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Optimization Model Aimed for the Aquaculture Industry for Fleet Composition and Routing of Wellboats

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Preface

This master thesis is the final result of my Master of Science Degree at the Norwegian University of Science Technology. The degree specialization is in Marine Design and Logistics at the Department of Marine Technology. The master is a continuation of the Project Thesis from the fall semester of 2016, and corresponds to a workload of 30.0 credits.

The purpose of the thesis has been to build on the knowledge gained in the project thesis to model the wellboat operations in the aquaculture industry, with the objective to provide an optimization model as a contributing decision-making support tool to be applied for fleet composition and routing in the industry.

I would like to express my gratitude to my supervisor Professor Bjørn Egil Asbjørnslett at the Department of Marine Technology, for his insight and invaluable guidance throughout the work with this master thesis. I would also like to thank my co-supervisor, Inge Norstad, at SINTEF Ocean AS for all his help and advice regarding the model formulation and implementation in Mosel Xpress, as well as for his guidance and problem discussions.

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Abstract

The Norwegian aquaculture industry is continuously seeking further growth, and aims to almost fivefold today's salmon production within the year of 2050. As the aquaculture industry is experiencing remarkable growth and technological development, so does the fleet of wellboats in order to respond to the development and production growth. The wellboats play a central role in the salmon farming industry, and constitute a significant economical investment for the farming companies. It could therefor be of high value to look into a decision making support tool to make and evaluate decisions regarding fleet composition and routing of wellboats in relation to the future transportation demands and requirements. The aim for this study is therefore to look into the modeling of wellboat operations, in order to create an optimization model to provide as a basis for further development of such a tactical decision-making support tool.

The problem for this study is to minimize the costs of operating a fleet of wellboats servicing the required demands in the aquaculture industry within a given area. The focus is therefore on the fleet of wellboats and the service tasks these vessels have to execute. The problem area is reduced to the area around Hitra and Frøya. It is for this area established the scope of locations and production volumes, along with the yearly demands for the different wellboat operations. Three vessel types are established according to size, all with the ability to service all operational tasks. The execution of these tasks is described, together with the assumed associated time-consuming factors.

A literature review is done in order to gain knowledge on similar problems. Literature and research on vehicle routing problems (VRP), pickup and delivery problems (PDP) and ship routing and scheduling problems are studied in order to obtain an idea of how to approach the problem at hand. The model is presented as an arc flow formulation of an industrial ship scheduling problem with full shiploads, with similarities to a VRP with pickup and delivery and time windows (VRPPDTW). This model aims to minimize the total cost of routing the vessels in the available fleet of wellboats, while servicing the required demand. The model is kept simple and generic by moving a lot of data pre-processing into Excel, with the attempt to make it more flexible.

The mathematical model is implemented in the commercial solver Xpress, running multiple demand scenarios to test the applicability of the model. The model is first tested with different seasonal demands in order to find a fleet composition to be suited

for all seasons. Further, the model is run with future additional tasks related to alternating lice demands and the introduction of exposed aquaculture. These scenarios are run in order to establish eventual alterations to the fleet composition due to the change in demand. The first demand scenario resulted in an optimal fleet consisting of at least two wellboats of type 3, and an additional wellboat of type 2. Running the model with the different future demands shows a need to expand the fleet set to handle the seasonal demands. A wellboat of type 3 should either replace the wellboat of type 2, or be added additionally together with a wellboat of type 1, which can be a suitable asset to handle the smaller demands.

The results seem quite reasonable with respect to the fleet compositions chosen for the different scenarios. Most of the scenarios imply the need for new or larger vessels when applying increased service demands or stricter time windows. The routing decisions for each scenario tend to follow the expected sequences in accordance with the transition costs and the time windows set.

Disregarding some shortcomings, the created model for this study is concluded to be a good basis for further development, to possibly become a contributing decision-making support tool to be applied for fleet composition and routing in the aquaculture industry. The approach to simplify the optimization model and focus on making the Excel-file flexible, makes the model quite susceptible for changes. New tasks, vessel types, locations or geographical nodes can therefor easily be added with associated data, without causing any alterations to the optimization model itself.

Sammendrag

Den norske havbruksnæringen søker stadig videre vekst, og har som mål å femdoble dagens lakseproduksjon innen 2050. Ettersom næringen opplever bemerkelsesverdig vekst og teknologisk utvikling, følger brønnbåtflåten opp med tilsvarende utvikling for å tilpasse seg produksjonsveksten. Brønnbåten er en viktig del av verdikjeden i havbruksnæringen, og utgjør en betydelig økonomisk investering for oppdrettsselskapene. Det er derfor av interesse å se nærmere på et hjelpende verktøy som kan bidra med beslutningstøtte angående flåtesammensetning og ruting av brønnbåter i samsvar med framtidige etterspørsler for brønnbåtoperasjoner. Formålet med denne oppgaven er å se på modellering av brønnbåtoperasjoner, for å lage en optimeringsmodell som kan danne grunnlag for videre utvikling av et slikt beslutningsstøtteverktøy.

Problemet i denne oppgaven er å minimere kostnadene relatert til drift av en flåte med brønnbåter, samtidig som alle etterspørsler for brønnbåtoperasjoner innenfor et gitt område er dekket. Fokuset i denne oppgaven er derfor på den eksiterende flåten av brønnbåter, og operasjonene disse båtene må gjennomføre. Problemområdet er snevret inn mot Hitra og Frøya, og det er for dette området etablert omfanget av produksjonsvolum og påfølgende årlige etterspørsler for de ulike brønnbåtsoperasjonene. Brønnbåten er kategorisert etter størrelse inn i tre skipstyper, alle med evnen til å betjene alle operasjoner. Utførelse av de ulike brønnbåtoperasjonene er beskrevet, med de antatt tilhørende faktorene som påvirker tidsbruken.

En litteraturstudie er gjennomført for å opparbeide kunnskap på lignende problemer. Litteratur på ulike ruteplanleggingsproblemer, som vehicle routing problems (VRP) og pickup and delivery problems (PDP), er studert for å danne et bilde av hvordan best tilnærme seg problemet. En modell er til slutt presentert som en arc-flow formulering av et industrielt planleggingsproblem med fulle skipslaster, med likheter til et VRP med henting og levering og tidsvinduer (VRPPDTW). Modellen er holdt enkel og generisk ved flytte mye databehandling inn i Excel, for å forsøke å gjøre modellen mer fleksibel.

Den matematiske modellen er blitt implementert i den kommersielle solveren Xpress, hvor flere ulike etterspørsel scenarier er kjørt for å teste modellens ytelse og anvendbarhet. Modellen er først testet med ulike sesongbaserte etterspørsler for å så bestemme flåtesammensetningen som er best egnet for alle sesongene. Videre er modellen kjørt med fremtidige tilleggsoppgaver relatert til varierende behov for lusebehandling og introduksjonen av eksponert havbruk. Dette ble gjort for å se på forskjeller

i flåtesammensetning grunnet endret etterspørsel. Det første scenariet resulterte i en optimal flåtesammensetning bestående av minst to brønnbåter av type 3, i tillegg til en brønnbåt av type 2. Ved å kjøre modellen med de ulike fremtidige etterspørslene, viste det seg et behov for å utvide flåten. En brønnbåt av type 3 burde enten erstatte brønnbåten av type 2, eller blir lagt til i tillegg sammen med en brønnbåt av type 1, som er et passende tilskudd for å håndtere mindre etterspørsler. Utfallet av kjøringene virker fornuftig med hensyn til flåtesammensetningene valgt ved de ulike scenariene. De fleste scenariene impliserer et behov for nye eller større skip ved økning av etterspørsel eller ved innsnevring av tidsvinduene. Rutingen for hvert scenario viser tendenser til å følge forventede sekvenser og rekkefølger, i samsvar med påsatte overgangskostnader og tidsvinduer.

Sett bort i fra enkelte områder hvor modellen kommer til kort, kan den foreslåtte modellen i denne oppgaven konkluderes med at er et godt grunnlag for videre utvikling av et beslutningsstøtteverktøy som kan bli anvendt for flåtesammensetning og ruting innenfor havbruksnæringen. Tilnærmingen ved å forenkle modellen og fokusere på å gjøre Excel-filen mer fleksibel, har gjort modellen mer mottakelig for endringer. Nye arbeidsoppgaver, skipstyper, lokasjoner eller geografiske noder kan dermed lett bli lagt til eller endret på, uten å måtte endre på optimeringsmodellen i seg selv.

Abbreviations

BREF	Brønnbåteiernes Forening
DARP	Dial-a-Ride Problem
FSMP	Fleet Size and Mix Problem
FSMVRP	Fleet Size and Mix Vehicle Routing Problem
MAB	Maximum Allowable Biomass
mVRPPD	Multi-VRP with Pickup and Delivery
OR	Operation Research
PDP	Pickup and Delivery Problem
RAS	Recirculating Aquaculture Systems
RSW	Refrigerated Sea Water
TAN	Total Ammonia Nitrogen
TSP	Traveling Salesman Problem
VRP	Vehicle Routing Problem
VRPPD	VRP with Pickup and Delivery
VRPPDTW	VRPPD with Time Windows
VRPSPD	VRP with Selective Pickup and Delivery

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Chapter 1

Introduction

The Norwegian aquaculture industry is continuously seeking further growth. Despite this sector´s tremendous growth since the slow commencement around 1970, the industry now aims to almost fivefold today´s salmon production within the year of 2050. If succeeded, the industry will reach an annual production volume of 5 million tonnes. In order to obtain such a strong expansion of the industry, Norway is today faced with multiple challenges. These challenges include environmental issues related to area scarcity, lice and the spreading of other diseases, in addition to the need for new technological solutions. Significant progress is being made related to development of systems and technologies, involving multiple new alternative concepts, to fight these issues. All depending on how these challenges are met and possibly solved, and the following development of the industry, a corresponding demand for wellboat operations is required.

