool available when strategic fleet renewal decisions are to be made. Such a tool should also be able to consider future uncertainty when the decision is made. The aim of this study has therefore been to propose a modelling approach for such a decision-making support tool.

In this study, the focus has been on well-boats and service vessels, and the tasks these vessels are needed to service in the Norwegian aquaculture sector. Important service tasks have been identified, and an estimated demand and time consumption for the tasks have been established along with some possible future developments in the sector.

Some previous work on maritime fleet renewal problems (MFRP) have been reviewed, and a two-stage stochastic programming model for the MFRP in the aquaculture sector has been presented. The model aims to minimize the total cost incurring when acquiring and operating a fleet of vessels. The demand is assumed to be known for the first set of time periods, while the demand in the second stage is illustrated by a set of scenarios. Vessels can be bought and sold in all time steps in both the first and second stage of the model. The first stage makes sure that the “here and now” decisions are equal for each scenario, and the scenarios are included to make the “here and now” decisions more robust with respect to future uncertainty. All routing decisions have been taken out of the optimization model and moved to a separate loop generator to ensure a simpler structure of the optimization model, and to ensure flexibility in the modelling approach.

The optimization model has been implemented in the commercial solver XPRESS IVE and the loop generation is done in MATLAB. To test the model`s performance, a test case with eight time steps and four scenarios was solved and the value of the stochastic solution was found. The case study finds that the model choses a fleet composition which seems reasonable, and that the solver can solve the problem within an acceptable amount of time. The test instance shows a low value for the stochastic solution, indicating that for the

particular case a deterministic model could be just as effective. However, the stochastic solution gave a more flexible solution, as the deterministic approach found no feasible solution for one of the scenarios.

The model presented in this study provides a good basis for further development of maitime fleet renewal models in the aquaculture sector, and can be seen as a flexible modelling platform which can easily be altered to include new tasks, new vessels or new acquisition and disposal methods for vessels in the fleet.

This modelling platform could be applied by salmon producers wanting to reduce the cost of servicing the demand of their farming locations. Then the model could be used to include all their current and planned locations. Furthermore, the model could be of interest to a ship owning company with a long-term contract with a salmon producer or who just wants to evaluate how the future demand for vessels might be, to be able to buy the right vessels at the right time.

Sammendrag

Akvakultursektoren i Norge har som mål å øke produksjonen fem ganger innen 2050. For at dette målet skal nås, er det sannsynlig at nye løsninger knyttet til sektorens fremtidige tjenestebehov må utvikles. For å støtte en slik utvikling, kan det være verdifullt å ha et beslutningsstøtteverktøy når strategiske flåtefornyelsesbeslutninger skal gjøres. Et slikt verktøy bør også kunne vurdere fremtidig usikkerhet i beslutningsøyeblikket. Målet med denne studien har derfor vært å legge frem en modelleringsmetode for et slikt beslutningsstøtteverktøy.

I denne studien har det vært fokus på brønnbåter og servicefartøyer og oppgavene disse fartøyene betjener i akvakultursektoren. Viktige oppgaver er identifisert, og en estimert etterspørsel og tidsforbruk av oppgavene er blitt bestemt, i tillegg til noen teorier om mulig fremtidsutvikling i sektoren.

Noen tidligere arbeider på maritime fleet renewal problems (MFRP) har blitt gjennomgått, og en to-trinns stokastisk programmeringsmodell for MFRP i akvakultursektoren er presentert. Modellen tar sikte på å minimere de totale kostnadene som oppstår ved å anskaffe og drive en flåte av skip. Etterspørselen antas å være kjent for alle tidsperioder i første trinn, mens etterspørselen i det andre trinnet representeres med ulike scenarier. Skip kan kjøpes og selges i alle tidssteg i begge trinnene. Det første trinnet sørger for at "her og nå" beslutningene er like for hvert scenario, og scenariene er inkludert for å gjøre beslutningene tatt "her og nå" mer robuste i forhold til fremtidig usikkerhet. Alle rutebeslutninger i modellen er flyttet ut av optimeringsmodellen og tatt hånd om av en rutegenerator for å sikre en enklere struktur av optimeringsmodellen, og for å sikre fleksibilitet i modelleringsmetoden.

Modellen har blitt implementert i solveren XPRESS IVE og rutegenereringen er gjort i MATLAB. For å teste modellens ytelse ble den brukt til å løse en test case med åtte tidssteg og fire scenarier i det andre trinnet, og verdien av den stokastiske løsningen (value of the stochastic solution VSS) ble funnet. Casestudien slår fast at modellen velger en flåtesammensetning som virker fornuftig, og at solveren kan løse problemet innen en akseptabel tidsramme. Testeksemplet viser en lav verdi for VSS, noe som indikerer at en deterministisk modell kan være like effektiv i dette tilfellet. Den stokastiske løsningen ga imidlertid en mer fleksibel løsning, da den deterministiske tilnærmingen endte opp med ingen mulig løsning for ett av scenariene.

Modellen som presenteres i denne studien gir et godt grunnlag for videreutvikling av marineflåtefornyelsesmodeller i akvakultursektoren, og kan betraktes som en fleksibel modelleringsplattform som lett kan endres for å inkludere nye oppgaver, nye fartøyer eller nye alternativer for å tilegne seg og kvitte seg med fartøyer.

Modelleringsmetoden kan brukes av lakseprodusenter som ønsker å redusere kostnadene ved å betjene behovene ved deres oppdrettsanlegg. I det tilfelle kan modellen brukes til å inkludere alle de nåværende og planlagte lokasjonene til produsenten. Videre kan modellen være av interesse for en reder som har langtidskontrakter med en lakseprodusent eller som bare ønsker å vurdere hvordan fremtidens krav til fartøy kan være, for å kunne kjøpe de rette fartøyene til rett tid.

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FSMP:	Fleet size and mix
MFSMP:	Maritime fleet size and mix problem
MFRP:	Maritime Fleet renewal problem
LP:	Linear programming

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1. Introduction

The Norwegian aquaculture sector has experienced a rapid growth in the later years, and intends to continue to grow. However, there are many elements of uncertainty with regards to the future development of the sector. This uncertainty will affect the future demand for services, and the number of vessels required to service these needs.

This report will present information about the Norwegian aquaculture sector, and discuss some of the uncertain factors regarding future growth. Five different vessel types will be introduced and the service tasks they can perform will be presented. Then some theory about fleet size and mix problems (FSMP) will be included before a fleet size and mix model for the aquaculture sector will be presented, followed by a computational study applying the modelling approach to a specific problem. Only the salmon and trout segment of the aquaculture sector will be considered in this study.

The Norwegian Aquaculture Sector

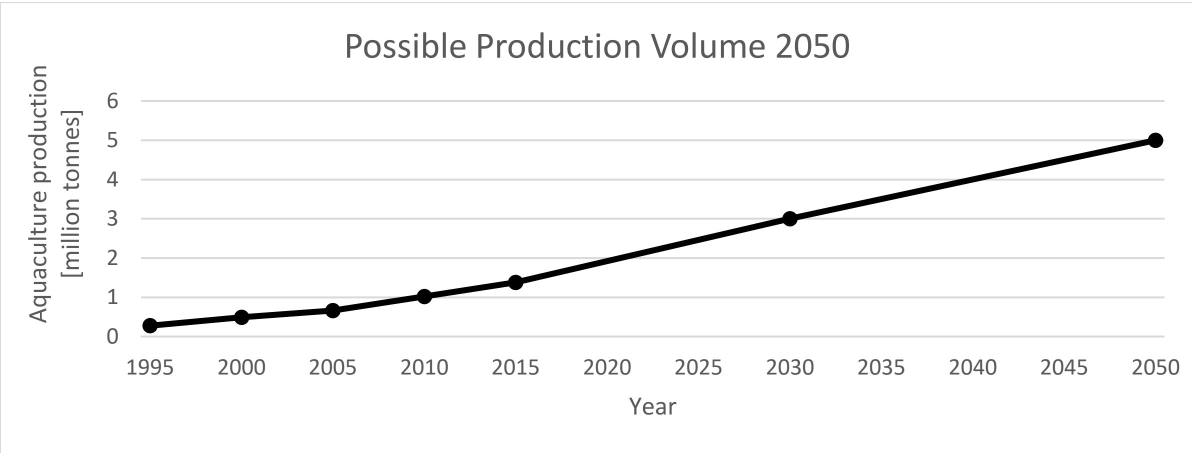
During the period from 1997 to 2012, the Norwegian aquaculture sector increased their annual sales of salmon from less than 400 000 tonnes to over 1 200 000 tonnes (SSB, 2016a). In comparison, the onshore meat production in Norway in 2012 was about 300 000 tonnes, making the meat production in the aquaculture sector four times larger than the onshore production (Asche, Guttormsen, Roll & Tveterås, 2013).

There are fish farming locations along the entire Norwegian coast, and this report will have a particular focus on the fish farming industry in Sør-Trøndelag. There are about 90 aquaculture locations producing salmon and trout in Sør-Trøndelag alone (Fiskeridirektoratet, 2017a). Most of these locations are in the region surrounding Hitra and Frøya. Lerøy, Salmar and Marine Harvest all have fish processing facilities located in the Hitra and Frøya region, and there are also several smolts producers in the region (Fiskeridirektoratet, 2017a).

A production cycle for salmon starts when smolts with a size of about 80 grams are transported to the farming location (Marine Harvest, 2016). Then the salmon live in the cages between 14-25 month before they are ready to be taken to a processing facility (Marine Harvest, 2016). Each farming location can hold several farming licenses, and each license allows for 780 tonnes of biomass at any given time (Fiskeridirektoratet, 2016a). As an example, a location with seven licenses can have a maximum of 5460 tonnes of biomass at any given time. After a location has been emptied for slaughter, it needs to have a two month fallowing period before a new production cycle can begin in order to avoid spreading of disease (Nærings- og fiskeridepartementet, 2008).

Even though the aquaculture sector has experienced a tremendous growth over the last 15 years, the sector still aims to grow at a high rate towards 2050. Figure 1 shows the growth in production volumes from 1995 to the present day and the future volumes which the sector aims to reach.

Figure 1: Future production volumes



(Authors own work based on SSB, 2016b; Olafsen, et al., 2012)

According to Olafsen, et al. (2012) the production volume in 2050 could reach 5 million tonnes, compared to 1.2 million tonnes in 2012. Olafsen, et al. (2012) points out several critical issues which will need to be addressed to reach this potential, four of these are listed below.

1. Environmental footprint
2. Lice and Disease
3. Need for new technological solutions
4. Availability of fish feed

This report will not discuss the issue of fish feed availability, but the other three will be discussed briefly later in this study.

There is a finite number of farming licenses in Norway, and any increase in the number of licenses is regulated by the Norwegian government (Fiskeridirektoratet, 2017b). The last time the number of commercial licenses was increased was in 2013 when 45 “green” licenses were sold (Fiskeridirektoratet, 2017c). “Green” licenses are commercial licenses with stricter requirements regarding environmental challenges such as salmon escaping from the cages and the spreading of lice (Fiskeridirektoratet, 2017c). There is no available information regarding plans for increasing the number of commercial license in the near future. However, the Norwegian government is trying to stimulate the development of new technological solutions for fish farming by making it possible to apply for development licenses (iLaks, 2015). So far, several different companies have applied for development licenses for a total of 43 different concepts (Fiskeridirektoratet, 2017d). Of these 43 concepts, only three has been granted development licenses as of April 2017 (Fiskeridirektoratet, 2017d). However, there are also a few concepts that still may get their approval soon. The three approved concepts, and one of the concepts that might get approved, will be presented briefly in this section, and discussed in the uncertainty section later in this report.

The approved concepts are Salmar`s “Ocean farming”, Nordlaks Oppdrett`s “Havfarm” and Midt-Norsk Havbruk`s “Aquatraz” (Fiskeridirektoratet, 2017d). Marine Harvest`s concept “Egget” is not yet approved, but will also be presented in this report because of its interesting properties. Both “Ocean farming” and “Havfarm” are concepts made to for more exposed waters than today’s conventional farm cages, while “Aquatraz” and ”Egget” are made for similar locations as the ones used in today`s fish farming.

The uncertainty regarding how the future growth of the sector will be realised can make a decision-making support tool a valuable aid when deciding on which vessels to invest in. Such a decision-making support tool could be of interest for salmon producers wanting to reduce the cost of servicing the demand of their farming locations. Furthermore, it could be of interest to a ship-owning company with a long-term contract with a salmon producer or who just wants to evaluate how the future demand for vessels might be, to be able to buy the right vessels at the right time.

In this report, an optimization model capable of including considerations about the uncertain future will be presented. Furthermore, a computational implementation of the model will be presented and some possible applications discussed.

1.1 Objectives

The aim of this report is to propose a general formulation of an optimal fleet size and mix models which can be used for service vessels in the Norwegian aquaculture sector with an uncertain future, and to perform a computational study on a generic case to assess the performance of the modelling approach. The aim of this study will not be to solve any specific problems, but rather provide a basis for the development of efficient maritime fleet renewal models for the aquaculture sector.

2. Problem Description

This section will provide a description of the problem which is to be modelled at a later stage in this report. This is done to give a better understanding of the problem and how to approach the model making. First the vessel types and service tasks considered in this report will be presented, then the core of the problem will be defined. This section will also discuss some of the important factors regarding uncertainty in the aquaculture sector.

2.1 Vessels and Tasks

Because most fish farms are located at sea with no road access, service tasks and transportation services must be done by boat. Different vessel types can solve different service tasks. These tasks range from delivering smolts to an existing location, to installing a new fish farming location.

This section will present each vessel type included in this study. Furthermore, the different tasks these vessels can perform will be presented. The vessels included will be separated into five different types, small and large well-boats and small, medium and large service vessels.

This study will not include the distribution of fish feed, as the vessels transporting fish feed are assumed not to be able to perform any of the other tasks included in this report. This means that the distribution of fish feed can be considered as a completely separate optimization problem, and can therefore be ignored in this study.

2.1.1 Small and Large Well-Boats

Well-boats are specially designed vessels with the purpose of transporting live fish. Modern well-boats are usually constructed with two large wells for carrying fish, separated by a longitudinal bulkhead (Guttvik, and Hoel, 2006). To make sure the fish have sufficiently good living conditions onboard, water is circulated through the wells (Guttvik, and Hoel, 2006).

Well-boats come in many different sizes and the large well-boat to date is “Ro Fjell” with a length of 72 meters, and a well capacity of 4500m3 (Skipsrevyen, 2013). In this report, a large well-boat will be defined as a vessel with a well capacity of 4500m3 and small well-boat will be defined as a vessel with a well capacity of 2800m3. 2800m3 well-boats are not really considered small well-boats, but in comparison the loading capacity for live salmon for the 2800m3 well-boats is about half of that of “Ro Fjell”.

Well-boats are mainly used for three different tasks. These tasks are lice treatment, transportation of live salmon to processing facilities and transportation of smolt out to the farming locations. About 60% of the operations undertaken by well-boats are transportation of mature salmon, 30% is lice treatment and 10% of the operations are transportation of smolt (Nodland, 2016).

Transportation of smolt is done at the beginning of the production cycle. The time it takes to load smolt at the smolt supplier varies a lot from supplier to supplier and can take between two and 18 hours (Industry source, 2017a)*. However, the average time can be assumed to be 4-5 hours (Industry source, 2017a). Unloading smolt at a location takes about one hour for each cage (Industry source, 2017a).

Both transportation of mature salmon and lice treatment starts with the salmon being loaded onboard the well-boat, and this operation is supported by at least one small service vessel (Ellefsen, 2014). The preparations done by the service vessel before the loading can start is assumed to take a little less than two hours per cage (Ellefsen, 2014). The actual loading time depends on the weather conditions and loading equipment, but is assumed to take about 2 hours for both large and small vessels (Industry source, 2017a). Once the salmon are loaded, lice treatment can be conducted. This can either be done by leaving the fish in fresh water for 6-9 hours or by adding chemicals such as hydrogen peroxide (Kyst.no, 2016a: Arff, Forbord and Steinhovden, 2016). When hydrogen peroxide is used the salmon are kept in the well-boat for about two hours (Ellefsen, 2014). The unloading back into the cage and unloading at a processing facility is assumed to take about 1 hour for both vessel types (Industry source, 2017a: Industry source, 2017b).

For the large well-boats “Ro Fjell” will be used as a reference vessel. For the small well-boats “Ro Master” will be used as a reference. Some of the main data for both small and large well-boats is shown in Table 1.

*The contact with these sources has been unformal talks, and not all of them have been asked explicit if they can be referred to by name. Furthermore, the specific identity of these sources will not impact the nature of this study. Therefor they are only referred to as industry source a-f and their role in the aquaculture sector, and the date of contact is written in the reference list

Table 1: Well-Boat Size, speed and Price

Parameters	Large Well-Boats	Small Well-Boats
Well capacity	4500m3	2800m3
Load capacity live salmon	700 Ton	380 Ton
Service speed	14.6 knots	15 knots
Contract Price	260 [mNOK]	130 [mNOK]

Source: Skipsrevyen. (2013): Zachariassen (2007): Rostein, (2017)

Small and large well-boats will be assumed to be able to solve the same kind of tasks. The only difference will be the service speed and the load capacity of the vessels. This will, for instance, mean that while a large well-boat can conduct lice treatment on a whole cage at a time, while a small well-boat only can treat half a cage. This means that lice treatment takes much longer time for a small vessel than for a large vessel. A small vessel will also need a larger number of trips to transport salmon from a location to a processing facility. The lice treatment with well-boats will be assumed to be carried out using hydrogen peroxide.

2.1.2 Small Service Vessels

Small service vessels are usually 14,9-meter-long catamarans able of undertaking a wide range of tasks at the aquaculture farming locations. These tasks include maintenance and inspection, supporting lice treatment and well-boat loading operations and washing nets and disinfecting farming locations (Frøygruppen, 2017a; Ellefsen ,2014). The reason for this size of the vessels is to avoid a lot of regulations which applies for vessels over 15 meters.

Nets are washed about once a week in August and September, 1-2 times a month in March-August and rarely between November and March (Norddal et al., 2010: Benjaminsen, 2012). Washing the nets takes about 3-5 hours per cage (Industry source, 2017c: Industry source, 2017d). The nets are washed to ensure that the vital flow of water through the cages are maintained (Benjaminsen, 2012). It is common to wash all the nets at a location at the same time (Industry source, 2017c).

Disinfection of farming location includes washing of rings and inspecting the cages at a location, this takes about six hours per cage, and is handled by two vessels, and is done between production cycles (Industry source, 2017d). The disinfection needs to be done before the fowling period of two months can begin.

Supporting lice treatment takes between 3 and 12 hours per cage depending on the treatment type (Industry source, 2017d). Replacing the nets are done between production cycles (Industry source, 2017d). The replacement of nets takes about 2-5 hours per cage, both for removing and for installing new nets and the job is done by two vessels (Industry source, 2017d). Anchor inspection is done with the use of a ROV and takes about 5 hours (Industry source, 2017d).

Some specifications of the small service vessels which are used in this study are shown in Table 2.

Table 2: Small Service Vessel Size, speed and Price

Parameters	Small Service vessel
Service speed	12 knots
Length and beam	14.99m and 10 m
Contract Price	17.5 [mNOK]

Source: Moen Marin (2017)

2.1.3 Large and Medium Service Vessels

Medium service vessels will be defined as catamarans with a length of 25 meters, and large service vessels will be defined as monohulled vessels with the length of about 40 meters. This is because a typical service vessel capable of conducting mooring tasks are about 25 meters long catamarans, and the 40-meter vessel included in this study is inspired by the vessel “frøy fighter” which is a monohulled 40-meter long vessel.

Large and medium service vessels can perform lice treatment, installation and removal of aquaculture installations, mooring operations, change nets, inspect anchors and disinfect farming locations (Frøygruppen, 2017b: Industry Source, 2017d). In addition, the medium vessels are assumed to be able to assist lice treatment conducted by other vessels.

Lice treatment conducted by service vessels can either be performed using mechanical treatment equipment or by the use of tarpaulin and chemicals (AQS, 2016; Frøygruppen, 2017b). In this study lice treatment done by service vessels will be assumed to be mechanical, and a capacity of 60 tonnes/hour will be assumed for medium vessels, and 90 tonnes/hour for large vessels base on the number of treatment lines installed on the vessel types (Industry Source, 2017d) Mooring inspection and maintenance takes between 9 hours to 2.5 days, and the inspections are conducted every 6 months (Industry Source, 2017e).

Installing new fish farming installations takes between 14-18 days, for a typical 12 cage installation (Industry Source, 2017c). This is done by one service vessel, to make the documentation prosses tidier (Industry Source, 2017c). The removal of a farming installation takes about 1-2 weeks depending on location size (Industry Source, 2017d).

Replacing nets, disinfection of location and anchor inspection is assumed to take the same amount of time as it would for a small vessel. Table 3 shows the price, service speed and dimensions of medium and large service vessels used in this study.

Table 3: Medium and Large Service Vessels, Size, Speed and Price

Parameters	**Medium Service vessel**	**Large Service vessel**
Service speed	10 knots	10 knots
Length and beam	25 m and 13 m	40 m and 12 m
Contract Price	50 [mNOK]	60 [mNOK]

Source: Fiskeribladet, 2016: Joakimsen, 2015

To make a service vessel able to conduct mechanical lice treatment, treatment equipment needs to be installed. Large vessels have the capacity of three lines of lice equipment, while the medium vessels have space for only two lines (Industry Source, 2017d). Table 4 shows the price and processing capacity of the mechanical lice treatment equipment.

Table 4: Mechanical Lice Treatment Equipment, Price and Capacity

Mechanical Lice Removal Equipment	
Capacity per system line	30 tonnes/hour
Contract Price per system line	25 per system line [mNOK]

Source: Steinsvik AS, 2017: Industry Source, 2017d.

Once a service vessel is fitted with lice removal equipment it cannot undertake heavy crane work such as mooring tasks and installing and removing locations, because of the space requirement of the lice equipment (Industry Source, 2017d).

2.1.4 Task Summary

The five vessel types in this study are assumed to be able to perform different sets of tasks. Some of the tasks can be performed by more than one vessel type, while other tasks can only be performed by one specific vessel type.

In this study 13, different tasks performed at faming locations will be considered. All the included tasks are listed in Table 5. Some of the tasks in Table 5 can be seen as subtasks. These are loading support and lice support. They are included as separate tasks for modelling purposes. For instance, every time the task of transporting salmon is performed it requires a loading support operation. However, the number of transportation tasks needed is determined by the capacity of the well-boat, therefore a demand for loading support cannot be determined without knowing which vessel is used for the transportation task. The inclusion of lice support is to ensure that both vessels able to conduct lice treatment and vessels able to support the operation are used in each lice treatment operation.

The time it takes for a vessel to perform a task will be the time the actual work at the installation takes in addition to the time it takes to travel to the installation and back. Furthermore, some tasks might have additional time added for commissioning and decommissioning, that will be added to the time it takes to perform the task. Some tasks may be done in a sequence without returning to the base in between the tasks. Therefore, the traveling time cannot be included in the time it takes to perform the task, but needs to be added on separately. Table 5 shows the tasks included in this study, and some information about the duration of the tasks and the vessels capable of performing the tasks.

Table 5: Task Types, Task Duration and Vessels Capable of Performing the Tasks

Job type	Task Duration	Capable vessel
Transport Salmon	Transit time and loading/unloading	Well-Boats
Transportation of smolt	Transit time and loading/unloading	Well-Boats
Loading salmon support	2 hours in addition to loading time	Small and medium service vessels
Lice treatment	3-12 hours/cage	Well-Boats and service vessels fitted with lice equipment
Support lice treatment	5-14 hours/cage	Small and medium service vessels
Mooring tasks	48 hours/location	Medium and large service vessels
Wash nets	3-5 hours/cage	Small service vessels
Remove and replace nets	2-5 hours/cage	All service vessels
Disinfect location	6 hours/cage	All service vessels
Anchor inspection	4 hours	All service vessels
Remove old location	1-2 weeks	Medium and large service vessels
Install new location	14-18 days	Medium and large service vessels
Miscellaneous		All types

2.2 Defining the Problem

Simply put, the problem to be modelled is to find a way to determine how many vessels of which kind is needed to serve the demands of the aquaculture sector at the lowest possible cost, including considerations about uncertainty regarding the future demand. For the sake of this study, there are five different vessel types that can be chosen, and two of these vessel types can also be configured with or without lice treatment equipment. The vessel types presented earlier in this chapter with the addition of service vessels fitted with lice equipment, can be seen in Table 6.

Table 6: Vessel Types and Vessel Type Numbering

Type number	Type name
1	Small well-boat
2	Large well-boat
3	Small service vessel
4	Medium service vessel
5	Large service vessel
6	Medium service vessel with lice equipment
7	Large service vessel with lice equipment

Table 6 also includes service vessels with lice equipment as separate vessel types. This is done to separate the capabilities of the vessel types in the later presented model, the numbering of the vessel types is also used in the model.

A fish farming location will have different demands throughout a production cycle. Some tasks have to be done at the beginning of a cycle while other tasks are demanded at the end of a cycle. Seasonal changes in demand might also occur, such as the increase in demand for washing of nets during the summer months. Since there are seasonal peaks in demand the length of the time periods used when modelling the problem will need to be short enough to capture these variations. Therefore, a time step of six months will be used when modelling the problem.

The different tasks can be performed by different vessels. Some of the tasks such as transporting mature salmon and smolt can only be done by well-boats, while other tasks may be serviced by several different vessel types. Some tasks such as lice treatment will demand a combination of vessel types in order to perform the task. Most tasks will have a frequency based demand, based on how often it is common for the task to be performed. However, the demand for transportation of salmon and smolt will be based on the size of the location and the capacity of the well-boat.

Performing a task will take a certain amount of time. This time may include getting ready for the task, transit time to the location of the task, carrying out the task and transit back to base. Some tasks will need added time for decommissioning, such as disinfecting the vessel between lice treatments at different locations (Industry Source, 2017d). Some tasks are assumed to be possible to do in a sequence without returning to base, while other tasks will require that the vessel returns to shore before starting a new task. The time for commissioning and decommissioning can either be included in the traveling time to and between tasks, or added to the time it takes to perform the task. In this study, decommissioning will be added to the time it takes to perform a task.

Each vessel type can be assumed to have a certain number of hours available for servicing tasks throughout a given period of time. The amount of time available depends on several different factors. One of which is whether the vessels are out working 24 hours a day or if they go to shore at night. Another might be how big the weather window is for operations with the different vessel types.

Large and medium service vessels with lice equipment and both large and small well-boats are assumed to be able to operate 24 hours a day, while small, medium and large service vessels are assumed to go to shore at night (Industry Source, 2017d). Further assumptions regarding available working hours will be addressed in the uncertainty section.

To minimize the costs of performing these tasks, while ensuring sufficient capacity, the number of vessels of the different types to be acquired at what time must be considered. There are several different ways to increase the number of ships available in a fleet. Vessels can be bought second hand or new ships can be built (Stopford, 2009). Second-hand ships can be delivered without any delay, while the delivery time for a newbuilding will be several months depending on the complexity of the build. Other options are to charter inn vessels, this can be done both by spot chartering or chartering on long contracts (Stopford, 2009). In this study, the only mean of acquisition will be new buildings, and no charter options or second-hand vessels will be considered as an option. The well-boats will be assumed to have a delivery time of 18 months. Large and medium service vessels will have a delivery time of 12 mounts and small service vessels can be delivered after six mounts.

2.3 Uncertainty

In this study, there are several sources of uncertainty that needs to be considered. Some of these are related to the duration of a given task performed by a given vessel type, and the frequency of demand for the specific task type. Others relate to the operational capabilities of the different vessel types. Furthermore, there are some long-term uncertainties regarding the future growth of the aquaculture sector.

This section will discuss some of the uncertain factors, and how they can be handled when modelling the maritime fleet renewal problem.

2.3.1 Task Duration and Frequency of Demand

The demand for certain tasks can vary a lot from time period to time period, while other tasks may have a more predictable frequency. Tasks such as mooring work, anchor inspection and disinfection of locations assumed to have quite predictable demands, as they are usually scheduled tasks. While tasks such as washing of nets and lice treatment are done when its necessary. Lice treatment must be done whenever there are more than 0.5 mature female lice per salmon in the farming cage (Mattilsynet, 2017). This means that the frequency of lice treatment, net wash, and other miscellaneous tasks can vary a lot with the seasons and other variables. Some mooring work might also be necessary if a visual inspection shows that something is wrong. However, since the duration of the time periods in the model is set to six months and the total durations of the analysed period is several years, an average frequency of demand can be assumed for each season. Meaning that if on average a task is performed 7 times every six months, but at extremes, it need to be done 9 times a month, and in low cases, 5 times a month the demand will be assumed to be on the average, namely 7 times a month.

All task durations will also vary with random variables such as weather which affects the time it takes to perform a task. When speaking to industry sources they have given an upper and lower estimated durations of each task, and a rough estimate of average duration. In the absence of statistical data regarding task durations, the estimated average durations given by industry sources will be used. The reason for the average times being used is because the planning period analysed is assumed to be sufficiently long to average out any effect of variation in task durations.

2.3.2 Operational Capabilities and Available time

The number of working hours available for a certain vessel type over the duration of six months can be difficult to determine. It varies among other things with whether the vessels can perform work 24 hours a day, how often they need to return to shore and the window of operations regarding weather condition. The service vessels will usually go to shore during the night (Industry source,2017d). However, the vessels may also spend the night at a farming location during the night to save time the next day (Industry source,2017c). Furthermore, the small and medium vessels are more vulnerable to waves than the large service vessels, as long as that the vessels are able to position themselves to get the waves from a desirable direction (Enerhaug, 2013).

In order to determine how many percent of the available working hours a vessel is unable to perform work due to the weather conditions, the operational capacity should be compared with historical weather data. Enerhaug (2013) has done a study on how high the significant wave height can be before it limits the ability of service vessels of different sizes to conduct crane operations. Since crane operations are particularly vulnerable, the operational margin will be increased a little to give an average for all operations. It will also be assumed that the vessels are able to position themselves in a desirable angel against the wave direction. By looking at the results presented by Enerhaug (2013) for unloaded vessels and adding on a margin of about 0.1 meters significant wave height, the small vessels are able to work in 1.3 meters significant waves, medium vessels in 1.5 meters significant waves and large vessels in 1.6 meters significant waves. The maximum significant wave height for each of the service vessels are shown in Table 7.