Several hundred farming locations are spread along the coast of Norway, requiring refill of smolt, harvest and transportation of fully grown salmon, and lice treatment of salmon infected by sea-lice. Here the wellboat plays a significant role in servicing the industry with these type of operations. The wellboat industry is developing in correlation with the great expansion of the salmon farming industry and the stricter regulations being set to fish health and welfare. This may lead to wellboats being phased out due to age and lack of technology and equipment, while high new-building activity is initiated to compensate the loss in transportation volume. The wellboat development shows tendencies towards larger and more complex vessels with high-level technology, contributing to maintain a good ambient environment for the fish during the operations of transport, handling and loading. The new regulations, together with the possible future production volumes and tasks, are important aspects when evaluating the future size and composition of the fleet of wellboats. Optimal routing of wellboats is equally essential in order to have a cost-efficient fleet, providing solid routing decisions while minimizing the costs of operating the fleet. A lot of economical savings can be made with improved routing decisions. The better the routing decisions, the better the basis is in order to enhance the fleet utilization with a suitable fleet adapted to handle the alternating demands in the industry.

Optimization is used as a tool to provide aid and support in making decisions regarding real-world problems. An optimization process consists of defining the real problem, simplifying it and creating a mathematical formulation, before implementing and running the model in a commercial solver for further testing and evaluation of the results. Fleet composition and routing and scheduling are essential planning problems in optimization that are gradually becoming more and more of interest in maritime transportation. The extent of optimization and modeling that has been done within the aquaculture industry is however quite limited, and no research papers have been found on the subject up to this date. There is therefore room for further research and investigation on modeling of real-life problems related to wellboats and the aquaculture industry. Good decision tools are valuable in planning problems in the real world. These tools with their contributions can result in reduced fleet size by removing unnecessary and costly vessel capacity, while maintaining efficient routing and operational service by the available wellboats. This can again contribute to significant cost savings.

A background study on wellboats, together with an estimation of the need of wellboats for 2017, were carried out in the project thesis prior to this master. Through the project thesis, and especially the estimation process, valuable information and a logical thinking approach was obtained. The aim for this thesis is to build on the knowledge gained in the project thesis, to model the wellboat operations in the aquaculture industry, and thereby propose an optimization model which can be used as a decision support tool for fleet composition and the routing of wellboats. There is additionally aimed for the model to be run in a commercial solver in order to perform a computational study, where the aim is to look at the applicability of the optimization model, and not to find exact and in-depth solutions to any problem. Testing the model with different scenarios and data, will hopefully give an indication of what the model is able to contribute with, as well as the shortcomings of the model.

This thesis is structured as follows. Chapter 2 gives an introduction to the salmon farming industry and provides background information on the wellboat and its role and use in the industry. This chapter also provides a thorough description of the execution of the wellboat operations, as well the challenges facing the industry and the possible effect. The problem description is given in Chapter 3, describing the simplified version of the real problem. Further will Chapter 4 provide a brief literature review of research done on similar problems. The mathematical formulation of the simplified problem is presented and described in Chapter 5, while Chapter 6 provides a computational study applying the modeling to specific demand scenarios. Chapter 6 also includes a large section dedicated to the pre-processing phase in Excel. The model, its implementation and the main results of the computational study are discussed in Chapter 7. Lastly, the conclusions of the study is presented in Chapter 8, also providing recommendations for further work.

Chapter 2

System Description

This chapter will contribute with all necessary and relevant background information in order to understand the concept of the wellboat, in addition to its position and its use in the value chain of the aquaculture industry. The chapter is based on previous work done in the project thesis, as it is considered relevant as background information for this study. All gained and provided information will contribute with insight in order to build the model described in Chapter 5.

The chapter begins with a description of the salmon farming industry with its value chain, industry players and localization of the industry in Section 2.1. Further on, Section 2.2 continues focusing on the wellboat and its systems and requirements, in addition to the wellboat fleet and the market development. Section 2.3 will present the operational tasks of the wellboat, followed by the challenges facing the aquaculture industry in Section 2.4. This last section also presents how the challenges of the industry possibly will affect the use of wellboats now and eventually in the future.

As the Norwegian aquaculture mainly revolves around salmon farming, the focus throughout this chapter, as well as the rest of the thesis, will be on the salmon farming industry and the related use of wellboats for transportation of salmon. Nevertheless, it is assumed that similar use applies to other species of farmed fish.

2.1 The salmon farming industry

Norway is the second largest seafood exporter in the world, and the world's leading producer of Atlantic salmon. The total harvested quantity of Atlantic salmon was in 2015 approximately 1 234 000 tonnes, resulting in a total export value of about

48 billion NOK (Kontali analyse, 2016). The Norwegian aquaculture has experienced serious growth the last decade, and aims to continue this growth by five folding the production within 2050. The industry constitutes multiple players participating in the different sectors and parts of the salmon farming value chain. All the individual participants of this value chain plays an important role for further growth of the industry.

2.1.1 The value chain

The fully integrated value chain in the salmon farming industry consists of the whole production process from salmon egg to finished product. This involves the processes of smolt production, farming, harvesting and processing, followed by further transportation and distribution to the world's consumers. The complete value chain is illustrated in Figure 2.1.

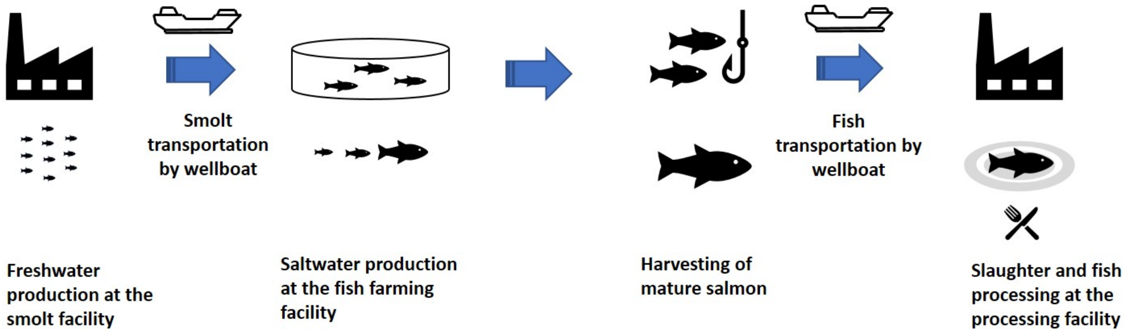

Figure 2.1: Salmon farming value chain

The whole salmon farming process begins on land at smolt plants, where fertilized roe are hatched into tiny fish (fry) in incubation tanks in fresh water. The fish are taken care of in larger freshwater tanks, developing into parr, until they reach a size of about 60-100 grams. At this stage the young salmon undergoes the process of smoltification, gradually adapting from living in fresh water to living in seawater. After this process, the young salmon can be referred to as smolt, and is finally ready to be placed at sea after 8-12 months in freshwater.

The smolts are transported in wellboats out to the sea and kept in farming cages for the salmon to grow. The growing phase takes place at carefully selected locations, providing the fish the best possible environment to grow. Such environments include good flow of water, correct temperature ranges, topography, oxygen content and exposure. Production time in these facilities varies from 12 to 24 months, depending on temperature, genetic potential and the quality of the farming and care of the fish during the period (Lerøy, 2016a). To ensure optimal conditions the environment is carefully monitored by sensors and cameras, ensuring optimal feeding and growth, as well as fish health and welfare.

When the fish have reached an optimal market weight of about 4-6 kg, the salmon is ready to be processed. The fully-grown fish are then being harvested and transported by wellboats from the cage at the farming location to the processing plant for further processing. The fish are normally transported to holding cages outside the slaughterhouse, holding the live fish until it is ready for processing (Lerøy, 2016b) (Marine Harvest, 2017).

Hence, based on this value chain, one can highlight the essential operational tasks of the wellboat to be transportation of live fish. This is either by transportation of smolt from the hatchery out to the farming location, or transportation of fully-grown fish from the farming location to the slaughterhouse for processing. Transportation of live fish will also be executed when the fish needs to be transferred from one sea-site to another, graded or moved internally between the net pens at the sea site, or lastly transportation of fish with highly infectious diseases for slaughter or destruction. In addition to these transportation tasks, the wellboats are also used for treatment against sea-lice and amoebic gill disease (AGD) (Norwegian Veterinary Institute, 2016). The different production phases and operational tasks will be further explained and described later in this chapter.

2.1.2 Industry players, farming regions and locations

The aquaculture industry constitutes several industry players which all contribute and participate within the different parts of the value chain. This, either being industry players or companies directly related to the fish farming process itself, or otherwise related to the aquaculture technology or the shipping of vessels. Additionally, there are several industry players in the form of institutions, activities or organizations playing a huge role when it comes to development and innovation, as well as regulation and management of the fish farming industry.

Most relevant for this study is to look at the industry players related to both the farming and the transportation of salmon, in order to get a better grasp of the structure and composition of the industry. This will also provide with a better understanding as to where the industry, with its companies and facilities, are located.

The fish farming companies plays the most central role in the value chain, and are typically involved with the farming process, fish processing, in addition to distribution and marketing. Ownership in the industry was for a longer period of time heavily regulated, with strict requirements ensuring that no one could have majority ownership of more than one license. Today the industry is dominated by some major players who have up to 20-25% of the Norwegian production volume. This includes major companies such as Marine Harvest, Lerøy, Salmar, Cermaq and Grieg Seafood (Norsk Industri, 2017).

These companies have divisions or subsidiaries with fish farming locations within multiple regions along the Norwegian coastline. Some of these companies, or divisions, are listed below in Table 2.1, together with their number of licenses and annual harvested quantity. The data is taken from "Kontali Analyse 2016", representing data from the year of 2015, which to some extent gives an indication of the bigger farming companies running the industry. With the industry rapidly changing, it is highly possible that the data is not in correspondence with today´s production.

Table 2.1: The dominant Seafood Companies of Norway as of 2016 - kontalianalyse2016

Company	**Licenses**	**Harvest Quantity[tonnes]**
Marine Harvest Norway AS	233	254800
Salmar ASA	111	136400
Lerøy Midt AS	56	71400
Cermaq Norway AS	52	55000
Nordlaks Holding AS	31	40500

As of 2015, there were about 95 farming companies or groups controlling farming licenses along the entire coastline of Norway. These licenses are assigned to approximately 1100 different farming locations, where multiple licenses can be contained within the same location. A standard license corresponds to 780 tonnes, which represents the maximum allowable biomass (MAB) per license at any time. This amount goes for all counties in Norway expect in the regions of Troms and Finnmark, where the MAB per license is 945 tonnes (Kontali analyse, 2016). Hence, will the maximum biomass possibly contained within a farming location be the total sum of licenses times the applied MAB for the given region. Out of the total amount of farming locations, between 500-700 of them are containing fish throughout the year. This gives an average of about 600 active farming locations.

The particular region of interest for this study is the salmon farming industry located in Sør-Trøndelag, which holds about 90 aquaculture locations, mostly concentrated around the islands of Hitra and Frøya. In the area surrounding these two islands there are registered about 65 farming locations, which constitute a great amount of the total farming industry in Norway, representing 20% of the annual harvesting quantity (Norsk Fiskenæring AS, 2016). Figure 2.2 illustrates the high density of on-growing farming sites in the region of Hitra and Frøya, marked in red. Included is also the localization of the slaughterhouses and the hatchery facilities in this area, marked in dark and light purple, respectively.

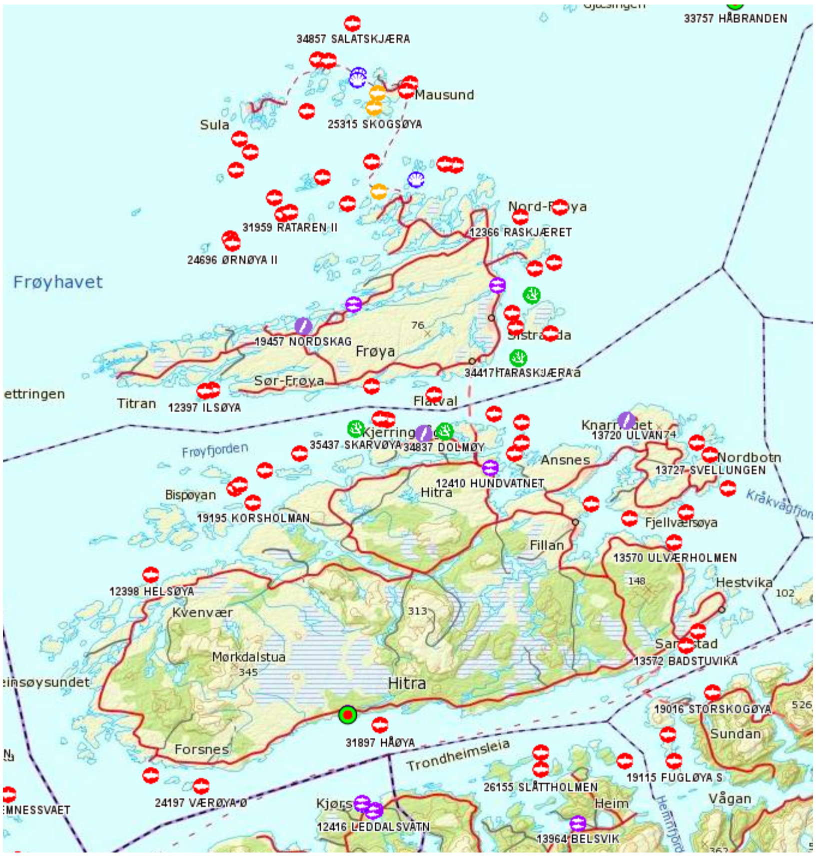

Figure 2.2: Farming locations around Hitra and Froya,Fiskedirektoratet (2017)

Lerøy Midt AS, SalMar ASA and Marine Harvest Norway ASA are three major farming companies with a lot of their production facilities located in this particular region. As one can see from the Figure 2.2, the slaughterhouses are located strategically with respect to the on-growing sites around the two islands. With both huge slaughter and processing plants, as well as access to several smolt plants located within the region, Hitra and Frøya provide and facilitate unique fish farming opportunities.

2.2 The wellboat

Within the aquaculture industry today the vessels used for transportation of live fish are called wellboats. The concept of wellboats originates from the idea to provide a viable transportation of live fish over greater distances while ensuring the welfare, the health and the quality of the fish. This includes all the way from smolt production to fish farming sites, as well as from on-growing sites until the point where the fish can be dispatched to a center of processing. A wellboat is a specialized vessel with live fish containers, better known as wells, as the most distinctive feature of the vessel. The wells are connected to a system of pipes and pumps for re-circulation of transport water, which is essential to ensure a proper and secure transportation of live fish.

Wellboats may either navigate with an open or a closed system, where the main difference revolves around the way the water circulates in or through the wells. A wellboat with a closed system is illustrated in Figure 2.3.

Figure 2.3: Schematic of a wellboat with closed system. Source: Sølvtrans (2008)

Most transportation of live fish combine the use of open and closed transport. The decision of open or closed transport is depending on the bio-security issues associated with the fish group it self, local regulations or risks of contamination with fish pathogens along the transport route (NIVA, 2011). The need for closed systems are related to the passage of transport routes with risk of contamination, in addition to the distance and length of the chosen route. The latter is related to the state of the water quality in the well throughout the transportation, which is associated with the amount of accumulated carbon dioxide (CO_2) and Total Ammonia Nitrogen (TAN) in the well, in addition to, amongst others, level of oxygen, temperature and pH- level. Contrary to the open system, not being able to have continuous exchange of the transport water, the closed systems are dependent on water treatment systems and other technical solutions.

The transportation of live fish is continuously requiring stricter regulations to ensure the well-being of the fish, especially with regards to transportation in closed wellboat systems. Hence, the following listed technical solutions are developed to meet the stricter requirements. Not all of the listed technical solutions are to be found on the existing fleet of wellboats, but due to the stricter regulations the majority will at least be found on the youngest fleet of vessels, as well as the upcoming new buildings.

- Water treatment systems
- Cooling system
- Loading and unloading systems
- Wash and disinfection systems
- Delousing system
- Monitoring system

The main purpose of the applied technology is to maintain a high level of oxygen, remove the accumulated metabolites, counteract the lowering of the pH-level and keep the metabolism low by lowering the temperature.

2.2.1 Requirements

With a particular focus on the wellboat and the transportation of the fish, ensuring a healthy fish is done by complying with recommended standards and requirements in relation to the transportation of live fish and the associated ambient environment. This also includes the processes of loading and unloading the fish. Due to the increased occurrences of infectious diseases being spread along the coast of Norway, the requirements are gradually getting stricter by the day, and by that setting stricter requirements to the wellboats, the routing of the vessels and the technology used in the industry.

One of the important aspect considering the welfare of the fish, is the maximum stocking density (MSD) in the well, given in kg/m^3. These different densities are given in Table 2.2, representing the different stocking densities allowed depending on the live weight of the fish (Sølvtrans, 2010).

Table 2.2: Maximum stoking density

Live weight of fish[kg]	**Maximum stocking density[kg/m^3]**
5.0	125
4.0	110
3.5	100
3.0	90
2.0	75
1.0	60
0.1	40-50

There are several requirements set more specifically to the wellboats and the routing of the different vessels. These mostly revolve around the topic of spreading infectious diseases. As of the 1st of January 2016 new regulations required that all wellboats must have an installed position reporting system and equipment that automatically registers the opening and closing of the valves. The objective of this implementation is the possibility to go over and verify the position of the valves up against the vessels geographical position, and thereby check if the valves have been closed when and where they should have been. This is especially important with respect to clarification of disease outbreaks and the spreading of infections (iLaks, 2016).

New requirements regarding treatment of the transport water will also take effect as of 1st of January 2021, which require all wellboats to be equipped with disinfection systems to disinfect transport water after transporting fish for slaughter. After the treatment the transport water is released at prescribed zones. These zones can be at the slaughterhouse, on the way away from the slaughterhouse, at the new locality before new water is taken in, or at places in agreement with the Norwegian Food Safety Authority (NFSA) (Norwegian Veterinary Institute, 2016). From 2021, with regard to transportation of juveniles or brood fish, all intake water must additionally be disinfected before being pumped into the well.

Due to all the stricter regulations and requirements being set, several of the existing wellboats today will be phased out, especially the vessels being 10-12 years old. This decrease is not seen as a big problem, as the demand of new vessels within the segment is expected to be met by building new and larger wellboats. The wellboat industry has had enormous development the last decade, and the increased use of wellboats for treatment of lice and AGD has sent the demand skyrocketing. The wellboat shipowners are contracting and building as never before, and the upcoming vessels are getting bigger and more modern for each vessel being built (iLaks, 2015a).