Table 7: Maximum significant wave height for service vessels conducting operations

Vessel Type	Maximum Significant Wave Height
Small service vessels	1.3 meters significant wave height
Medium service vessels	1.5 meters significant wave height
Large service vessels	1.6 meters significant wave height

Based on Enerhaug (2013)

To determine the portion of the time the vessels are unable to performed tasks due to wave conditions exceeding these operational capabilities, wave data need to be collected and compared against the operational capabilities of the different vessel types. SFI Exposed is a collaboration project between industry and researchers aimed to develop knowledge about exposed aquaculture operations. SFI Exposed has two weather data collection buoys placed close to Sula and Mausundvær outside of Frøya (Exposed Aquaculture Operations, 2017). Since the buoys are placed at two quite different location in terms of wave conditions, an average of the wave heights recorded by the two buoys has been used to determine the number of hours the weather prohibits operations. Furthermore, the data has been divided into six months of winter season and six months of summer season to account for seasonal variations. This resulted in the portion of time that each vessel is unable to perform tasks to be as shown in Table 8.

Table 8: Portion of time the weather prohibits service operations during winter and summer

Vessel type	Summer	Winter
Small service vessels	1.68 %	19.63 %
Medium service vessels	0.68 %	12.11 %
Large service vessels	0.41 %	9.2 %
Well-Boats	0.41 %	6 %

Based on Exposed Aquaculture Operations (2017) and Enerhaug (2013)

The difference between summer and winter seems to be quite extreme, and the portion of time a small service vessel is unable to perform tasks increase from 1.68% during summer to 19.63% during winter. Since the statistics are based on only one year of data, these variations can be due to more extreme weather than usual during the winter or a very calm summer. However, in the lack of more complete weather data, these percentages will be used. The operating capabilities of the well-boats will be assumed to be the same as for large vessels during summer, and with a reduction down to 6% during winter compared to the 9.2% for the large service vessels. This is due to the well-boats being significantly larger, and they can therefore be expected to be less sensitive to waves.

2.3.3 Future Development of the Sector

There are several uncertain elements regarding how the aquaculture sector will develop in the future. Some of these factors may cause radical changes as to how the sector develops and in turn the need for service vessels. Two of these factors are, new technical solutions and designs of farming cages, and a new way of handling salmon lice and disease.

If a solution to the salmon lice problem and problems with spreading of disease is found, it would make it possible to produce more salmon from denser production units. Meaning that there could be an increase in farming cages within a smaller geographical area. This could allow very compact production units with both smolt producers and processing facilities within the same area. A development like this would mean that the cages could remain in shelter location similar to today's placements. The transit between each location would be short and the need for bigger and more robust vessels would probably be small. This is quite opposite of the trend today, where both well-boats and service vessels are increasing in size. With the lice problems gone, lice treatment would not be in demand anymore. This could lead to a shift in fleet composition as other tasks would take up a bigger portion of the demand for services.

New technological solutions can also radically change the demand for service vessels. There are three new concepts that have been granted development licenses, and a few others that might get approval soon. One concept that is approved and one that might get approval is "Aquatraz" and "Egget". Both concepts can have a similar impact on the sector as a solution to lice and disease would have, as some of their key conceptual aims are to solve these problems themselves. "Egget" is a closed construction which aims to solve the lice problems, spreading of disease and environmental issues (iLaks, 2016). This will allow for increased production inside the shelter of the fjords (iLaks, 2016). This could lead to very compact production, similar to what was mentioned when discussing a solution to the lice problem.

"Aquatraz" is a concept made to solve problems with lice and the salmon escaping (Berge, 2016c). The concepts look quite similar to a conventional cage but has a rigid steal structure. Furthermore "Aquatraz" has a closed section in the upper 6 meters of the cage, this is to prevent salmon lice from entering the structure. "Aquatraz" is made to substitute conventional cages and to enable a denser production. This design is approved, and the units may be built and tested in the near future. Figure 2 shows the two concepts, "Aquatraz" and "Egget".

Figure 2: Aquatraz and Egget

Aquatraz unsubmerged	**Egget**
	

Source: Berge, 2016a: Berge, 2016b

While the two previous mentioned designs are made to keep aquaculture in sheltered waters, “Ocean farming” and “Havfarm” aims to lead the aquaculture sector into more exposed waters. “Ocean farming” was the first concepts to be granted development licenses (Fiskeridirektoratet, 2017d). The concept bears resemblance to an offshore installation with living quarters on top of the farming cage (Haugstad, 2016). By moving aquaculture installations to more exposed waters with better circulation, both the environmental and salmon lice problems could be drastically reduced (Haugstad, 2016). Furthermore, this will allow for fish farming locations to be spread across larger areas, enabling higher production volumes nationwide. However, by making bigger installations and moving them further offshore, bigger and more robust vessels will be needed. First of all, to be able to perform the heavier tasks in rougher weather, but also to be able to collect the salmon in a cost-efficient manner once the transit is increased. “Havfarm” resembles a huge ship with farming cages along the 431-meter-long hull (Nordlaks, 2017). This concept is also made to make it possible to move the aquaculture to more exposed location, but can also enable more efficient use of the areas within the sheltered fjords (Nordlaks, 2017). Figure 3 shows the two concepts for more exposed fish farming.

Figure 3: Havfarm and Ocean farming

Ocean farming **Havfarm**

Source: SalMar, 2017: Nordlaks, 2017

All the four concepts mentioned in this section will be rigid structures. This makes it possible to remove some of today's service needs. This includes washing of nets which can be done by a permanently mounted unit. Loading and unloading of salmon could be done without assistance from service vessels. Furthermore, the installation of the first "Ocean Farming" cage is to be handled by an offshore service company (Kyst.no, 2016b). This includes the anchor handling and mooring work. This could mean that mooring and anchor related tasks might not be conducted by today`s service vessels, but instead by offshore service vessels. All the concepts aim to solve the problems regarding lice, making lice treatment, which is an important task today, less relevant. "Ocean farming" and "Havfarm" will also have crew living and working on the installations, this could introduce supply tasks as a new demand for these installations. An even more significant change these new concepts could mean to the problem at hand, is that if loading support and lice treatment are no longer needed, then the service vessel fleet size problem and the well-boat fleet size problem could be divided into two separate problems. This is because there would no longer be any tasks which could either be serviced by well-boats or service vessels, making fleet size and mix problems possible to separate, unless other tasks would appear that would require both vessel types.

Some of the possible changes in future demand for service tasks due to new cage concepts are listed in Table 9. In addition to the changes new concepts might cause in the type of demand for services, the future can also be divided into low, medium and high production scenarios. This will be discussed in the computational study chapter.

Table 9: Potential Changes in Demand with new Technical Solutions

Change	Exposed	Closed/semi closed
Demand for lice treatment	x	x
Longer transit between task	x	-
Shorter transit between tasks	-	x
Demand for net washing	x	x
Demand for maintenance	x	x
Demand for bigger vessels	x	-
Demand for supply delivery	x	-
Separate well-boat and service vessel MFSMP	x	x

3. Literature Study

This section will start with a short introduction to fleet size and mix models. Following this introduction, there will be a literature study presenting some relevant studies on the field. Finally, the section will briefly discuss fleet size and mix with uncertainty.

3.1 Introduction to Fleet Size and Mix Models

The maritime fleet size and mix problem (MFSMP) can be divided into single-period MFSPM and multi-period MFSPM (Pantuso, Fagerholt and Hvattum , 2014). The multi-period MFSPM will be referred to as maritime fleet renewal problems (MFRP) while the single-period will remain simply MFSMP. In a MFRP the fleet size may be changed after the initial fleet is chosen, meaning that vessels may be removed or added in different time steps. In a single period MFSPM the decisions about how many vessels to be included in the fleet will have to be done in the first period, as this is the only period included in the problem.

The most basic form a fleet size and mix model can take is that of a vehicle routing problem with a homogenous fleet, where a cost is added for each vehicle included in the solution (Pantuso, Fagerholt and Hvattum, 2014). While more complex problems might have several different vessel types and include stochastic elements.

A generic simple MFSMP could have an objective function as follows:

$$\min z = \sum_{v \in V} C_v^f y_v + \sum_{v \in V} \sum_{r \in R_v} C_{vr} x_{vr}$$

Where C_v^f is the fixed cost of including vehicle v in the solution, and C_{vr} is the cost of using vehicle v on route r. y_v is 1 if vehicle v is included and 0 if not, and x_{vr} is 1 if vehicle v is used on route r and 0 if not. A model using this objective function will also have to include constraint ensuring that a demand is met and that the fleet of vehicles have sufficient capacity (Pantuso, Fagerholt and Hvattum, 2014).

A demand constraint could look as follows:

$$\sum_{v \in V} \sum_{r \in R_v} A_{ir}\, x_{rv} \geq F_i \qquad\qquad i \in N$$

Here F_i is the frequency demand for a certain service and A_{ir} is 1 if route r includes service i and 0 if it does not.

The capacity of a vessel can be measured in anything from time available, to the carrying capacity of the vessel (Pantuso, Fagerholt and Hvattum, 2014). A capacity constraint using time as the capacity may look as follows:

$$\sum_{r \in R_v} T_{rv} x_{rv} \leq \mathrm{T}_v^{\mathrm{o}} y_v \qquad\qquad v \in V$$

Where T_{rv} is the time it takes for vessel v to perform route r and $\mathrm{T}_v^{\mathrm{o}}$ is the total available time for vessel v for the entire planning horizon.

Fleet size and mix models often include routing decisions, since these are necessary to consider the structure of the real-life problem (Halvorsen-Weare et al., 2012). However, the routing decisions can also be handled in a separate route generation problem (Halvorsen-Weare et al., 2012). This will make the fleet size and mix model simpler, as the need for routing constraints is removed.

3.2 Relevant Literature

There are many studies on the field of MFSMP in the different sectors of the shipping industry. Furthermore, there are also some stochastic modelling papers which apply principles that can be used when modelling a MFRP. There are however only a few studies available on service vessels, and no studies have been found on vessels in the aquaculture sector. This literature review will focus both MFSMP studies and studies with applicable stochastic principles.

Pantuso et al. (2014) presents a literature survey focusing on MFSMP and MFRP. The review focused on all sectors of the shipping market, but the studies on offshore service problems are assumed to be the most applicable for this study. Therefore, the four offshore service articles are the only studies the survey made by Pantuso et al. (2014) which will be mentioned in this literature study.

Fagerholt and Lindstad (2000) presents a study on how to efficiently supply a given set of offshore installations from a single base. For the study, they have created scenarios relating to how many visits the installations need every week, and the open hours of the installations. Based on the opening hours and demand for quantity delivered, every feasible ship schedule is created in a route generation problem. This route generation takes care of the cargo capacity restrictions and time window restrictions, making the optimization model similar to a set partitioning problem where the number of times each route is serviced is determined. However, to ensure the robustness of the solutions, qualitative assessments of the solutions are conducted for the optimal solutions to each scenario. One of the robustness measures discussed in the paper is to reduce the number of available operating hours per vessel per week to compensate for poor weather conditions. This approach for taking weather condition into account is also considered in this study. Furthermore, the main structure of the modelling approach used by Fagerholt and Lindstad (2000) can be used for the MFRP at hand.

Halvorsen-Weare et al. (2012) presents a study of a similar problem to the one described by Fagerholt and Lindstad (2000). The solution method used is also quite similar, with a candidate voyage generation phase and an optimal voyage composition stage. Halvorsen-Weare et al. (2012) presents a very structured description of the method used, and the specific restrictions and assumptions. The robustness issue is also briefly included, as the implementation of mandatory slack in voyage duration is discussed. This could be used to consider the effects of unexpected events such as rough weather conditions (Halvorsen-Weare et al., 2012). The use of slack could be used in the aquaculture problem as well, either by adding additional time to each task duration or by imposing restrictions dictating a minimum number of operating hours to be unused.

Shyshou, Gribkovskaia and Barceló (2010) presents a discrete event simulation model for determining the optimal number of anchor handling tug supply (AHTS) vessels to be hired on long contracts. The model simulates several of the stochastic parameters such as weather conditions, duration of operational tasks and spot prices. According to Shyshou, Gribkovskaia and Barceló (2010) the model was quite insensitive to high spot rates, but much more sensitive to rates below average. Such simulations could be considered for weather conditions, duration of tasks and the frequency of demand for tasks such as lice treatment. This will however not be included in this report, but it could be an interesting extension for future work. Especially if a deployment model is to be made to check the performance of the fleet mix found in the MFRP.

Halvorsen-Weare and Fagerholt (2011) presents a paper discussing robustness measures for the problem presented in Halvorsen-Weare (2012). The robustness measures are related to weather condition being a source of uncertainty. Halvorsen-Weare Fagerholt (2011) proposes three different measures.

- Minimum hours of slack for each sailed voyage
- Benefit from maximum number of voyages sailed in a week
- Punishment for average not delivered volume for the voyages

The not delivered volumes were found by running simulations of the candidate voyages with changing weather conditions. The implementation of punishment for average not delivered volume and the implementation of a combination of the measures gave lower predicted costs (Halvorsen-Weare Fagerholt, 2011). However, the effectiveness of the measures varied with the size of the routing problem (Halvorsen-Weare Fagerholt, 2011). As mentioned earlier, simulation will not be used in this research, but can be considered for future extensions. However, a robustness measure relating to slack or added time for operations during seasons with rough weather may be considered.

The articles mentioned so far are the once chosen from the literature study performed by Pantuso et al. (2014). These articles have covered some important aspects; such as generating all possible candidate routes in a separate problem, and some robustness measures such as weather simulation and the inclusion of slack in different forms.

Steffensen (2012) presented a single period deterministic fleet size and mix model for an auto liner shipping company in his master`s dissertation. The model included both frequency and quantity demands. This model was different from the ones presented by Halvorsen-Weare (2012) and Fagerholt and Lindstad (2000) as it did not include a voyage generation stage but rather had an arc flow structure, meaning that the model included routing restrictions. The reason for this structure was that Steffensen (2012) also presented a deployment model which had the same structure. The results from the deployment model showed that the fleet size form the fleet size and mix model was undersized, and that the performance of the fleet size and mix model decreased as the length of the planning period increased. The deviation was caused by the assumptions in the fleet size and mix problem being too optimistic. Since the

MFSMP model have no distinction between the different vessels when assigning routes, leading to the total number of operation days for the different vessels not being considered.

Stålhane et al. (2016) presents a two-stage stochastic model to determine the optimal fleet size and mix for the support and maintenance of offshore wind farms. The model also includes decisions regarding the number of offshore bases for the vessels to operate from. The planning horizon of the problem is the life span of an offshore wind farm. The aim is to minimize the cost of planned and unplanned maintenance, while ensuring that the fleet has sufficient capacity to undertake all tasks. The paper by Stålhane et al. (2016) is of particular interest to the problem in this study, as it considers service vessels with different task capabilities. Stålhane et al. (2016) conclude that the trade-off between detailed routing and a model that is practical to solve is one of the biggest issues when making such a model. This will probably be a consideration that must be included when making a model for the aquaculture sector as well.

Balland et al. (2013) presents a two-stage stochastic model for determining which emission controls to install on a vessel in order to reach the emission reduction targets. The model makes the same kind of decisions in both stages, making the restriction in the first and second stage almost identical. The uncertainty in the study is related to how the different emission control interact, and how well they perform. Balland et al. (2013) generated 25 different scenarios using a scenario generating algorithm, and compared the stochastic solution to the deterministic solution. Balland et al. (2013) concluded that the uncertainty had a relatively high impact on the solution, and that a stochastic model would be preferred. However, it was argued that since the model will be re-run at the beginning of the second stage and since the second stage is only an indication of possible futures, then there would not be a significant change to the quality of the solution if more stages were included.

Pantuso, Fagerholt and Wallace (2016) presents a model for a maritime fleet renewal problem with uncertainty. The main decisions in the model are when and how to acquire and dispose of vessels. The model includes a few alternative methods for both increasing and decreasing the fleet size. Vessels can be bought on the second-hand market or as new buildings, sold on the second-hand market or scraped. In addition, the vessels can be laid up, and vessels can be chartered inn and out. The uncertainty in the model is related to vessel costs and demand. The model is a stochastic model for determining how a predefined fleet should evolve over a period of time. To test the model a case study based on Wallenius Wilhelmsen Logistics was conducted. Pantuso, Fagerholt and Wallace (2016) conclude that the stochastic model gives better fleet renewal decisions than solving the problem deterministic. Moreover, it is also concluded that the importance of uncertainty is reduced in a market with easy access to charter vessels.

3.3 Fleet Size and Mix with Uncertainty

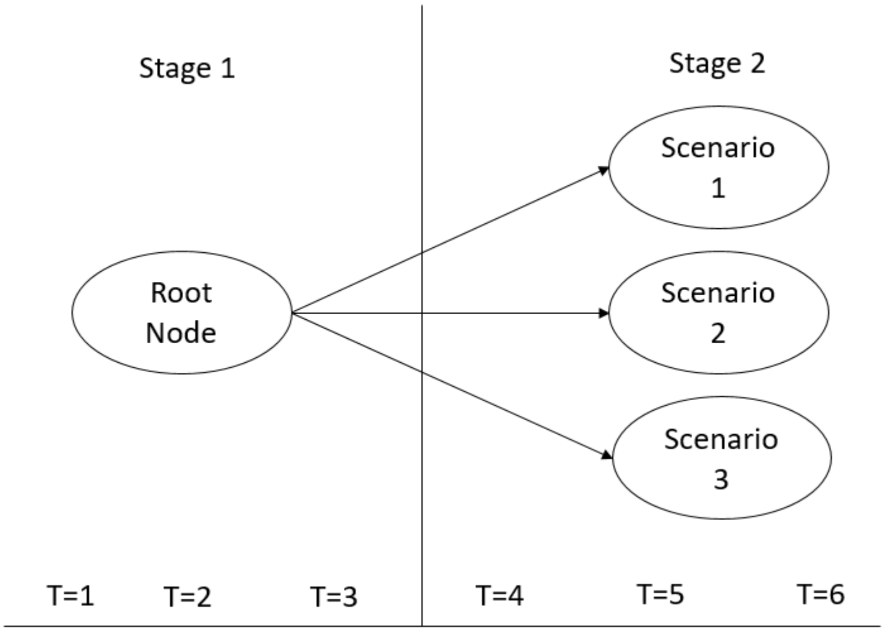
Linear programming (LP) is a tool intended to solve deterministic problems (Higle, 2005). However, when modelling a real-life problem with a long planning horizon and uncertain elements, it might not be possible to assume that all data elements are known. When modelling a MFRP the investments are often large, and the future development of the market is hard to predict. Therefore, it can be important to consider uncertainty when developing the model.

An uncertain future may cause problems when trying to solve a deterministic linear programming problem. Two possible ways to solve a problem with uncertain future scenarios is using expected values for all the different possible scenarios, or solving for each scenario and combining the solutions (Higle, 2005). It is also possible to use sensitivity analysis to determine how much the different factors can change before the optimal solution changes (King and Wallace, 2012). When using these deterministic approaches, the solution obtained is restricted to a combination of the optimal solutions of the deterministic problems solved for each scenario. This may possibly exclude some of the solutions that can be found by solving the problem with a stochastic model.

In a stochastic model, some of the decision must be made before the information about the outcome of the uncertainty is known (Higle, 2005). The aim of stochastic modelling is to obtain a solution that performs well under uncertainty (King and Wallace, 2012). Stages in stochastic modelling are the points in time when new information is available, and decisions are made (King and Wallace, 2012). The initial decision is called the first stage decision, and the next stage is defined as the point in time when new information is available. Stochastic models can be either two stage or multiple stage, depending on how many times new information will be made available. Each stage can contain several time steps.

In the case of the MFRP with a long planning horizon factors such as future demand, prices and costs may be hard to predict. These uncertainties can be introduced to the model by using stochastic variables. Instead of using continuous stochastic variables, it is common to create discrete scenarios with a probability distribution similar to the probability distribution of the stochastic variables. This is done to avoid having to solve integrals in the objective function when modelling the problem (Pantuso, Fagerholt and Wallace, 2015). Figure 4 shows an example of a scenario tree for a two-stage problem with three scenarios.

Figure 4: Example of a Scenario Tree



The first stage in Figure 4 has three time steps, then at time step four new information is available and new decisions can be made. Each scenario will have a certain probability, and represent a discrete realization of the uncertain variables. A scenario tree can have many stages where new information is available. This can lead to a more realistic prediction of the future, but it will increase the complexity of the problem. However, even the most intricate and complex future predictions can be wrong. Furthermore, it is the "here and now" decisions in the first stage that are of interest to the decision makers (Pantuso, Fagerholt and Wallace, 2015). The later stages are only included to make the decision made in the first step better. For this reason, only two stages will be included in the model presented in the next chapter.

There are many methods for creating scenario trees. The most important aspect to consider is that the scenario tree should give a realistic representation of the probability. However, since the aim of this study is to make a model capable of considering uncertain futures and not to make good future predictions, the scenarios used will be quite simple scenarios with low, medium and high demands. This means that the scenarios used in this study will be of a limited number and with quite simple assumptions.

A common way to evaluate a stochastic modelling problem is to calculate the value of the stochastic solution (VSS) (Maggioni and Wallace, 2010). VVS is a method used for measuring the gain from using a stochastic model instead of a deterministic model (Maggioni and Wallace, 2010).

VVS can be defined as the difference between the stochastic programming solution (SS) and the expectation of the expected value problem (EEV) (Maggioni and Wallace, 2010). The expected value problem (EV) is a problem where all the random variables are removed and replaced by their expected value. This means that the weighted average of the scenarios will be used to solve a deterministic model to find the EV.
Then by using the first stage solution from the EV problem and evaluating every scenario, the EEV is found. For some scenarios, one might end up with no feasible solution when using the first stage EV solution as the first stage decision. If this occurs a decision has to be made as to what this should mean for the EEV value. Equation 1 shows how VSS is calculated for a minimization problem.

Equation 1: Value of the stochastic solution

$$VSS = EEV - SS \tag{1}$$

If the VSS is very low, it is an indication that the inclusion of uncertainty has little value. Meaning that it would be more advisable to use a deterministic model.

4. Maritime Fleet Renewal Model for the Aquaculture Sector

In this chapter, a mathematical two-stage stochastic programming model to determine the fleet size and mix of vessels in the aquaculture sector is presented. The model is made to decide how many of which types of vessels to be invested in, and when the vessels should be acquired.

4.1 Model Description

This section will present the logic behind the mathematical model, including important assumptions.

Task Assumptions and Vessel Capacity

Each vessel type can perform a given set of tasks, and each task takes a given amount of time to perform for each vessel type. The time it takes to perform a task includes transit time, the actual time to perform the task and may also include commissioning and decommissioning. Some tasks are assumed to be compatible in the sense that a vessel can perform them in a sequence without returning to base in between. Other tasks however, will require the vessel to return to base before performing the other. Each vessel type will have a maximum number of hours available before it must return to base. This means that if a vessel can be out for 12 hours at a time then it will have to return to base instead of starting a new task after the 12 hours have passed. Each vessel will have a maximum total amount of time available inn each modelling time period. This total number of hours are based on information about how long they operate each day, weather windows and a few days a year for maintenance and other events requiring time spent in base. There will not be any specific routing decisions made in the model, and the sequence of the tasks performed are not considered. This means that if a location needs the nets to be washed five times in the planning period, the model does not consider if the nets then are washed five times in one week, or spread evenly. The only requirement is that the tasks are performed a sufficient number of times within the time period, and that the vessels do not exceed the maximum working hours in the same period. When a task has a quantity demand, the only requirement is that the total carrying capacity designated to a transportation task in a given period, has to be bigger than the quantity demand for that task in the same period.

Routing and Loop Generation

The optimization model is not meant to give any concrete advice regarding the deployment and day to day routing of vessels. However, some routing decisions have to be made in order to make sure that the chooses fleet has enough capacity to cover the demand for each task. The routing decisions will be considered by creating loops for each vessels type. Each loop is a route consisting of one or more tasks a vessel can perform in a sequence before returning to the base of origin. All possible loops will be created for each vessel type, based on which tasks can be done in a sequence and how long the vessel can operate before it needs to return to base. It is assumed that only one task with a quantity demand can be included in each loop. There are no restrictions as to how many times a vessel type can service a loop, as long as it does not exceed the total available operation time for the vessel type in the period.
Since the loops are serviced by a type of vessel and not individual vessels, the traveling times between the different starting point of the loops are not included. The assumptions that the vessels have to return to the base of origin and that the traveling times between bases are excluded, will hopefully give a fair balance between optimistic and pessimistic factors. On one hand, the total sailing distance may be underestimated by not including the traveling distance between bases (Pantuso, Fagerholt and Wallace, 2015). However, since the loops are assigned to vessel types and not specific vessels, there may be different vessels servicing the loops starting from different bases. Furthermore, the loops force the vessels to return to the base of origin even though this may not be the most time effective use of the vessels (Pantuso, Fagerholt and Wallace, 2015).

The reason why the loops are generated outside the actual MFRP model is to remove the routing constraints from the model, making it much more efficient to solve and reduces the number of constraint in the model. Furthermore, once all the desired loops are created, the MFRP model can be run for different scenarios and demands without the need for generating loops again and again. This is because the same loops can be used as long as all locations and tasks are included during the loop generation. This gives the model more flexibility and makes it easier to apply changes to the model without changing the model structure.

Demand Restrictions

Most of the tasks will have a frequency demand, meaning that the vessels will have to service a selection of loops servicing these demands a given number of times to fulfil the demand. However, transportation of smolt and salmon will have a quantity demand. This means that the number of times these tasks need to be serviced is a function of the capacity of the vessels servicing the loops. The capacity of the vessels used multiplied by the number of times the loops are serviced will have to be greater than the quantity demand of the task. The loading of salmon onboard the well boats will have to be done once for every time a vessel is assigned to carry salmon from the location. Meaning that a service vessel will have to assist every loading operation. Therefore, the load support tasks will have their own restrictions ensuring that they are done at least once for each transport task.

Lice treatment and treatment support are separated into two different tasks. This is to ensure that both a vessel capable of treating lice and the required number of vessels needed for support is included in the operation. However, the model does not take into account whether or not the treatment and support tasks are done at the same time, as long as the demand is met within the time period of the demand. The time it takes to support a lice treatment operation is dependent on which vessel it is that performs the treatment. Therefore, there will be separate restrictions for each vessel type performing lice treatment, in order to make sure that the right amount of time is spent supporting the treatment.

Vessel Acquisition and Disposal

In this model, only one acquisition method for vessels will be available. The vessels will have to be bought as newbuildings. This means that there will be a delay from the time the vessels are ordered to the delivery time. Even though newbuildings are usually paid in instalments over a period of time, the vessels will be assumed to be paid for at full when the ship is delivered. The vessels can be sold on the second-hand market for a price which will always be assumed to be lower than the newbuilding price. Furthermore, since the large and medium service vessels need to have lice treatment equipment installed to be able to treat lice, they will be split into different vessel types depending on whether they have the equipment installed. For a service vessel to convert into a service vessel with lice equipment the investment cost of the equipment must be paid. To ensure that there is a downside to switching a vessel back and forth only 90 % of the equipment cost will be paid back if a vessel is converted back again. Changing back and forth can only be done between time periods, meaning that a vessel will need to either be equipped with lice treatment equipment or not for a whole time period at the time. No time penalty is assumed for the installation of lice treatment equipment. For each vessel type, there will be a fixed cost associated with having the vessel in the fleet. There will also be variable costs for each hour the vessels of each type spend servicing loops.

The Two Stages

For the time periods included in the first stage of the model, the demands for the different tasks are assumed to be known. In the second stage, the demand is unknown and there can be many different scenarios for this stage. Vessels can be ordered and sold in every time period, and the fleet composition at the end of the first stage will be the initial fleet for the second stage.

The first stage decisions represent the decisions that needs to be taken now, while the second stage is included to increase the robustness of the decisions made in the first stage. The only decisions of importance today are the “here and now” decisions made in the first stage, the second stage is only provided to make the decision made in the first step more robust (Pantuso, Fagerholt and Wallace, 2015). The model can also be used as a deterministic model by removing the second stage from the model.

4.2 Mathematical Formulation

In this subsection, the mathematical formulation of the model will be presented. First, the indices, sets and parameters will be defined. Then the variables used in the model will be presented. After all the elements indices, sets, parameters and variables used in the model is presented, the objective function is stated. For this problem, the objective function is a minimization function, as the goal is to minimize costs while fulfilling the demand for all services. Following the objective function, the restrictions which apply for the time periods in the first stage is presented. Then the second stage restrictions for the uncertain time periods are presented. All restrictions will be commented at the end of the mathematical formulation.