2.2.2 The existing fleet of wellboats

In line with the significant growth in aquaculture, the wellboat has increasingly become an important part of the fish farming industry in Norway. The Norwegian fleet of wellboats has evolved to become world leading both in size and technological solutions, and is expanding with significant new building activity. As of May 2017, the registered number of wellboats listed at *Kystrederiene* was stated to be 65, with a total gross tonnage (GT) of 108.813 (Kystrederiene, 2017).

The wellboat owners in Norway are organized into the wellboat owners association, Brønnbåteiernes Forening (BREF). The majority of the existing wellboats are owned by four large companies; Rostein AS, Sølvtrans AS, Norsk Fisketransport AS and Frøy Sjøtransport AS. Focusing solely on these four wellboat companies, an attempt was made to list all of their wellboats with associated descriptive data. In total, these leading companies are together in possession of 50 wellboats with a transport volume of 89.874 m^3. Table 2.3 displays the internal distribution between the four companies, representing each company with their associated fleet size, both with number of vessels and corresponding transport volume. The whole list can be found as an attachment in Appendix B, including information such as the name of the vessel, the owner, year built, and the main dimensions of the vessel.

Table 2.3: The leading wellboat owners and their fleet size

Owner	**Number of vessels**	**Total transport volume[m^3]**
Sølvtrans AS	22	36700
Rostein AS	12	29424
Norsk Fisketransport AS	10	17470
Frøy Rederi	5	6280
In total	50	89874

Based on the data found and comparing the vessels transport volumes up against the year built, the development shows clear tendencies and movements towards larger vessels with increased transport volume. This is demonstrated in Figure 2.4.

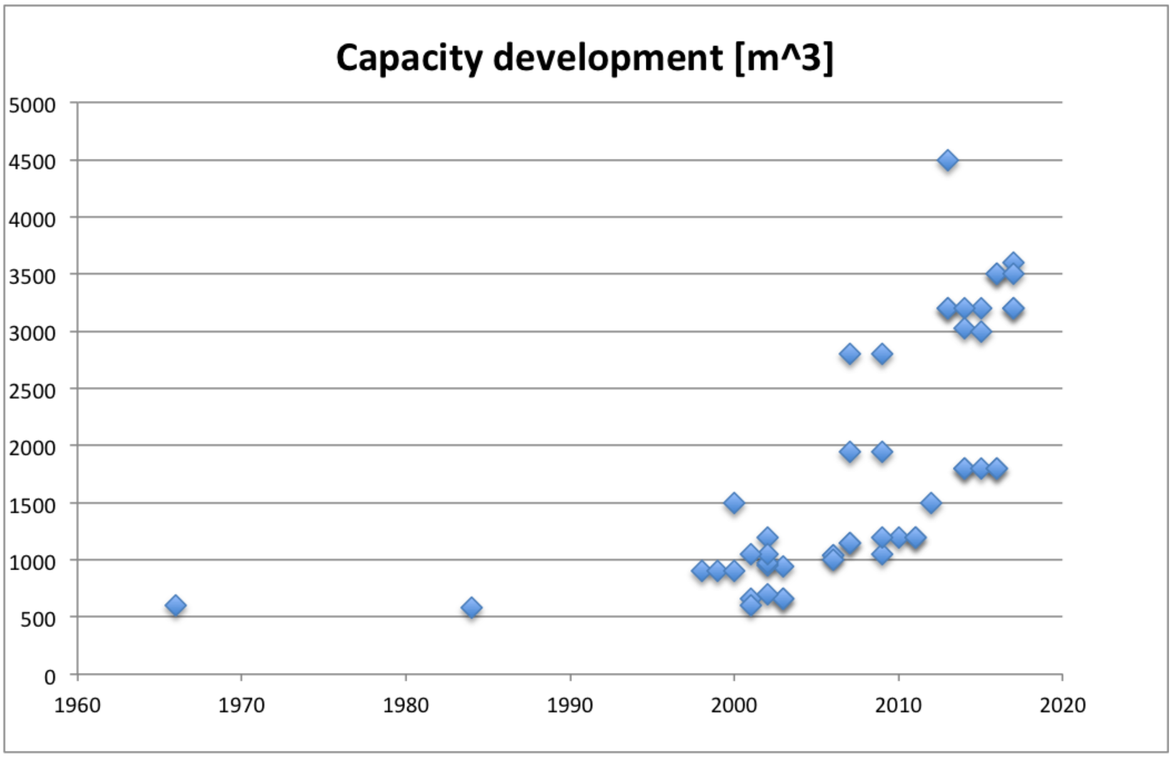

Figure 2.4: Wellboat development in capacity

The wellboat development also shows that the large companies are investing in more specialized and well-equipped vessels. These tendencies can be verified by the fact that all the vessels introduced at the market after 2013 are of large sizes above 1500 m^3 and normally approaching 3000 m^3. Rostein AS has the worlds largest wellboat with "Ro Fjell" at 4500 m^3, in addition to their latest wellboat additions from 2016 and 2017, "Ro Server", "Ro North" and "Ro West", all with a transport volume of 3500 m^3. In addition to installation of all the typical technology and equipment, these vessels are also equipped with innovative equipment for lice removal by the use of hot water. This method replaces the chemical method, and is said to be more gentle and less polluting Rostein (2016). This goes to show that the operators and the players in the industry are constantly pushing themselves to improve, seeking further growth and a more sustainable industry with a focus on the environment.

The wellboats represent significant investment costs, ranging from 100 to 300 million NOK, depending on size. Taking a vessel with a capacity of 1200 m^3, the cost would be estimated to reach 150-170 million NOK, while vessels above 2500 m^3 are representing larger investment costs and are closing in on costs around and above 300 million NOK.

2.3 Operational tasks

The wellboat plays a significant role in the aquaculture industry, performing multiple operational tasks servicing the fish farming companies to ensure animal health, welfare and quality fish. The value chain and the production process introduced in Section 2.1, gives an indication as to where, when and how the wellboat interacts and services the industry. This namely being transportation of smolt out to the farming locations, transportation of live salmon from the farming locations to the processing facilities, and lice treatment of the salmon out at sea. A brief description of the different tasks will be given below, with further indication as to how much, where, when and how the tasks are executed.

2.3.1 Smolt transportation

Access to good quality smolt is a prerequisite and essential for further development of the aquaculture industry in Norway. The annual smolt production as it is today enables transportation and release of about 320 millions smolts at different sea sites in the fjords of Norway. In Norway, with a desire to maintain a steady salmon production throughout the year, smolt release mainly occurs twice a year; one spring release (S1) and one autumn release (S0). In the calendar year 2015, approximately 310 million smolts were released; 158 million during the spring release and 152 million during the autumn release (Kontali analyse, 2016).

Smolt production

The smolt production occurs at land-based smolt facilities, and is most often of large scale production. Though the annual smolt production stays quite constant, the finite number of facilities for smolt production is somewhat uncertain, but lies around 230 (Nodland, iLaks). The level of production depends on the size and capacity of the facility, and mainly range between 1-2 million up to 13 million at the bigger facilities. Tendencies show that the number of facilities are diminishing, as the facilities are increasing in capacity and becoming more centralized. Additionally, more of the newer facilities are of Recirculating Aquaculture Systems (RAS), which have proven themselves to improve the water quality and thereby the fish strength and growth. This also allows for production of larger smolt, also called post-smolt, a term used after the smolt has gone through the process of smoltification. In traditional farming over the last years, it has been normal with production of smolt up to a size of 100 grams before release. Now, with post-smolt production, the aim is sizes between 250 grams up to 1 kilo, or for some producers even bigger. By the release of bigger smolt at the locations, one can reduce the production time at sea down from 16-17 months to 11-13 months, at the same time as obtaining a more robust fish with a higher survival rate. Reduced turnover-time will limit the hazardous exposure to sea-lice and diseases at sea, and lead to less treatments, which again will be cost saving (iLaks, 2015b). Thus, farming of post-smolt is an action contributing to solve the challenges limiting further growth in the salmon farming industry towards 2050. This creates a new operational task for the wellboat, having to transport post-smolt out to the locations.

Smolt transport

Healthy and robust smolt is fundamental for further growth and production. Thus is the transportation of smolts a crucial operational task to be performed, transferring the smolt out to the sea sites in the same condition as it left the smolt plant. This is especially challenging in areas with widespread diseases, or areas with sick and infected fish, endangering the smolt for infection. When sailing in or through highly contagious and infected zones, closed transport is required (Mattilsynet, 2013).

Farming companies have after own risk assessments implemented measures introduced before transportation of smolts, minimizing the risk of infection. This is done by requirements for wash and disinfection of the wellboats before new transportation assignments. This is not needed if the wellboat immediately returns to the same hatchery to transport more smolts to the same sea site. The wellboats are usually assigned to transport smolt for a longer period of time to reduce the risk of introducing pathogens to new groups of smolts (Norwegian Veterinary Institute, 2016). The intake of transport water is also expected to be done within certain zones, as far away as possible from fish farms, no closer than 10 km. As mentioned in the section of requirements, as of 2021 the intake water must be disinfected when transporting smolts. Another important remark is that, when transporting smolts, it is not allowed to split the load of smolts between different farming locations. At the different production sites, it is not allowed to release and stock new smolt into the same site before the original fish has been harvested out. The site should after harvest be left empty or fallow, for at least two months, before a new generation of fish can be transferred into the site again (Norwegian Seafood Federation, 2011).