Indices

v Type of vessel

i Task

t Time period

s Scenario

l Locations

r Loop

Sets

L Set of locations

V Set of vessel types *v*

V_c Subset of vessel types that can be converted

V_{cl} Subset of vessel types that can be fitted with lice equipment

V_{cr} Subset of vessel types that can have lice equipment removed

T Set of time periods

T_1 Subset of time periods *t* in decision stage 1

T_2 Subset of time periods *t* in decision stage 2

I Set of tasks *i*

I_1 Subset of tasks *i* with a frequency demand

I_2 Subset of tasks *i* with a quantity demand

I_T Subset of tasks *i* which are salmon transport needing loading support

I_S Subset of tasks *i* which are support for loading operations

I_L Subset of tasks *i* which are lice treatment tasks

I_{LS} Subset of tasks *i* which are lice treatment support tasks

S Is the set of scenarios

R Set of loops *r*

T_L Is the last time period

Parameters

C_v^{VAR}	Cost per hour of using a vessel of type *v* to service loops
C_v^I	Investment cost of a vessel of type *v*
C_v^F	Fixed cost per time period of having a vessel of type *v* in the fleet
R_v^{SE}	Revenue of selling a vessel of type *v*
R_v^{RES}	Residual value of a vessel of type *v*
D_{ilt} , D_{ilts}	Demand for task *i* at location *l* in time period *t* and for scenario *s* in the second stage
C_v^{CL}	Cost of installing lice equipment on a vessel of type *v*
R_v^{CR}	Revenue for removing lice equipment from a vessel of type *v*
T_{rv}	The time it takes for a vessel of type *v* to perform loop *r*
T_v	Number of time periods it takes from order to delivery for a vessel of type *v*
$\mathrm{T_{vt}^{o}}$	Maximum allowed operation time for a vessel of type *v* in time period t
Q_v^M	Maximum allowed cargo on a vessel of type *v*
P_s	Probability of scenario *s*
A_{lirv}	1 if task *i* is serviced at location *l* by loop *r* for vessel type *v* and zero if not
Y^{Lice}	Number service vessels required to support a lice treatment operation

Variables

x_{rvt} , x_{rvts}	Number of times a vessel of type *v* services loop *r* in period *t* and for scenario *s* in the second stage
Z_{vt}^N , Z_{vts}^N	Number of vessels of type *v* joining the fleet in period *t* and for scenario *s* in the second stage
Z_{vt}^O, Z_{vts}^O	Number of vessel of type *v* ordered in period *t* and for scenario *s* in the second stage
Z_{vt}^c , Z_{vts}^c	Number of vessels being added to the vessel type because of conversion in period *t* and scenarios s
Z_{vt}^{cb} , Z_{vts}^{cb}	Number of vessels being removed from the vessel type due to conversion period *t* and scenarios s
Z_{vt} , Z_{vts}	Number of vessels of type *v* in the fleet at period *t* and for scenario *s* in the second stage
Z_{vt}^{SE} , Z_{vts}^{SE}	Number of vessels of type *v* sold in period *t* and for scenario *s* in the second stage

Objective function:

$$Min\ Z = \sum_{v\in V}\sum_{t\in T_1} C_v^F Z_{vt} + \sum_{v\in V}\sum_{t\in T_1} C_v^I Z_{vt}^N \tag{1a}$$

$$+\sum_{r\in R}\sum_{v\in V}\sum_{t\in T_1} C_v^{VAR} x_{rvt} T_{rv} \tag{1b}$$

$$+\sum_{v\in V_{cl}}\sum_{t\in T_1} C_v^{CL} Z_{vt}^c - \sum_{v\in V_{cr}}\sum_{t\in T_1} R_v^{CR} Z_{vt}^{cb} \tag{1c}$$

$$-\sum_{v\in V}\sum_{t\in T_1} R_v^{SE} Z_{vt}^{SE} \tag{1d}$$

$$+\sum_{s\in S} P_s \left[\sum_{v\in V}\sum_{t\in T_2} C_v^F Z_{vts} + \sum_{v\in V}\sum_{t\in T_2} C_v^I Z_{vts}^N \right. \tag{1e}$$

$$+\sum_{r\in R}\sum_{v\in V}\sum_{t\in T_2} C_v^{VAR} x_{rvts} T_{rv} \tag{1f}$$

$$+\sum_{v\in V_{cl}}\sum_{t\in T_2} C_v^{CL} Z_{vts}^c - \sum_{v\in V_{cl}}\sum_{t\in T_2} R_v^{CR} Z_{vts}^{cb} \tag{1g}$$

$$\left. -\sum_{v\in V}\sum_{t\in T_2\backslash\{T_L\}} R_v^{SE} Z_{vts}^{SE} - \sum_{v\in V} R_v^{RES} Z_{v(t=T_L)s} \right] \tag{1h}$$

Restrictions stage 1:

$$Z_{vt} = Z_{vt}^N \qquad t = 1, v \in V \tag{2}$$

$$Z_{vt} - Z_{v(t-1)} = Z_{vt}^N - Z_{vt}^{SE} \qquad t \in T_1\backslash\{1\}, v \in V\backslash\{V_c\} \tag{3}$$

$$Z_{vt} - Z_{v(t-1)} = Z_{vt}^N - Z_{vt}^{SE} + Z_{vt}^c - Z_{vt}^{cb} \qquad t \in T_1\backslash\{1\}, v \in V_c \tag{4}$$

$$Z_{(v=v\ converted\ to)t}^c = Z_{(v=v\ converted\ from)t}^{cb} \qquad t \in T_1\ v \in V_c \tag{5}$$

$$Z_{vt}^N = Z_{vt-T_v}^O \qquad t > T_v \in T_1, v \in V \tag{6}$$

$$\sum_{v\in V}\sum_{r\in R_v} A_{lirv}\, x_{rvt} \geq D_{ilt} \qquad i \in I_1\backslash\{I_s,\}, t \in T_1, l \in L \tag{7}$$

$$\sum_{v\in V_L}\sum_{r\in R} A_{l(i=I_T)rv}\, x_{rvt} \leq \sum_{v\in V_S}\sum_{r\in R} A_{l(i=I_S)rv}\, x_{rvt} \qquad t \in T_1, l \in L \tag{8}$$

$$\sum_{v\in V}\sum_{r\in R} Y^{Lice} A_{l(i=I_L)rv}\, x_{rvt} \leq \sum_{v\in V}\sum_{r\in R} A_{l(i=I_{LS})rv}\, x_{rvt} \qquad t \in T_1, l \in L \qquad (9)$$

$$\sum_{v\in V}\sum_{r\in R_v} Q_v^M A_{lirv}\, x_{rvt} \geq D_{ilt} \qquad i \in I_2, t \in T_1, l \in L \qquad (10)$$

$$\sum_{r\in R} T_{rv} x_{rvt} \leq \mathrm{T}_{vt}^{\mathrm{o}} Z_{vt} \qquad t \in T_1, v \in V \qquad (11)$$

$$Z_{vt}, Z_{vt}^N, Z_{vt}^{SE}, Z_{vt}^O, Z_{vt}^c, Z_{vt}^{cb} \in \mathbb{Z}^+ \qquad t \in T_1, v \in V \qquad (12)$$

$$x_{rvt} \in \mathbb{Z}^+ \qquad t \in T_1, v \in V, r \in R \qquad (13)$$

The second stage will have most of the same restrictions, but with the addition of the index s on the variables and some of the parameters. Furthermore, there will be an alteration to the first fleet restriction, as the initial fleet for the second stage must be equal for all the scenarios and equal to the fleet at the end of the first stage. Similarly, the fleet being transferred from the first to the second stage, the order book will also have to be equal at the start of the second stage

Restrictions stage 2:

$$Z_{vt} = Z_{vts} \qquad t \in T_1, v \in V, s \in S \qquad (14)$$

$$Z_{vts}^O = Z_{vt}^O \qquad t \in T_1, v \in V, s \in S \qquad (15)$$

$$Z_{vts} - Z_{v(t-1)s} = Z_{vts}^N - Z_{vts}^{SE} \qquad t \in T_2, v \in V \backslash \{V_c\}, s \in S \qquad (16)$$

$$Z_{vts} - Z_{v(t-1)s} = Z_{vts}^N - Z_{vts}^{SE} + Z_{vts}^c - Z_{vts}^{cb} \qquad t \in T_2, v \in V_c, s \in S \qquad (17)$$

$$Z_{(v=v\ converted\ to)ts}^c = Z_{(v=v\ converted\ from)ts}^{cb} \qquad t \in T_2, v \in V_c, s \in S \qquad (18)$$

$$Z_{vts}^N = Z_{v(t-T_v)-s}^O \qquad t > T_v \in T_2, v \in V, s \in S \qquad (19)$$

$$\sum_{v\in V}\sum_{r\in R} A_{lirvs}\, x_{rvts} \geq D_{ilt} \qquad i \in I_1 \backslash \{I_s,\}, t \in T_2, s \in S, l \in L \qquad (20)$$

$$\sum_{v\in V}\sum_{r\in R} A_{l(i=I_T)rvs}\, x_{rvts} \leq \sum_{v\in V}\sum_{r\in R} A_{l(i=I_S)rvs}\, x_{rvts} \qquad t \in T_2, s \in S, l \in L \qquad (21)$$

$$\sum_{v\in V}\sum_{r\in R} Y^{Lice} A_{l(i=I_L)rvs}\, x_{rvts} \leq \sum_{v\in}\sum_{r\in R} A_{l(i=I_{LS})rvs}\, x_{rvts} \qquad t \in T_2, s \in S, l \in L \qquad (22)$$

$$\sum_{v \in V} \sum_{r \in R} Q_v^M A_{lirvs} x_{rvts} \geq D_{ilt} \qquad i \in I_2, t \in T_2, s \in S, l \in L \qquad (23)$$

$$\sum_{r \in R} T_{rv} x_{rvts} \leq \mathrm{T}_{vt}^{o} Z_{vts} \qquad t \in T_2, v \in V, s \in S \qquad (24)$$

$$Z_{vts}, Z_{vts}^N, Z_{vts}^{SE}, Z_{vts}^O, Z_{vts}^c, Z_{vts}^{cb} \in \mathbb{Z}^+ \qquad t \in T_2, v \in V, s \in S \qquad (25)$$

$$x_{rvts} \in \mathbb{Z}^+ \qquad t \in T_2, v \in V, r \in R, s \in S \qquad (26)$$

The Objective Function

To make the objective function easier to read it is broken down into several parts (1a)-(1h). The parts of the objective function corresponding to stage 1 is (1a)-(1d). (1a) is the fixed costs of having each vessel in the fleet in time period t, and the costs occurring when a vessel is ordered. (1b) is the cost of servicing loop r with vessel v in period t. (1c) is the cost of installing lice treatment equipment on a vessel, and the revenue of removing lice treatment equipment from a vessel. The revenue from selling a vessel in time period t is covered by (1d).

Parts (1e)-(1h) corresponds to the second stage of the model. They are the weighted sum of all the different scenarios, and contain all the same elements as the first stage objective function with the addition of (1h) which is the residual value of the fleet at the end of the planning period.

First Stage Restrictions

Restrictions (2)-(12) are the restrictions for the first stage of the first stage of the problem. Restriction (2) states that the fleet in the first time period is equal to the number of vessels joining the fleet in the first time period. This is to allow a fleet to be created in the first time period, instead of loading an initial fleet. If there is an initial fleet in the problem, this restriction should be changed to ensure that the fleet in the first stage is equal to the initial fleet.

Restriction (3) and ensures that the change in the number of vessels that cannot have lice equipment added or removed from one time period to the next is the same as the number of vessels being bought and sold in the period. Restriction (4) and ensures that the change in the number of vessels that can have lice equipment added or removed from one time period to the next is the same as the number of vessels being bought, sold and conversions to and from the vessel type.

Restriction (5) ensures that the number of vessels added to a vessel type due to lice equipment conversions corresponds to the number of vessels leaving the vessel type that vessel is converted from. As an example, medium service vessels can be converted to medium service vessels with lice equipment. In this case the number of vessels added to medium service vessels with lice equipment must be the same as the number of vessels being converted from medium service vessels.

Restriction (6) ensures that a vessel that is ordered joins the fleet at the end of the delivery time.

Restriction (7) ensures that all the frequency demands are fulfilled. Restriction (8) makes sure that the number of loading support operations corresponds to the number of times salmon is loaded for transport. Restriction (9) is quite similar to restriction (8) and makes sure that the lice treatment is supported by the right amount of service vessels. Restriction (10) makes dure that carrying capacity assigned to the tasks with a quantity demand is greater than the quantity demand.

Restriction (11) makes sure that the amount of time each vessel type spends on servicing loops does not exceed the total amount of time they have available.

Restrictions (12) and (13) are non-negativity integer constrains.

Second Stage Restrictions

Restrictions (14)-(26) are the second stage restrictions. They have the same structure and the same function as the first stage restrictions with a few exceptions, (13) and (14).

Restriction (13) ensures that the fleet from the first stage is transferred to the second stage, making sure that the initial fleet is the same for all scenarios.

Restriction (14) makes sure that the order book from stage 1 is transferred to the second stage, so that a vessel can be ordered in the first stage and delivered in the second stage.

The rest of the second stage restrictions are similar to the first stage restrictions.

5. Computational Study

This chapter will present an implementation of the mathematical model presented in the previous chapter. The aim of the implementation is to make the computer model as generic as possible, to make it adaptable to specific cases and specific input.

First, an introduction of the modelling logic will be presented, together with necessary input and assumptions used to create the model. Then the implementation of the loop generation will be presented, followed by the implementation of the MFRP model. Finally, a few scenarios will be analysed, and the performance of the model will be commented.

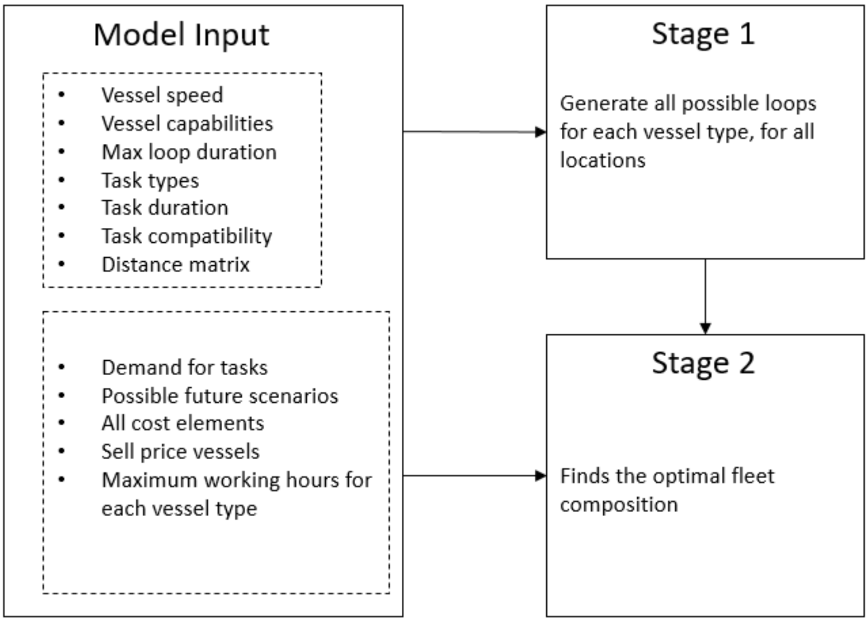
Software and Computer Specifications

Xpress-IVE Version 1.24.08 64 bit is used to solve the implementations with Xpress Optimizer Version 28.01.04. Mosel Xpress is the modelling language used in Xpress. MATLAB version R2016a was used for the loop generation. All runs are performed on a computer running Windows 10 Home operating system, having an Intel® Core® i7-4710MQ Quad Core CPU @ 2.50 GHz and 16 GB RAM.

5.1 Model Structure and Assumptions

The modelling is done in two modelling stages. The first stage is to create all the possible loops that the vessels can service. This stage requires input regarding the vessels, the different tasks and the distance between the farming locations. All the locations and tasks which may be included in a future scenario should be included in the loop generation input. This will enable the loop generation to only be done once, regardless of how the demand will evolve in the different scenarios. This is because the loops are not affected by changes in cost, demand or other uncertain factors. Figure 5 shows how the modelling approach is structured.

Figure 5: Modelling approach



Once all the loops are generated these can be used as input in the MFRP, along with demand, costs and the number of hours each vessel has available.

5.1.1 Cost and Operational Data

In the problem description chapter, the investment cost of the different vessel types was mentioned. However, the investment cost is only one of several cost elements that need to be included when evaluating which vessels to choose. The remaining cost elements can be divided into voyage dependent and voyage independent costs, or fixed and variable costs (Amdahl et al., 2011). The fixed costs consist of, crewing costs, repair and maintenance, insurance, administration and other general costs (Stopford, 2009: Amdahl et al., 2011). The variable costs consist of fuel and consumables, and other voyage specific costs (Amdahl et al., 2011). Furthermore, to account for the reduction in value a vessel has over the years, a deprecation cost could also be included. According to Stopford (2009), 42% of the fixed costs comes from crewing costs. These 42% are found for a cape size bulk carrier, with an international crew. For the smaller vessels used in this report, this percentage will be assumed to be significantly larger as the crew is Norwegian, and the crew size of a smaller ship is bigger relative to the size and investment cost of the vessel. Therefore, the fixed costs of the vessels in this study will be assumed to be two-thirds crewing cost and one-third other fixed costs. Stopford also states that 76% of the voyage based costs are fuel oil costs and diesel oil costs. For the sake of this report, the voyage costs will be assumed to be 80% fuel cost and 20% other costs.