2.3.2 Transportation of live salmon

At the farming locations the released smolts take about two years to grow and reach their optimal market weight, before being transported to the slaughterhouse. Harvesting of Atlantic salmon must take place before the fish reaches sexual maturity, which can slow down the growing process and deteriorate the quality of the fish. Normally the harvesting quantity is largest in the last quarter of the year as this is the period of best growth (Harvest, 2016). Annually, the wellboats in Norway transport about 1.3 million tonnes of harvested fish from the growing-sites to the processing plants. These processing plants are as with the smolt facilities strategically placed along the coastline, showing tendencies towards becoming larger and more centralized.

The harvesting of mature fish is a process consisting of multiple phases. This includes a thorough planning phase, before preparing both the fish and the wellboat for harvesting, followed by the phases of loading, transporting, unloading and finally the phase of wash and disinfection. All these phases include proposed "best practices" for live fish transport, and are taken from a report written by the Norwegian Institute for Water Research (NIVA, 2011). These phases applies inasmuch to transportation of smolt, though with slight differences when it comes to requirements.

1. Planning and preparations
The planning phase revolves around the preparation of the whole transportation process, making sure everything is in order and ready to be executed. Planning involves obtaining and ensuring information about the health status of the group of fish prior to the transport. Equally important is it to gather information about everything related to the choice of transportation route, including areas of higher bio-security risk and expected weather conditions along the route. Lastly is it of importance to be in contact with both the sender and the recipient of the fish, to make sure preparations are made with respect to transport, loading and unloading.

Preparation of the fish is done by restricting the fish from feeding days before the transport to calm the fish down, and by checking the correct numbers of fish prior to the transport by using applied technology. Preparation of the vessel on the other hand requires a wash and disinfection of the wellboat before loading the fish, as well as degassing the water in the well to avoid the risk of supersaturation with nitrogen. Lastly, testing the systems is done to make sure they are functioning according to plan and able to provide a good environment and high water quality for the fish. This also includes checking the potential weak points along the transfer line of fish from the sea-site to the wellboat.

2. Loading

During the loading phase it is recommended to apply technology verifying the amount of biomass loaded into the vessel, and carefully observing the fish during the loading operations. These operations should be performed by low pressure loading systems. With a strong focus on the welfare of the fish, the loading process should be as quick and smooth as possible, preferably avoiding damages to the fish and unfavourable oxygen levels. Hence, meeting the regulations considering water intake and bio-security is of great importance.

Before starting the process of loading, the wellboat has to manoeuvre its way between the different cages at the farming location before mooring at the side of the selected cage. During the loading process the wellboat is being assisted by a service vessel and multiple cranes. The next step is then the crowding and harvesting of the fish in the cage by the use of cranes, pumps and hoses to load the fish through the pipes and into the wells of the wellboat (Ellefsen, 2014).

3. Transportation

The choice of transport route is of crucial importance during transportation of live fish, preferably avoiding areas with other fish farms or areas putting the welfare of the fish into risk. Other procedures and standards to follow regarding the transportation of live fish, are thoroughly explained in previous sections about technology and requirements. Most important is it to throughout the transportation obtain and maintain high water quality by monitoring all the significant parameters, ensuring a good environment for the fish, maintaining the health, welfare and quality of the fish. One consideration to make is possibly reducing the biomass in the well, giving the fish sufficient of space and lowering the risk of fish scrubbing up against each other and being damaged.

4. Unloading the fish

After the transportation and arriving at the location of the slaughterhouse, a good practice is to check the fish's condition and verify that the fish is relatively unstressed. Then the unloading process can begin, unloading the fish into holding cages outside the slaughterhouse where the fish will stay until processing. The same goes for the unloading operation as for the loading phase; to minimize the possible stress inducing factors and causing the least possible damage to the fish during unloading. Unloading operations is executed, as previously explained in the section of used technologies, by a moving bulkhead and/or by vacuum pumps where the pressure drives the fish through the pipe or hose and into the holding cage.

5. Wash and disinfection

Wash and disinfection of the vessel is to prepare the vessel for the next assignment and the new generation of fish to be transported. Here it is of importance to follow regulations and use approved chemicals and doses, ensuring high and sufficient quality. Regarding the farming facility, after being harvested, the location must be fallowed a least for two months before a new group of fish can be released at the same location.

Relocation of fish

In addition to the more essential operational transportation task previously mentioned, the wellboats also contribute with transportation services when a group of fish needs to be transferred between different farming locations, graded, or moved internally between the cages at the farming location. Lastly, by the occurrence of highly infectious diseases, a wellboat may be hired in to transport the infected fish for either slaughter or destruction. These additional wellboat operations will be disregarded further in this study.

2.3.3 Lice treatment

One of the biggest challenges in the aquaculture industry is the spreading of diseases and infections, endangering the health and welfare of the fish. Sea lice and amoebic gill disease (AGD) are two of the more significant disease issues facing the salmon and Norwegian aquaculture industry today, and the wellboats are gradually becoming more important to fight them. The farming facilities are especially susceptible for lice infestation, and without any executive measures possibly very harmful and costly for both the fish and the aquaculture industry. With the commercial aquaculture and its growth, the number of fish at sea increases, simultaneously increasing the number of hosts for the salmon lice. Too high levels of lice may force farming companies to harvest the fish earlier than wanted. A consequently lower harvested weight and thereby smaller amount of salmon to be sold, leads to a huge loss in income for the farming companies with the salmon price being as high as it is these days.

Treatment done by wellboats

The technologies being used for lice treatment are either chemical, mechanical or biological. Traditionally, the most common way to remove sea lice has been by chemical methods, either by medicated feeds or chemical baths. The most common method for sea lice removal is done by enclosing the water volume close to the surface, crowding the fish within this volume and then add bath treatment medicine. This method can alternatively be executed in wellboats by pumping the fish and having the treatment inside the wells. Several types of bath treatment have been tested over the years with regard to substances used, but the most common substance used today is hydrogen peroxide, H_2O_2. A treatment method recently taken into use by a wellboat, Ro Server, is the use of hot water to remove the lice. This method is said to be more gentle to the fish, and has no other emission other than tempered water (Rostein, 2016).

The use of wellboat is limited to the availability, costs and the time consumption executing the delousing. A wellboat is primarily considered if it coincides well with other operations in addition to the lice treatment, such as grading or transfer of fish. Time spent on treating the whole facility has to be considered as well. Wellboat delousing is considered unsuitable for facilities where the delousing is assumed to span over more than two to three days ((SLK), 2000).

2.4 Challenges

In order to obtain the strong expansion aimed by the industry, Norway is today faced with multiple challenges. Some of these challenges are shortly listed below (Norsk Industri, 2017), where the lice situation and area scarcity will be of most interest for this study, while the rest will be disregarded.

1. Sea-lice, diseases and fish escapes
2. Area scarcity
3. Availability of fish feed
4. New technological solutions

If the industry is to succeed in achieving further growth, then development and implementation of new systems, facilities and technologies is seen as a prerequisite in order to address the environmental challenges. Some of these prerequisites are listed below

(Norsk Industri, 2017).

1. Development of new farming facilities
2. Offshore aquaculture
3. Improved methods for lice treatment
4. Digitization and new technologies
5. Breeding of more robust salmon

A strong expansion of the industry will require more area access combined with more efficient production. The expansion can come both on land, along the coast and further at sea. The industry players are considering the production of larger smolts in the smolt facilities, land-based facilities, closed and semi-closed systems at sea, and utilization of more exposed areas.

The Directorate of fisheries in Norway are in the possession of so-called "development permits", which they can assign to projects developing technology which addresses one or more of the challenges in the industry (NRK, 2016). Significant progress is being made related to development of new systems and technologies, involving multiple new alternative concepts to fight the issues especially related to sea-lice and area scarcity (Fisheries, 2014). Two already approved concepts addressing these issues are Salmar's "Ocean Farm 1" and Nordlaks' "Havfarm" -concept. Both concepts are designed for more exposed ocean areas, constructed to withstand extreme weather conditions, to be extremely escape-proof even under harsh conditions, and to reduce the biological challenges posed by diseases and sea-lice.

As mentioned previously, tendencies also shows an increased interest in production of larger smolts either in land-based systems or in floating enclosures before the transfer to farming locations at sea. This action contributes to breeding of a more robust smolt with a higher survival rate at sea, in addition to reduced production time at sea.

Chapter 3

Problem Description

This chapter will present a thorough description of the problem to be modelled at a later stage in Chapter 5. In order to give a proper modelling of the problem, this chapter will provide with information that will enhance and better the understanding of the problem, facilitating as to how the problem and modelling should be approached. First the problem area will be presented, establishing the tasks, vessels and the scope of locations and production volumes. Further on, the core of the problem will be more thoroughly defined, looking at yearly demands and frequencies, before presenting some uncertainty issues, as well as some future perspectives with regards to the use of wellboats.

3.1 Problem Area

As it is too extensive to look at the fish farming industry along the entire coast, Sør-Trøndelag is chosen as a representative area to illustrate the use of wellboats in order to arrive at a model formulation describing the routing of the wellboats. By eventually expanding the problem, this may additionally contribute with an holistic impression of the wellboat situation in Norway, looking into whether there are enough vessels to service the Norwegian salmon farming industry and its demand.

The problem area will be further narrowed down to the area around Hitra and Frøya to get an appropriate size of the problem. This particular area is chosen due to its high density of farming locations and associated industry, representing a high production volume and an important role within the aquaculture industry. Table 3.1 displays the farming locations of Norway, first on a national level, then of Sør-Trøndelag, before narrowing it down to the locations gathered within the zones around Hitra and Frøya. Based on the information found regarding the average number of locations actually containing fish in Norway throughout the year, it was assumed equivalent proportional amount of locations containing fish within the smaller regions.