To estimate the crewing cost of the vessel types, salary statistics for shipsdeck officers and shipsdeck crew is used. Indirect labour costs such as taxes and social contributions will also be added to the crewing costs. The average monthly salary for a shipsdeck officer in 2012 was 56 000 NOK and for a shipsdeck crew member 36 200 NOK (SSB, 2014). By adding on the scaled average indirect labour costs due to the difference in income, the shipsdeck officer costs about 850 000 NOK per year and a shipsdeck crew member costs about 580 000 NOK per year (SSB, 2013). Large well-boats have a crew consisting of 16 crewmembers divided into two shifts (Maritimt Magasin, 2016). Three of which will be assumed to be officers on each shift. The small well-boats will be assumed to have the same crew as the large well-boats. The large service vessels have a crew of 14 crewmembers divided into two shifts (Industry Source, 2017d). Two of which are assumed to be officers on each shift. Medium service vessels are assumed to have 8 crew members divided into two shifts based on the number of cabins onboard (Blich, 2016). The small service vessels will be assumed to only have one shift consisting of three crew members based on the number of cabins (FrøyGruppen, 2017c). Both medium and small service vessels are assumed to have one officer on each shift. Table 10 shows the number of crew and the crewing cost per time period (half year) for each vessel.

Table 10: Crew Composition and Cost for All Vessel Types

Vessel Type	Officers	Crew	Crewing Cost [NOK]
Small well-boat	6	10	5 450 000
Large well-boat	6	10	5 450 000
Small Service Vessel	1	2	1 005 000
Medium Service Vessel	2	6	2 590 000
Large Service Vessel	4	10	4 600 000

Given that the crewing costs are assumed to be two-thirds of the fixed costs for the vessels, the total fixed cost per time period for each vessel type will be as shown in Table 11.

Table 11: Fixed Cost per Time Period for all Vessel Types

Vessel Type	Fixed Cost [NOK]
Small well-boat	8 257 575
Large well-boat	8 257 575
Small Service Vessel	1 522 727
Medium Service Vessel	3 924 242
Large Service Vessel	6 969 696

Small, medium and large service vessels have a fuel consumption of about 70-100 litres per hour when traveling at service speed (Industry Source, 2017f: Moen Marin, 2017). The reason why the consumption is similar for the different sizes is that the vessels all have 1000 BHP propulsion, due to stricter regulations when exceeding 1000 BHP. When a large service vessel with three lice treatment systems are treating lice, it consumes about 100 litres per hour (Industry Source, 2017f). However, the smaller vessels and vessels without lice treatment equipment are assumed to consume less fuel when performing services as they don't use as much fuel consuming equipment. Therefore, the large vessel with lice treatment equipment will be assumed to use 100 litres per hour and medium vessel with lice equipment will be assumed to use 80 litres per hour. While the large, medium and small service vessels without lice treatment equipment will be assumed to consume 70 litres per hour, 70 litres per hour and 60 litres per hour in average. Average meaning the average of both transit and working states. Table 14 shows the assumed fuel consumption for the service vessels.

Table 12: Fuel Consumption

Vessel Type	Fuel consumption [litres/hour]
Small service vessel	60
Medium service vessel	70
Large service vessel	70
Medium service vessel with lice equipment	80
Large service vessel with lice equipment	100

The price per litre of fuel is roughly 10 NOK, and this will be used as fuel price to determine voyage specific costs (CircleK, 2017: YX, 2017)).

Since the fuel costs are assumed to be 80% of the voyage specific costs the voyage specific costs per hour for the different service vessels are as shown in Table 13.

Table 13: Voyage Cost Service Vessels

Vessel Type	Voyage costs [NOK/hour]
Small service vessel	750
Medium service vessel	875
Large service vessel	875
Medium service vessel with lice equipment	1000
Large service vessel with lice equipment	1250

These costs will be multiplied by the number of hours the vessels spend on servicing loops, to find the variable costs of using the vessels. The variable cost could be divided into cost of transit and cost of performing tasks, but since the cost of performing tasks have not been investigated an average cost of time spent is used instead.

Fuel consumption for large and small well-boats is between 300 and 400 litres per hour, independent of whether they are in transit or performing tasks (Industry Source, 2017a). Large well-boats will be assumed to consume 400 litres per hour and small well-boats will be assumed to consume 350 litres per hour. With the assumption that 80 % of the voyage costs are fuel costs, and the fuel price assumed to be 10 NOK/litre, the voyage costs per hour will be as shown in Table 14.

Table 14: Voyage Cost Well-Boats

Vessel Type	Voyage costs [NOK/hour]
Small Well-Boat	4375
Large Well-Boat	5000

As mentioned in the problem description, there are 13 different tasks included in this study. The duration of a task is often dependent on the vessel type used to perform the task, the number of cages at a location and individual factor on the different location. Lice treatment will be assumed to be done for five cages at the time. This is because the carrying capacity for hydrogen peroxide is assumed to only be enough to carry out treatment of five cages, and since it is common for only parts of a location to have a lice count of over 0.5 lice per salmon in a few cages at the time.

The duration of a lice treatment will also include six hours of disinfection of the vessel. Small well-boats will spend much more time on a lice treatment than a large well-boat. This is because a large well-boat can treat a whole cage at the time, while the small well-boat can only treat half. Therefore, the lice treatment support task will be divided into three different tasks depending on which vessel type it being supported. The rest of the tasks will be assumed to have the same duration regardless of vessel type performing the task. The miscellaneous task is only included to account for tasks that are not defined. The duration used in the modelling for each task is a shown in Table 15.

When deciding how many hours the vessels can operate during a time period of half a year, some assumptions have to be made. One of these is how much of the time the vessel types are unable to perform tasks due to the weather. This question was addressed in the problem description. Furthermore, the medium and large service vessels with lice equipment and both large and small well-boats are assumed to be able to work 24 hours/day. While all regular service vessels can operate 16 hours/day. The reason for the service vessels only being able to work 16 hours a day, is because most service tasks are conducted during the day. The service vessels with lice equipment have a 24 hours/day capacity, since lice operations are conducted on a 24-hour basis (Industry Source, 2017d). In addition, a week will be deducted from the available time each period to account for maintenance or other disturbances. The resulting hours per time period both before and after the weather reduction is shown in Table 16.

Table 15: Task Durations Used in Computational Study

Task type	**Task Duration**
Transport Salmon	4 hours + transit time
Transportation of smolt	5 hours loading + 1 hour unloading + transit time
Loading salmon support	4 hours
Lice treatment	26 hours for large well-boats 46 hours for small well-boats 51 hours for large service vessel with lice equipment 71hours for medium service vessel with lice equipment
Support lice treatment large well	31 hours/location
Support lice treatment large service/ medium well	51 hours/location
Support lice medium service	76 hours/location
Mooring tasks	48 hours/location
Wash nets	4 hours/cage
Remove and replace nets	4 hours/cage
Disinfect location	6 hours/cage
Anchor inspection	4 hours/location
Remove old location	12 days/location
Lay out new location	16 days/location
Miscellaneous	10 hours/location

Table 16: Operating Hours Available per Time Period

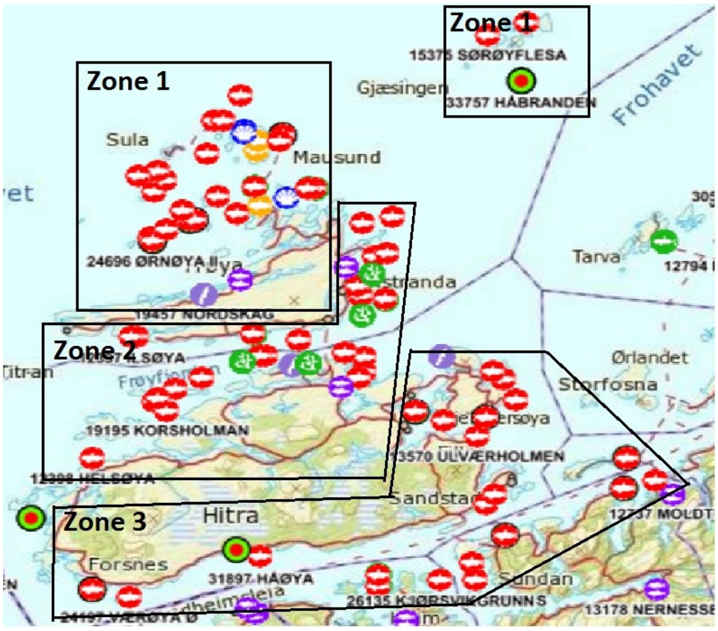
Vessel type	Gros Hours	Net hours' summer	Net hours' winter
Small service vessel	2808	2761	2257
Medium service vessel	2808	2789	2468
Large service vessel	2808	2797	2550
Medium service vessel lice	4212	4183	3702
Large service vessel lice	4212	4195	3825
Small well-boat	4212	4195	3959
Large well-boat	4212	4195	3959

5.1.2 Locations and Demand

For the computational study the region of Sør-Trøndelag, with an emphasis on Hitra and Frøya has been chosen. This is due to the important position of Hitra and Frøya in the aquaculture business, and that the industry contacts used to obtain information for this study are based in this region. Only salmon/trout location are included in this study. The location on Hitra and Frøya have been divided into three zones serviced by one base each.

The locations included in this study are shown on the map in Figure 6

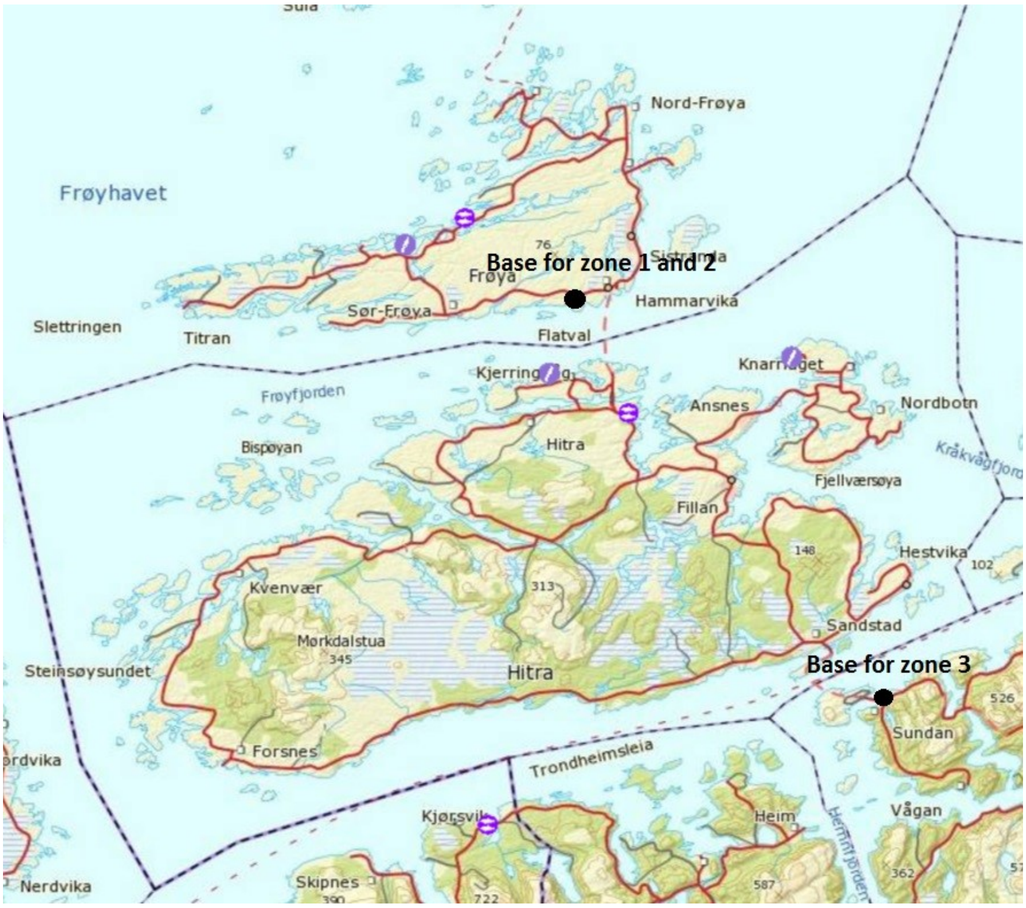
Figure 6: Map of Farming Locations, red locations are the salmon/trout location included in the study.



Source: Fiskeridirektoratet, 2017a

Each zone contains about 20-25 location, adding up to a total of 65 locations. Every location in each zone is assumed to get the smolt from the same location, and to deliver salmon to the same processing facility. This can be changed by simply changing the duration of the transportation of smolt and transportation of salmon task for the individual location. In addition, a more remote location is added in a separate zone to illustrate a more exposed farming location, making the total number of locations 66 divided into 4 zones. Figure 7 shows the placement of the bases used in this study.

Figure 7: Map with the locations of bases.



Source: Fiskeridirektoratet, 2017a

This example case does not distinguish between which locations are owned by which salmon producer. If the model was to be used by a real company such as Salmar, for a real problem, they would probably only include the locations which are owned by them. Furthermore, they could include all locations they plan to use in the future.

Each location has its own maximum allowed production volume, based on the number of licenses they hold. The production volumes allowed for each location can be seen in Appendix II. All locations are assumed to have the same demand for service tasks, with a few exceptions, and the frequency of which these tasks need to take place is presented in Table 17.

Table 17: Frequency of Demand for each Task used in Computational Study

Task Type	**Frequency Summer**	**Frequency Winter**
Lice Treatment	Twice a month	Once a month
Mooring work	Every six months and three months after a new installation	Every six months and three months after a new installation
Wash nets	Once a week	Once a month
Remove/replace nets	Before and after fallowing	Before and after fallowing
Disinfect location	Before fallowing	Before fallowing
Anchor inspection	Once a year	Once a year
Remove old location	Once if location is removed	Once if location is removed
Install new location	Once if new location is opened	Once if new location is opened

Transportation tasks are not included in Table 17, as the frequency of the transport tasks are dependent on the capacity of the well boats. However, Transportation of salmon will only be assumed to be required every fourth time period as the life cycle included the fallowing period will take about two years. In the time period following time period with salmon transportation, smolt transportation will be demanded. To convert the smolt demand into equivalent units as the salmon demand, the smolt carrying capacity of “Ro Master” has been used. “Ro Master” can carry 1000 000 smolt, this corresponds to five cages as the maximum allowed limit is 200 000 individuals per cage (Rostein, 2017: Nærings- og fiskeridepartementet, 2008). Five cages with an assumed capacity of 780 tonnes corresponds to 3900 tonnes of produced salmon, this means that to deliver smolts corresponding to 3900 tonnes of production one needs 380 tonnes salmon equivalent of carrying capability.

In order to reduce the problem size, the locations in each zone are merged into sets of “super locations”, which contain 1-6 farming locations depending on how close the locations are to each other. This reduces the number of locations to 19. The locations included in each “super location” can be seen in Appendix II. The service demand of the “super locations” will be the sum of demands of the locations contained within the “super locations”. This measure is assumed to have little effect on the solution of the problem, since the transit distances from location to location within the zones are very short, and will have little impact on the amount of time spent by the vessels. The average number of cages at the location will be used to determine the duration of the tasks with cage number dependent durations.