Table 3.1: Overview of the number of locations contained within different regions

Area	Number of locations	Avg # containing fish	Avg %
Norway	1100	600	55
Sør-Trøndelag	110	60	55
Hitra & Frøya	53	29	55

In addition to the farming locations, other central locations to be aware of are the smolt facilities, processing plants, as well as an assumed home port for the wellboats when they are not in operation. All these facilities represents important locations involved with the wellboat operations. Figure 2.2 presented in the previous chapter, gives an overview of the farming industry around Hitra and Frøya. All these farming locations with its production volumes are listed in an Excel-file attached in Appendix B.

3.2 The wellboat operations

The wellboat contributes to the aquaculture value chain by providing the industry with safe transportation of the fish, ensuring the welfare, health and the quality of the fish over the greater distances. Each of the farming locations contains a certain number of licenses, which in total makes up the MAB for the location. These locations are what forms the basis for the demand of wellboat operations, given that the locations need refill of young smolt, harvesting of the mature salmon, and occasionally lice treatment at the facility. These demands represent the operational tasks which are undertaken by wellboats, and can be summarized as in Table 3.2, together with the average annual quantities of smolt release, harvesting and lice treatment in Norway. Representative quantities are found for Hitra and Frøya, and is accounted for in the rightmost column in the same table. The transportation tasks related to transportation of infected fish and of fish between the sites, will be disregarded and not be discussed any further within this scope of work.

Table 3.2: Annual average transported quantities

Operation	National quantities	Quantifies at Hitra&Frøya
Smolt transportation	320 million individuals	4215 tonnes
Fish transportation	1.2 million tonnes	210730 tonnes
Lice treatment	Varying % of the volume at farming facilities	

3.2.1 Execution of the operational tasks

Out of the operations executed by wellboats, the wellboat spends about 60% on transportation of live salmon, 30% on lice treatment, and the remaining 10% on transportation of smolt (iLaks, 2015a). Each of the respective operations has it own generalized operation profile, describing the execution of each operation. Included in these descriptions is the time usage represented through the influencing parameters for each sub-operation. All the operational profiles are shown below, representing transportation of smolt, transportation of harvested fish and lice treatment, respectively in Table 3.3, 3.4 and 3.5. Due to some lack of information within the area, it is assumed a possibly simplified model of the operations. The related time elements is also simplified to enable the modelling and computational study demonstrated later in this thesis.

Table 3.3: Sub-operations and associated time-use during smolt transport

Operation	Time usage
Maneuvering+docking at smolt plant	Location
Loading of smolt	Loading capacity and weather
Transit to fish farm	Distance, service speed and weather
Maneuvering+ mooring&prep at fish farm	Location and farming density
Unloading of smolt	Loading capacity
Transit back to smolt plant or home port	Distance, service speed and weather
Eventual wash and disinfection	Vessel size

Table 3.4: Sub-operations and time-consuming factors during transportation of harvested fish

Operation	**Time usage**
Maneuvering+mooring&prep at fish farm	Location and farming density
Loading of mature salmon	Loading capacity and weather
Transit to processing facility	Distance, service speed and weather
Maneuvering and mooring at the proc.fac	Location
Unloading into holding cages	Loading capacity and weather
Transit to fish farm/home port	Distance and service speed
Need for wash and disinfection	Vessel size

Table 3.5: Sub-operations and associated time elements during lice treatment

Operation	**Time usage**
Transit from current location to fish farm	Distance, service speed and weather
Maneuvering, mooring&prep at fish farm	Location and farming density
Average lice treatment	Current contained biomass (4-5 hours)
Preparation of the cage	Cage size (60 min)
Transit from fish farm to port	Distance, service speed and weather

As one can see from the listed time usage in the tables above, the most influential factors are related to the vessels' capacities and capabilities. In addition to the loading capacity of a vessel, a loading rate will highly influence the time-use related to executing the loading operations. The distances and service speeds will however influence the time-use related to the transit time, while the weather conditions possibly affecting all operations. The sub-operations revolved around maneuvering, mooring and preparation of the facilities are highly dependent on the location and the nearby density of other farming facilities. The related time-use for these operations will therefore probably vary a great deal from location to location, and will for this study be disregarded for simplifications.

It is for all operations assumed that the time it takes to execute a total demand initially constitutes loading-, unloading- and transit time. Some tasks may require additional time-use due to wash and disinfection of the wellboats before proceeding with new transportation assignments. This goes especially for salmon transportation and lice treatment, tasks including fish with higher possibility of carrying infectious diseases. Time-use related to wash and disinfection will be added directly onto the time it takes to execute the task. For transportation of smolt, this is not needed if the wellboat immediately returns to the same smolt facility to transport more smolts to the same farming location. The wellboats are usually assigned to transport smolt for a longer period of time to reduce the risk of introducing pathogens to new groups of smolts (Norwegian Veterinary Institute, 2016). Another important remark is that it is not allowed to split the load of smolts between different farming locations. At the different production sites, it is not allowed to release and stock new smolt into the same site before the original fish has been harvested out. The site should after harvest be left empty or fallow, for at least two months, before a new generation of fish can be transferred into the site again (Norwegian Seafood Federation, 2011).

When it comes to sequences as to in which order the tasks can be performed, it is presumed that all operations can be executed in any arbitrary order. Nevertheless, it will be certain imposed transition fees in order to switch between the different operations. These fees are related to wash and disinfection, in addition to other smaller tasks related to requirements and necessary preparations in order to proceed with a new task. Applying these costs will favor continuing and completing the same type of task before moving onto the next.

Having assumed that the wellboat use H_2O_2 for lice treatment, an important remark is the limited amount of chemicals the wellboat is able to carry per trip. This available amount will hence restrict the vessel to a limited number of cages and demand that can be treated before being forced to return to base for eventually refill.

3.2.2 Demand and frequency

Statistics from *Fiskeridirektoratet* may give an indication of the demand for wellboats throughout the year, by looking at the monthly released and harvested quantities of smolt and salmon, respectively. Data found of smolt release and salmon harvest between 2014 and June 2017 are displayed below through diagrams in Figure 3.1 and Figure 3.2, respectively.

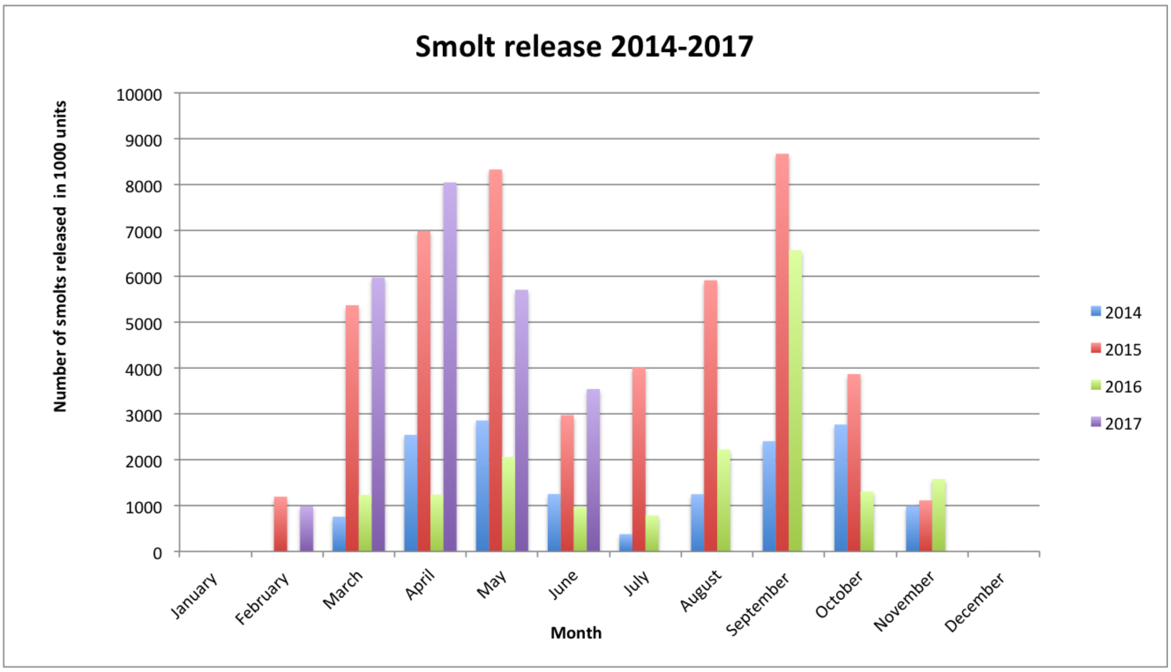

Figure 3.1: Smolt release in Sør-Trøndelag 2014-2017

The annual tendencies coincides well with the theory of smolts being released at spring and autumn, mainly around the months between March to May and between August and October, respectively. The spring release normally is harvested at winter time around January or February, while harvesting of the autumn release normally occurs around the summer months of July or August. All harvesting occurs about 20 months after release, before leaving the farming locations fallowed at least two following months before introducing a new generation of fish. The national levels of salmon harvest are more even throughout the year than smolt release, but as Figure 3.2 indicates, there are peaks around February/March and August.

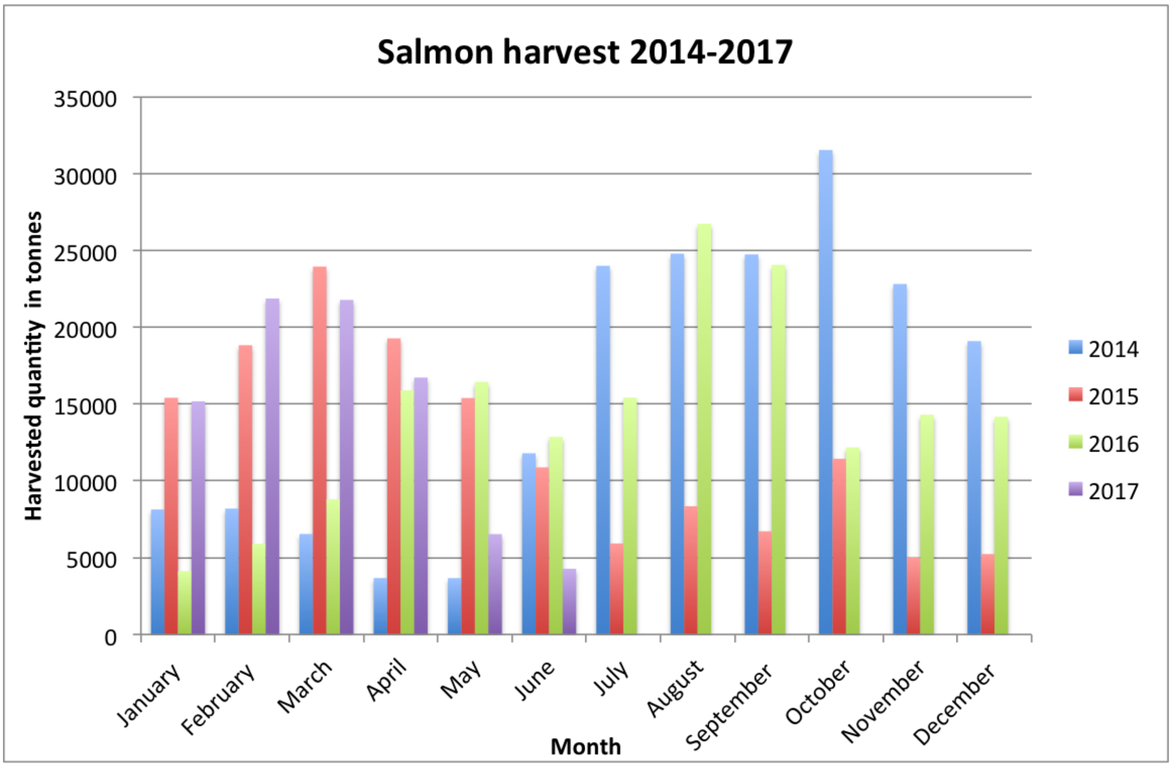

Figure 3.2: Salmon harvest in Sør-Trøndelag 2014-2017

According to *Mattilsynet*, lice treatment is found necessary and mandatory whenever it has been measured and counted more than 0.5 mature female lice per salmon within the cage. The salmon lice reproduce all throughout the year, but more rapidly when the temperature is increasing, thus especially during late summer. For the sake of the young wild salmon, there is an additional focus on lowering the levels of lice around spring time when the wild smolts are migrating (Mattilsynet, 2016a). An illustration of the national levels of salmon lice can be seen in Figure 3.3, clearly showing peaks around the late summer months.

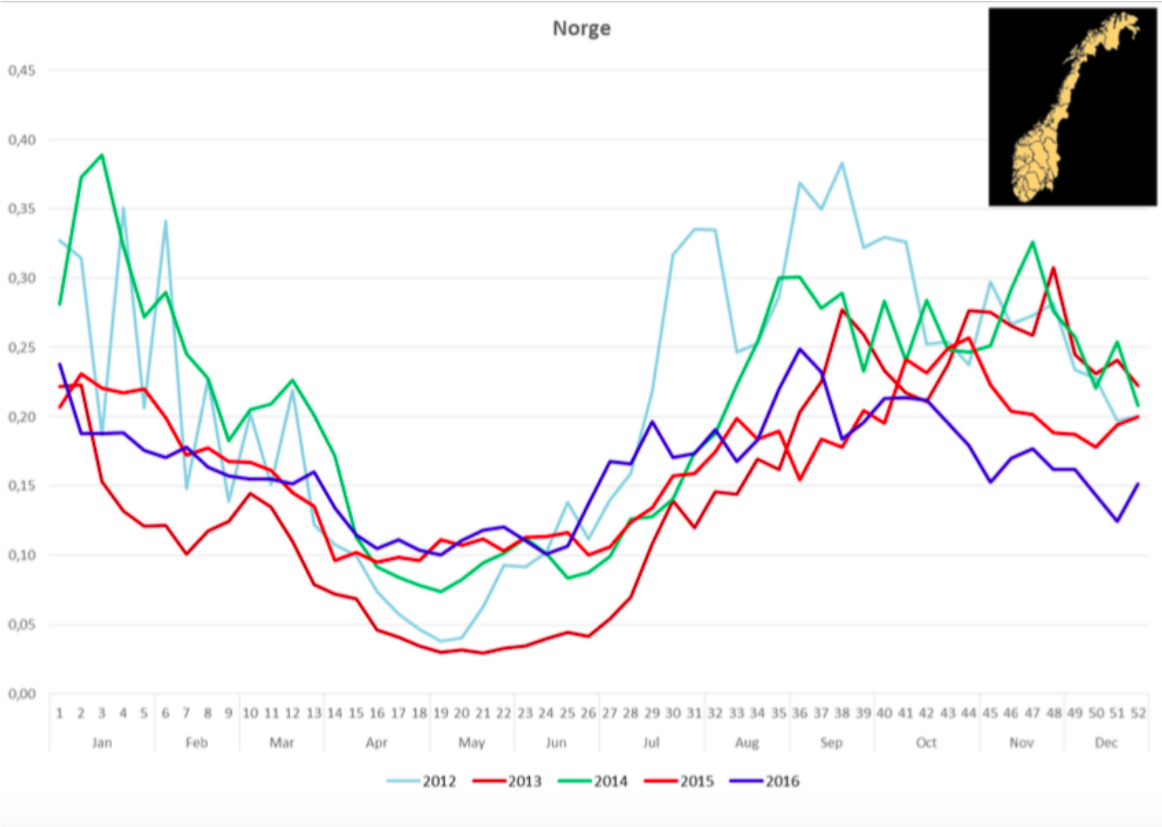

Figure 3.3: Levels of salmon lice on a national basis in Norway, 2012-2016. Source: (Mattilsynet, 2016b)

All the data previously found and illustrated in figures 3.1, 3.2 and 3.3, are to be used as representative data to implement into the model in Chapter 5, in order to represent the real world the best possible. All tasks, including the involved locations, demands and seasonal peaks, are summarized in Table 3.6. The tasks are here abbreviated to FT, ST and LT, for fish transportation, smolt transportation and lice treatment , respectively.

Table 3.6: Wellboat task summary. FT= fish transportation, ST= smolt transportation, LT= lice treatment

What?	Between?	How much?	When?
ST	From SF to FL	32 000 tonnes	Spring and autumn
FT	From FL to PF	1 200 000 tonnes	All year
LT	At FL	% of locations	Late summer months

.

3.3 The fleet of wellboats

A thorough description of the wellboat was given in the previous chapter, but its purpose can shortly be summarized to be transportation of live fish. The wellboat contributes to the aquaculture value chain by providing the industry with safe transportation of live fish, ensuring its welfare, health and quality over greater distances.The wellboat as a transportation unit has experienced tremendous development since first entering the market, and the market is continuously seeking further development and new innovative technology. Thus, does the market today consist of a wide range of different sized wellboats, equipped with a varying level of technology. With a focus on the wellboat capacity, the vessels can be divided into three categories; small, medium and large. Based on the reference vessels attached in in Appendix B, the number of wellboats falling within the respective categories are listed in Table 3.7. In this report, small vessels are categorized as vessels with transport volume below 1500 m^3, medium vessels between 1500 and 3000 m^3, and large vessels above 3000 m^3. The table also includes the average vessel size within each category, rounded up or down to the most appropriate or common size.

Table 3.7: Size distribution of wellboats

Size range	Number of vessels	Average size [m^3]
$<$ 1500 m^3	26	1000
1500 - 3000 m^3	12	2000
$>$ 3000 m^3	12	3500

The average vessel sizes are assumed 1000 m^3, 2000 m^3 and 3500 m^3 within the different ranges categorized as small, medium and large, respectively. Taking these average sizes and looking into the vessels representing the different categories, the corresponding characteristics and parameters for each average vessel size is shown in Table 3.8.

Table 3.8: Main data for small, medium and large wellboats

Parameter	Small	Medium	Large
Transport volume [m^3]	1000	2000	3500
Loading capacity [Tonnes]	150	300	500
Service speed [knots]	10	12	15
Investment cost [mNOK]	150	200	300

More or less all of the wellboats today are built multi-functional in order to undertake all operational tasks. Tendencies do show that the smaller vessels below 1500 mm^3 are becoming more specialized and used for transportation of smolt and short transfers of harvested fish, while the larger vessels are being used for lice treatments and bigger transportation operations Sølvtrans (2016). These tendencies will be disregarded in this study, and it will be assumed that all vessels can undertake all operations. A difference will though appear in the time it takes for the respective vessels to execute the different operations, with regards to sailing and service time. This again depends on the service speed and the loading capacity of the vessels. The service speed does not differ much between the distinctive vessels, and will most likely not have the highest impact on the total time-use. The loading capacity on the other hand will have a greater impact, indicating that a larger vessel will use less time both executing the operation itself, and thereby also requiring less trips to complete the whole task.