Increases in future demand and production volumes can be illustrated in the model by increasing the volumes and demand at one or more of the locations already included in the model, if the new demand is located at a similar distance from the base as any of the locations already included. The demand for installing a new location should be used to simulate the installation of a new set of cages, and similarly if a location is to be removed the removal demand should be used to illustrate this. However, if production is to be increased for a location which is more exposed than today’s locations, a “dummy” location with a longer transit distance can be included in the loop generation, enabling an increase in demand for services at more exposed locations. This means that the loop generation can include possible future locations, which can be included in the optimization model by including a demand for services at these locations in certain scenarios. For the scenarios used in this computational study, an increase in production volumes in sheltered waters will be handled by increasing demand at existing location. While an increase in exposed fish farming will be handled by including a location with a longer transit distance, to illustrate possible future exposed locations.

The service demand for the” Ocean farming” cages and “Havfarm” cages will be assumed to only be transportation of smolt and salmon, and possibly some miscellaneous service operation. While “Aquatraz” and “Egget” will be assumed to also have a demand for mooring and anchor inspection.

5.2 Modelling Step 1: Loop generation

The optimization model is based on assigning vessels to service different loops containing a set of tasks. This is done instead of having routing constraints included in the optimization model. The reason for this is that the optimization model itself can be written much simpler when there are no routing and no subtour constrains included. It also makes the model more flexible since no significant changes need to be done to the optimization model itself to include new vessel types, new demands or new routing restrictions. However, this choice means that an additional model for generating the loops needs to be created.

In a loop, each task can only be serviced once, and every loop must end where it starts. The locations are divided into zones, and it is not possible to travel from a location in one zone to a location in another zone. By doing so the number of possible combinations drops significantly, and the number of loops becomes more manageable. Since the loops are assigned to a type of vessel and not an individual vessel, the time it takes to travel between the different starting point of the loops are not included. This can be seen as an optimistic assumption since this excludes traveling the traveling time from base to base. However, even if the same vessel type services two loops far away from each other it may be done by two different vessels. Furthermore, the loops force the vessel to return to the port of origin even if this is less time efficient than sailing to another destination directly. The vessels may, in reality, need to return to shore less often than the loops dictate, making the assumption pessimistic to some extent.

The loop generation model is constructed as a tree search algorithm, and is programmed in MATLAB. The scrip read its input from an excel spreadsheet. The input for each vessel type consists of transit time from base to the different location, a transit time matrix from task to task, the duration of each task, latest time a task can start and which tasks can be included in the same loop. The tasks a vessel is unable to perform is given a latest starting time at zero hours, this excludes the task from all loops created for that vessel type. The task duration is given in hours for each task a vessel can perform at each location. The latest task start does also limit the number of tasks included in each loop. The latest start time makes it impossible to perform a new task after a time-consuming task is done, so that the vessel needs to end the loop and start a new one. Figure 8 shows an example of some of the input used in the loop generation.

Figure 8: Example of input for loop generation

		Task number	Location	Latest start	Task Duration
1	Transport Salmon	1	1	0	99999
2	Transport smolt	2	1	0	99999
3	Lice Treatment	3	1	0	99999
4	Mooring	4	1	12	48
5	Anchor	5	1	12	4
6	Remove cage	6	1	12	288
7	Lay out cage	7	1	12	384
8	Replace nets	8	1	12	26
9	Disinfect Location	9	1	12	40
10	Wash nets	10	1	0	99999
11	Lice support LW	11	1	0	99999
12	Lice support MW LS	12	1	0	99999
13	Lice support MS	13	1	0	99999
14	Load support	14	1	0	99999
15	Misc	15	1	12	10

The data in Figure 8 is an example for a large service vessel. The latest start times set to zero means the large service vessels cannot perform tasks such as net wash or salmon transport. In addition to the input shown in Figure 8 the transit time from base to each task, and the transit time between each task is also included. To make sure that a vessel does not travel between tasks that are mutually exclusive or in different zones, the traveling time between these tasks can be set to zero. Figure 9 shows a simplified pseudo code for the MATLAB script.

Figure 9: Simplified pseudo code for loop generation

-For all *Tasks*
  -If *travel time to task is bigger than 0 and smaller than latest task start, create a loop with the task and update the time counter.*
   -**While** *the number of tasks in the loop is lower than the maximum amount*
    -**if** *check if the time plus the traveling time to another task is bigger than 0 and smaller than latest task start, then add the task to the loop and update the time counter.*
-end

The actions described in Figure 9 is repeated for all the vessel types. Since this loop generation does not distinguish between two loops with the same tasks in a different order, only one of such loops will be saved and the others will be removed. After the loops are created and only the unique loops are left, the loops and the duration of the loops are sorted in the manner of which they are read by XPRESS IVE and printed to a text file. The MATLAB script is found in Appendix III. The spreadsheet used as input for the loop generation in this study can be found in Appendix III.

The loop generation script can generate hundreds of thousands of loops within minutes. However, since there are decision variables for the number of times a vessel type services a given loop in a given time step, the number of decision variables explodes if the number of loops gets too high. This is even worse for the second stage variables as they are created for each scenario as well.

To test how the number of loops created affects the time it takes to solve the optimization model, a test with all 19 "super locations", eight time steps divided into four in stage 1 and two in stage 2 and three scenarios was solved with two different loop generation results. For the first loop generation, only two tasks were allowed in each loop, this gave a total of 7428 unique loops. The time windows applied when generating the loops have also been used to reduce the number of feasible loops. For the second loop generation, some of the service vessel types were allowed three tasks in each loop, giving a total of 35 225 unique loops. The number of loop service variables for the first and second stage for both the loop generation runs are shown in Table 18.

Table 18: Number of loop service variables for two different number of loops

Number of loops	Stage 1 loop service variables	Stage 2 loop service variables
7428	207 984	207 984
35 225	986 300	986 300

The optimal solution to the two problems differed with less than 0,017% of the optimal solution value. This is well within what can be considered sufficiently small difference to justify only considering the 7428 loops. This is due to the uncertainty regarding all the input parameters being much greater than 0,017%. Furthermore, the results show the same fleet composition in both cases, which is the most important part of the solution. The reason for the difference in cost being so small is most likely due to the transit times between the tasks and from the base to the tasks are very short in comparison to the task durations. The computational time of solving the problem with 35 225 loops is several times greater than solving with 7428 loops. For these reasons, the loop generation settings generating 7428 loops will be used when testing the optimization model with different scenarios.

5.3 Scenarios

The first stage will consist of four time steps, as this will allow for all locations to complete one production cycle, ensuring that the fleet in the first stage at least is capable of performing today`s tasks. This stage is used to create an initial fleet, and make decisions in regard to ordering vessels for the second stage.

The national production volume of salmon in 2015 was about 1.38 million tonnes (SSB, 2016). To reach the aim of 5 million tonnes by 2050 the production must increase by about 7.5 % of the 2015 production volume every year. An increase of 7.5 % of the 2015 volume every year will be assumed to be a high increase scenario. The increase in production volumes will be divided between growth in shelter locations using technical solutions such as “Aquatraz” or “Egget”, and more remote locations illustrating the “Ocean Framing” or “Havfarm”. A 7.5 % growth will not be assumed possible with a growth in conventional cages.

The medium scenario will be assumed to be with a 3.75 % of the 2015 production volume a year. The increase in production volumes will be handled the same way as on the high scenario.

For both the high and the medium scenario the increased volumes will be assumed to have no effect on the need for lice treatments, as this problem will be assumed to be non-existent for the new locations. The same for net wash and replacement and washing of locations. Furthermore, there will be assumed to be no need for support when loading the well-boats, as all the proposed future concepts have an automatic loading mechanism.

The low scenario will be a scenario with no increase in production volumes, and the same kind of production as today.

A very low scenario will be with 1 % annual decrease, with conventional production. The very low scenario will also include a 25 % increase in lice treatments.

The location used in this study are all the 18 “super locations” with an addition of one more remote location to illustrate more exposed farming. The total allowed production volume for these locations is about 275 000 tonnes (BarentsWatch, 2017). This means that the annual increase and decrease in production volumes in the different scenario types are as shown in Table 19.

Table 19: Change in production volumes in each scenario

Scenario type	Change in production volumes [tonnes/year]
High	21 000
Medium	10 500
Low	0
Very low	-2 800

The probability of the different scenarios types, high, medium, low and very low, will be assumed to be 25% each. This will make the expected value of the future growth 7125 tonnes a year, corresponding to an increase 2,63% of the initial production volume every year.

5.4 Results from the Scenario

This section will present a solution to a stochastic programming problem using the four scenarios presented in the previous section. The problem will have four time steps in stage one and four time steps in stage two. The reason for only four time steps in the second stage is because the longest delivery time of a vessel is assumed to be three time steps in this example, and the fact that the second stage is only included to ensure a better basis for deciding on the first stage variables. XPRESS IVE was used to solve the problem, and the script can be found in Appendix III. The model used is basically the same as the mathematical model shown in Chapter 4 with a few small exceptions to fit the scenarios used. Since location 19 and 9 is assumed to be locations with new technical solutions in scenario 1 and 2 these locations will not require support for loading salmon in scenarios 1 and 2.

No initial fleet is assumed when solving the problem. Therefore, the delivery time for vessels in the first time period is zero, to allow a fleet to be generated in time to serve the demands of the first time period.

The sum of all demands in the first stage of the problem is shown in Table 20.

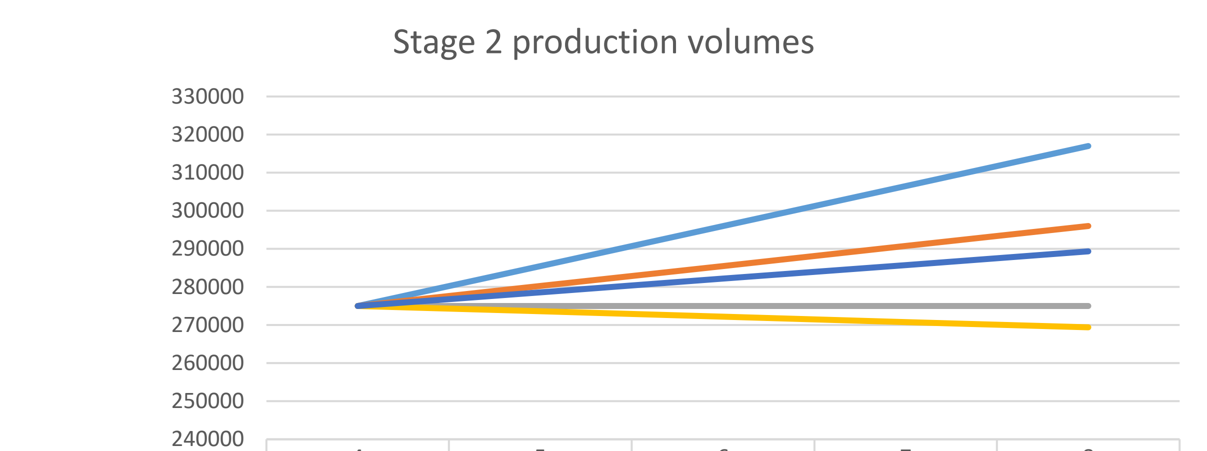
Table 20: Suma of demand for each task in the first stage

Task type	Time step	Demand
Transport salmon	1	102570
	2	64480
	3	42120
	4	63180
Transport smolt	1	6156
	2	9994
	3	6283
	4	4104
Lice Treatment	1	792
	2	396
	3	792
	4	396
Mooring	1	66
	2	66
	3	66
	4	66
Anchor Inspection	1	32
	2	34
	3	32
	4	34
Remove and Replace nets	1	48
	2	42
	3	16
	4	26
Disinfect Location	1	24
	2	21
	3	8
	4	13
Wash nets	1	1716
	2	396
	3	1716
	4	396
Miscellaneous	1	264
	2	264
	3	264
	4	264

The demand for lice and load support is a derived demand originating from the demand for lice treatment and transport of salmon, and is treated special restriction and do not have their own demand. Furthermore, no locations are assumed to be installed or removed in the first stage, leaving these demands to zero as well

For the scenarios, the development of the production volume will be as described in the previous section and the development will look as shown in Figure 10.

Figure 10: Production volumes development for each scenario



	4	5	6	7	8
Scenario1	275000	285500	296000	306500	317000
Scenario2	275000	280250	285500	290750	296000
Scenario3	275000	275000	275000	275000	275000
Scenario4	275000	273600	272200	270800	269400
Expected Value	275000	278587,5	282175	285762,5	289350

Time step 4 is the last time step of the first stage and is only included in Figure 10 to show the starting point of the development in the scenarios. The increased production volumes in scenario 1 and 2 will be assumed to be divided equally between location 9 and 19, which illustrates shelter and exposed locations. In these scenarios, there will be no need for loading support for location 9 and 19 since they will be assumed to have new automatic loading solution. Furthermore, location 19 will only have a demand for the transportation tasks, anchor inspection and miscellaneous. This is due to the rest of the tasks being either unnecessary for the new larger concepts or not possible for conventional service vessels to undertake. Location 9 will have a demand for installation of locations and mooring in addition to the tasks location 19 has a demand for. Scenario 4 will in addition to having a decrease in production volumes also have a 25 % increase in demand for lice treatment at all installations. A 25 % increase in lice treatment demand might not be particularly likely. however, it is till included to increase the difference between the scenarios. While scenario 3 will have the same demands as the first stage. The demand used in both stages can be seen in Appendix III. The solution to the problem is shown in Table 21

Table 21: Optimal solution and fleet composition for the stochastic problem

Vessel type	**End Stage 1**	**Delivered at start of second stage**	**End Stage 2**			
		Scenario:	1	2	3	4
Small well-boat	0		0	0	0	0
Large well-boat	5		5	5	5	5
Small service	35	9	35	36	36	43
Medium service	2		2	2	2	2
Large service	0	3	0	0	0	1
Medium service lice	0		1	0	0	0
Large service lice	1		1	1	1	4
Optimal Objective value			**2 317 030 000 NOK**			

This problem had a total of 6 664 possible loops making the number of loop service variables in the first stage 186 592 and the number in the second stage 746 368.

The solution shows that the increase in production volumes have very little impact on the fleet composition, as the number of well-boats remains the same for all the scenarios. However, the change in lice treatment demand increases the number of large service vessels with lice treatment equipment for scenario 4, with a corresponding increase in small service vessels. The solutions to the first stage and scenario 1,2 and 3 shows that the preferred lice treatment option in these cases are the large well-boat. This seems reasonable since the treatment with large well-boat is much quicker that with the other options, and the well-boats probably have some excess capacity after all the transporting tasks are done, since no new well-boats are needed to handle the increase in transport demand in scenario 1. The other mean for treating lice chosen by the model, is the large service vessels with lice treatment equipment. The use of large well-boats and large service vessels to remove lice corresponds well with the way most of the lice treatment seems to be done today.

Solving the problem with the stochastic model to get the optimal solution takes several hours. However, due to the amount of uncertainty regarding both demand, task durations and the future scenarios, it can be argued that finding the exact optimal solution is unnecessary. If a maximum gap between the best bound and the best solution is set to 2% then the solver spends about six to seven minutes. For the level of uncertainty in this particular example, a

2% maximum gap between the best bound and the best solution would be well within acceptable limits. The fleets chosen in the first stage with a 2% allowed gap only differs by one small service vessel being substituted by a medium service vessel, making the fleet size decisions very similar for the two different solver configurations. This further justifies the use of a 2% gap between the best bound and the best solution. However, when calculating the value of stochastic programming the optimal solution was used, in order to give an exact answer.

5.4.1 Value of the Stochastic Solution

To evaluate the value of using a stochastic model, VSS was calculated. To do this the solution to the expected value problem was found, using the weighted average demand for the second stage. Then the first stage solution from the EV is used as the initial fleet to solve the second stage for each scenario. By adding the weighted objective value of all the four cases together, the EVV is found. However, by using the first stage solution of the EV as the initial fleet for scenario 4 no feasible solution could be found. This is because there are no options included for buying second-hand ships, or chartering vessels in or out making the fleet unable to meet the demand of the first time step in scenario 4. Therefore, the scenario 4 case had to be solved with no initial fleet to find a cost for this scenario. Then the cost of changing the first stage EV solution fleet into the optimal fleet for scenario 4 was added to the cost of scenario 4. This added cost of converting the fleet can be seen as a punishment for not being able to service the tasks with the first stage solution from the EV problem. The resulting EVV, SS and VSS values are shown in Table 22.

Table 22: Value of the stochastic solution

EVV [NOK]	SS [NOK]	VSS [NOK]	VSS [% of SS]
2 361 142 500	2 317 030 000	44 112 500	1.9

As seen in Table 22 the stochastic solution is 1.9% better than solving the deterministic expected value problem. However, the uncertainty relating to the inputs used in the model would make a 1.9% difference quite insignificant. Furthermore, the 1.9% is mainly due to the punishment for not being able to solve scenario 4 with the deterministic problem. This indicates that there is little need for using a stochastic model for this specific instance, since the solutions obtained had very similar objective values, and the first stage fleets were also very similar. However, the EVV solution failed to find a feasible solution for the last scenario, indicating that the stochastic solution is more flexible.

The scenarios used for this test weren't very different in nature, and the solutions to each scenario are therefore quite similar. Therefore, is it to be expected that the value of the stochastic solution is low. If more dramatically different scenarios were used, the value of stochastic programming would probably increase.

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6. Discussion

This chapter will discuss some of the features in the stochastic model, the modelling approach, possible adaptions and applications of the model presented in this study. Furthermore, this chapter will also briefly discuss some of the input used in the model.

6.1 Input and Scenarios

For this study, most of the information about the different main tasks performed by service vessels and well-boats was gathered through contact with industry sources. After establishing the main categories of services, both service vessel operators and aquaculture installation owners were asked about the frequency and duration of the different task types. This revealed that there is a significant variation in both the frequency and the duration of each task, and there was also not total a consensus amongst the industry sources regarding the lower and higher bounds of frequency and the duration for many of the tasks. This has led to the assumptions taken regarding frequency and demand being very uncertain. Furthermore, there might also exist tasks that are important to the real-life problem that have not been included in the model. However, the aim of this study is to develop a suitable modelling approach to the strategic fleet size and mix problem for well-boats and service vessels in the aquaculture sector, and not to find an actual solution. For the purpose of developing a model, and finding ways to include different tasks, the input collected is of sufficient quality. Changes in the duration and frequency of the tasks will have little or no impact on the modelling approach, but the inclusion of new task types, new vessel types will require some adjustments to the model. However, the structure would most likely not need to be changed.

The scenarios developed in this study are only used to show how the uncertainty can be included in the model, and how different scenarios can have different special restrictions and demands. This illustrates some of the flexibility of the modelling approach. However, neither the scenarios or task durations or frequency used to make the example in this report will give an accurate description of the actual real-life problem, but it gives a sufficient basis for the development of the modelling tool.

The costs used in the model are based on newbuilding prices, fuel consumptions and salaries. These inputs and the selling prices are included to be able to test the model. Therefore, only one selling price is assumed for each vessel, and are not subject to change in relations with the changing scenarios or number of vessels sold and bought in this particular example. The inclusion of changing vessel costs or selling prices could be added to the model to give more realistic cost estimates. This could be done by simply changing the set of vessel prices used in the model from a one-dimensional array, to a matrix with indices for time steps and scenarios. This would make the vessel prices vary with time and scenarios, the same could be done with the selling prices. Furthermore, a maximum number of vessel bought and sold at a certain price could be imposed. The voyage specific costs could also be subject to changes in the fuel price from scenario to scenario if desired. However, none of these changes in prices for the different time steps or scenarios will affect the structure of the model, but it would require a thorough investigation of the service vessel and well-boat market. This study has not had a focus on the cost elements. This has led to these variable costs being ignored for the purpose of keeping the model as simple as possible, while knowing that the inclusion of these elements would not change the structure of the model.

6.2 The Modelling Approach, Flexibility and Applications

The modelling approach used in this study is a stochastic two-stage model, with a separate loop generation model. The separation of the loop generation makes the model more flexible, as several analyses can be done with the same set of loops. This means that most of the input data can be changes without having to run the loop generation more than once. It also makes it easy to include new tasks and location in the loop generation model without having to apply changes to the optimization model. If all task types and locations included in any scenarios are implemented in the loop generation, the optimization model can be used to asses any scenarios desired. The problem can then be scaled up and down by setting the demand for a location back and forth from zero to and actual demand, without running the loop generation again.

To include a new task or a new location, they can simply be included in the loop generation input, and a new set of loops including the new task or location or both can be generated. If a new vessel type is to be included, a new section can be added in the MATLAB script similar to the sections generating the loops for each of the other vessel types. All of these changes can be done in a matter of minutes, and no changes will necessarily have to be done to the optimization model, unless the new task is of a different nature than the once already included. This separation between the two modelling stages makes the model highly adaptable, and gives good flexibility for including new tasks, location or other features to the model.

The model does only include one acquisition method for new vessels, namely new buildings. The reason for only including one acquisition method is that no specific information about the second hand and chartering markets have been collected. This is chosen because the inclusion of other means of acquisition would not change the model structure significantly, and cost specifics has not been the focus of this study. Chartering options can be included by adding two new integer variables, z_{vt}^{CI} and z_{vt}^{CU} , and two new parameters, C_{vt}^{CI} and R_{vt}^{Cu}. The addition to the objective function could be:

$$\sum_{v \in V} \sum_{t \in T} C_{vt}^{CI} z_{vt}^{CI} - R_{vt}^{Cu} z_{vt}^{CU}$$

Where C_{vt}^{CI} is the cost of chartering inn a vessel of type v in period t and R_{vt}^{Cu} is the revenue of chartering out a vessel of type v in period t. z_{vt}^{CI} and z_{vt}^{CU} would be the number of vessels chartered inn and out in the time period respectively.

The fleet capacity restriction would have to be changed to include the chartered vessels.

$$\sum_{r \in R} T_{rv} x_{rvt} \leq \mathrm{T}_{vt}^{o}(Z_{vt} + z_{vt}^{CI} - z_{vt}^{CU})$$

There would also need to be included a restriction to make sure that the number of vessels chartered out does not exceed the number of vessels in the fleet.

Second-hand ships could be handled in a quite similar manner as the new buildings, but without including a delay between ordering and delivery.

To include additional task specific restrictions ensuring the number and type of vessels assigned to the task are sufficient, the same approach as the one used on the lice treatment, lice support and loading support can be applied. Furthermore, as an example of scenario and location specific constraints, the example problem solved in the computational study included the possibility of not needing loading support at specific locations in specific scenarios.

This modelling approach could be applied by salmon producers wanting to reduce the cost of servicing the demand of their farming locations. Then the model could be used to include all their current and planned locations, and all the tasks they wish to include and using their own fleet as the initial fleet. Furthermore, the model could be of interest to a ship-owning company with a long-term contract with a salmon producer or who just wants to evaluate how the future demand for vessels might be, to be able to buy the right vessels at the right time.

6.3 Model Performance

Finding the optimal solution to a large problem with the stochastic model can take several hours. However, if a gap between the best bound and the solution found is allowed the solver time is reduced to an acceptable level. This may seem as less than ideal at first glance, but since there will always be several elements of uncertain in any stochastic model related to the input values and demands used in the model, the optimal solution may not necessarily be any better than a solution with a few percent gap between the best bound and the solution found. Because of the short computational time needed when a few percent gap between the best bound and best solution is allowed, the model can be considered efficient enough to solve.

The value of the stochastic solution found in the computational study was quite low. However, one of the scenarios could not be solved when applying the first stage of the EV problem, indicating that the stochastic solution is more flexible. Furthermore, if more dramatically different scenarios were used in the second stage, the value of the stochastic solution would be likely to increase. In cases with little difference between the EV demand and the demand in the scenarios a deterministic approach would most likely be more applicable. The stochastic model can easily be converted to a deterministic model if a deterministic approach is desired, or if there are no uncertain scenarios to be analysed.

7. Concluding Remarks

In this report, an optimization model for the maritime fleet renewal problem in the aquaculture sector is presented. The model is made to find a fleet composition able to perform all the service tasks and fish transport needs of aquaculture locations, while minimizing costs and taking the uncertain future into account. With a number of new concepts for fish farming on the doorstep and several different approaches to lice treatment, a decision-making tool could prove valuable for different players in the aquaculture sector.

The model proposed is a two-stage stochastic programming model, where scenarios are used to represent future uncertainty. The modelling is divided into two modelling steps, one where all candidate loops are created, and one where the optimal fleet size is chosen. This separation is done to simplify the optimisation model, and to make the model more flexible.

To test the model's performance, it was implemented in XPRESS IVE and MATLAB. The model was then run for a test case and the solution was compared to that of the expected value problem to find the value of the stochastic solution. The test shows that the model chooses a fleet composition which seems reasonable, and that the stochastic model provides a more flexible solution than the one obtained using a deterministic approach. The value of stochastic solution however, was less than 2% of the objective function value. This is most likely due to all scenarios in the test case being quite similar to the expected value problem, resulting in quite similar first stage decisions. The aim of this study was not to find a solution to a specific problem, but to propose a modelling approach to the MRFP in the aquaculture sector, therefore the flexibility of the model and the possible applications are more importation than the results of the computational study.

The model presented can be a good basis for further studies on the MFRP in the aquaculture sector. To the extent of the author`s knowledge this is the first model proposed for this problem. To make the model applicable to specific scenarios and cases more task, vessel and demand data will have to be collected. However, the modelling approach provides a great deal of flexibility with regards to implementing changes as more data is collected. The model proposed can, therefore, be concluded to be an interesting contribution toward developing efficient fleet renewal models for the aquaculture sector.

A modelling approach such as the one presented in this study could be applied by salmon producers wanting to reduce the cost of servicing the demand of their farming locations while considering possible future development, or vessel owners looking for potential future investments.

8. Further Work

To the author`s knowledge this study presents the first model for a MFRP in the aquaculture sector. Since the topic is new, there are a lot of possibilities for future work. Some of these possibilities will be presented in this chapter.

Task Duration and Frequency

It would be very interesting if a future study could be conducted in collaboration with a salmon producer. This is because the salmon producers most likely have records of how often different tasks have been conducted at their farming location in the past. This could make it possible create probability distributions for the frequency of each task type. This could also lead to the inclusion of other tasks than those used in this study. Historical data about task durations could also be collected to find more realistic task durations. This in combination with future work on establishing vessel capabilities could make the loop generation and demand more realistic, and make the model able to yield better results.

Other Means for Acquiring and Disposing of Vessels

Future studies could consider the inclusion of second-hand vessels, scrapping and chartering options. How charter options and second-hand vessels can be included is mentioned in the discussion. To make these changes the study would need to investigate how the market for service vessels behaves, and investigate how the chartering market works in the sector. Along with these changes, more specifics regarding fixed and variable costs for the vessels should be included since all cost elements should be considered together to gain good results.

Future Scenarios

To make the inclusion of future scenarios as valuable as possible, a thorough study on how the future might look and how this will affect the need for service vessels should be conducted. This would also be valuable for other studies conducted on the aquaculture sector, as the future development in regard to new technical solutions is one of the most importation unanswered questions in the sector.

Deployment Modelling

In order to validate the results of the MFRP model, a deployment model should be made. This can be used to see whether the fleet found in the MFRP model is over or under sized. In the deployment model, some robustness measures should be included to ensure that the fleet from the MFRP model is flexible enough. These measures could be simulation of weather, task frequency and task duration, or the inclusion of a minimum amount of slack in the fleets total time capacity.

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Appendix I-Scope of Work

MASTER`S THESIS IN MARINE TECHNOLOGY

SPRING 2017

For stud.techn. Adrian Stenvik

Maritime Fleet Renewal optimization for the Norwegian aquaculture sector

Background

The aquaculture sector in Norway aim to increase the production five times by 2050. In order for this aim to be reached it is likely that new solutions relating to the future service needs of the sector need to be developed. To support such a development, it could be of value to have a decision making support tool available when strategic fleet renewal decisions are to be made. Such a tool should also be able to consider future uncertainty when supporting the decision.

Objective

The aim of this report is to propose a general formulation of an optimal fleet size and mix models which can be used for service vessels in the Norwegian aquaculture sector. The performance of the modelling approach should then be tested by implementing the model in a solver software

Tasks

The candidate shall/is recommended to cover the following tasks in the project thesis:

a) Present the real-life system
b) Describe the problem which the model shall describe
c) Briefly review other optimization models to understand how other\similar problems have been solved
d) Present a general model formulation for the problem
e) Implement the model in a commercial solver to test the performance of the modelling approach

General

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

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

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

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

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

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

Deliverable

- The thesis shall be submitted electronically:
- Signed by the candidate
- The text defining the scope included
- Any programming scripts or other relevant attachment shall be delivered in a zip file along with the thesis

Supervision:

Supervisor:

Bjørn Egil Asbjørnslett

Co-supervisor:

Inge Norstad (SINTEF)

Deadline: 18.06.2017

Appendix II – Locations, "Super Locations" and Production Volumes

"Super Location" Number	Location ID	Production Capacity[Tonnes]
	12394	4680
	24696	3900
	37197	6240
	28636	5460
1	31959	5460
	33737	3120
	12449	6240
	31557	6240
	36877	3120
2	35377	6240
	12380	1560
	12385	1560
	26775	3120
	33557	1560
3	20559	2730
	10232	7020
	24456	3120
	12435	7020
	34857	6240
	30437	3120
4	14042	4680
	33757	6240
	15375	1560
5	13886	2340
	12397	3900
	12392	5200
	19195	3120
	29056	3120
6	12383	6240
	32677	4680
	30137	3120
	14041	3900
7	12370	1560
	34017	2340
	12406	2340
	12407	1560
8	10240	1560

	33957	4680
	12993	3120
9	12361	3900
	31517	2860
	34597	2340
	12366	2080
10	12357	2860
	24115	7020
11	24197	4680
12	31897	5460
	30257	6240
13	26155	3120
	26135	7020
	13724	2340
14	19115	6240
	19016	6240
	13572	5460
15	13892	3120
	13570	3120
	13503	3120
	13887	5460
16	12348	4680
	13888	3120
	13727	3120
17	35657	5460
	10375	7020
	12784	7020
18	12789	6240
19	Dummy location	

Source: BarentsWatch, 2017

Appendix III – Attachments

Included in the attached zip-file:

- XPRESS IVE code for the MFRP
- MATLAB script used for the loop generation
- Input spreadsheet for the loop generation script
- Input file for the stochastic example problem with four scenarios
- Spreadsheet showing the demand for the stochastic problem
- Description of the notation used in the input documents
- The input document with the loops created by MATLAB
- Academic poster