Loading capacity gives an indication of how many tonnes of salmon or smolt the vessel has the capacity to load onto the vessel, while a loading rate will indicate the amount of fish the vessel is capable of loading per hour. Depending on the task and the type of fish load to handle, there are different requirements when it comes to maximum stocking density. On average, a salmon will be on board a wellboat a least three times during its lifetime. This indicating that the fish will be at different stages and sizes during these distinctive times, and must be stocked accordingly to ensure the fish's health and welfare. In this study, it will be assumed smolt release at 100 grams and salmon harvest at 5 kg. Though lice treatment may occur multiple times during a fish's lifetime, it is here assumed that the fish will be at a size of 2 kg.

It is assumed for this study that lice treatment executed by wellboats are done with the chemical H_2O_2, and that this type of treatment only can by given a maximum of three times during the fish's life cycle due to its health and welfare. The wellboat has a limited amount of H_2O_2 available per trip, something that will restrict the vessel to a limited number of cages that can be treated before returning to base. According to *Sølvtrans*, a medium sized wellboat (1900 m^3) is equipped with two 20 m^3-containers filled with H_2O_2, supplying with sufficient dosage for 8-10 treatments. This corresponds to two days without refill. Dependent on the size of the fish and temperature, about 1000-1200 tonnes of fish can be treated each day.

3.4 Defining the problem

The core of the problem is to model the wellboat operations in order to determine the most cost-efficient fleet to handle the various demands in the aquaculture industry. This can be obtained through optimizing the routing of the vessels and their operational patterns.

The problem can be illustrated through Figure3.4 together with the problem area presented earlier in Figure2.2. Figure3.4 presents all the main operations and associated facilities when discussing wellboat operations.

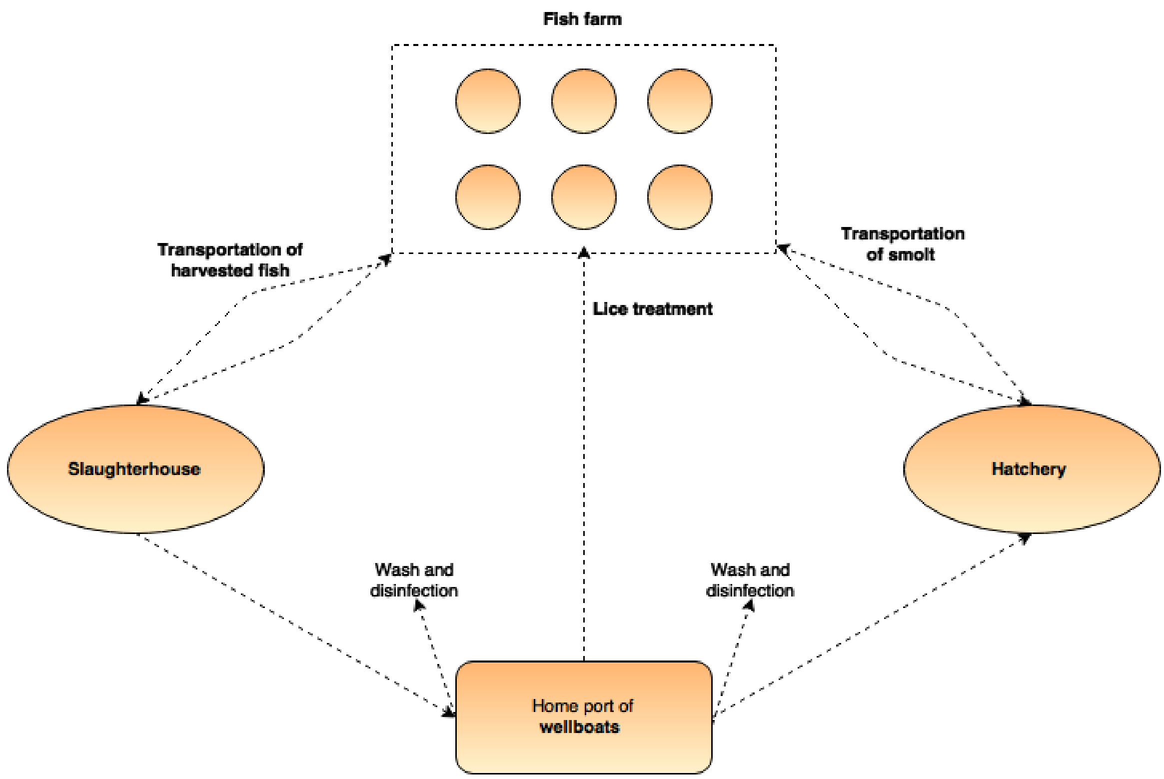

Figure 3.4: Wellboat operations

The planning problem originates from the necessity to transport smolt out to the farming locations, harvest and transport the salmon to the processing facilities, as well as assisting the industry with lice treatment. The problem consists of several participants, including the farming locations, the smolt and processing facilities and a home port as a base for the wellboats. For this study, the wellboat operations are assumed to involve one home port located in Trondheim and a variable amount of farming locations around Hitra and Frøya. Additionally, for this scope of work it is assumed one smolt facility and one processing plant which will provide with sufficient capacity to deliver and receive the respective amounts of fish, respectively. Between these facilities, wellboats of different sizes are used to execute the different operational tasks. For the sake of this study, there will only be used the three distinct sizes of wellboats listed previously in this chapter to execute the operations; small, medium and large wellboats. Based on this size selection, an optimal combination of different sized wellboats is to be obtained in order to meet the service demand.

Each wellboat operation involves a demand that needs to be picked up at one location and delivered at another within given time frames. Smolt release constitutes picking up smolt at the smolt facility and delivering the load at the farming location. Similarly does fish transportation involve picking up salmon at the farming location and delivering the load at the processing facility, and lice treatment both pickup and delivery at the same location at sea. Time windows can be applied to put pressure on when the different tasks must be done, in accordance with the critically of each task.

The demand for wellboats is seasonally dependent, and follows the production cycle of the salmon. Smolt release is strategically planned and placed to months providing the best possible growing opportunities. Salmon harvest naturally follows after a given number of months growing at sea. The quantity demand for these transportation operations depends on the size of the farming location, the season and the current fish weight at the time. For simplifications, lice treatment is assumed to only occur once during the production cycle. The quantity demand will in this case be assumed to be the number of cages at the location in need of treatment, multiplied by the current quantity of fish, at 2 kg, contained within one cage.

The time-use has previously been discussed in the form of which factors that contributes to the duration of a task. The actually time-use executing a task will heavily depend on the size of the location, the capacity of the vessel and its availability. All wellboats, independent of size, are assumed to be able to work 24 hours a day. It will be further assumed that all vessels independent of size, can execute all operations. Though will it be interesting to look at the distribution of tasks between the available vessels, and how this distribution changes in accordance with changes in the industry. These industry changes may appear in the form of an increase or decrease in the demand of an operational task, or even so, the removal of old or appearance of new tasks. Examples of such changes may come in accordance with alterations to the current lice situation, with further development and extension of the exposed aquaculture, or with introduction of new revolutionary technology and systems. These change are all responses to the constant challenges facing the industry, and will be discussed further in the following section.

3.5 Uncertainty

Most of the fish farming industry´s challenges, as well as uncertainties, are related to the future development and growth of the aquaculture sector. The challenges addressing the lice situation and area scarcity will be in particular focus for this study, especially looking at the corresponding effect on the fleet composition and the use and routing of the wellboats. The focus for this section will therefore be on these uncertainties, their possible effects and how they can be addressed when modelling the routing problem.

The wellboat market is in line with the aquaculture industry experiencing continuous changes, constantly with the intent to improve their capacities, technology and routines to meet the steadily stricter regulations and higher demands. All depending on how the industry challenges are met and possibly solved, and the following development of the industry, a corresponding demand for wellboat operations is required. Thus, an interesting question is how the fleet of wellboats will respond to the challenges, and how the future production volumes and demand will affect the fleet composition and routing.

Most important will be looking at the eventual modifications to the fleet composition as a result of possible changes with regards to the lice situation and the introduction of exposed aquaculture, moving of the industry farther offshore. All fleet modifications depends on the development of each situation, and can either remove or introduce new demands of operational tasks for the wellboat to undertake. Larger fish cages located farther offshore in more exposed waters indicate a higher production volume and thereby a greater amount of fish to be transported by wellboats over greater distances than before. These offshore locations will require increased wellboat capacity and more robust vessels to withstand the tougher weather conditions. Offshore aquaculture could on the other hand contribute to reduced environmental issues related to sea lice and fish escape, and thereby reduce the demand for lice treatment.

The lice situation in Norway is already challenging enough as it is, continuously demanding more participation from the wellboats for lice treatment. The lice population might tend to grow even more, and handling that issue is a central topic for the farming companies today and for the years to come. Limiting the spreading of sea-lice and infections along the coast of Norway, and thereby implementing stricter regulations regarding transportation, is also essential for the farming production to grow. With these stricter regulations being set, the question is which wellboats can continue with their operations, and how many will possibly be phased out due to lack of technology and equipment. An interesting point of view could be looking at the situation in a more optimistic manner, considering the possibility of solving the problems related to sea lice and the spread of diseases. With lice treatment having become such an significant operational task, it could be interesting to see how the demand for wellboats would respond to such a drastic change.

Addressing the challenges of the industry and facing them with either the new concepts or a renewal of the wellboat fleet, will quite possibly change the demand and time-use for the different operational tasks of the wellboats. It is therefor of high interest to look into the time-use and the routing of the wellboats today, see if the availability is sufficient to handle today's production, and further look into how the challenges and future demands will affect the use of wellboats and the fleet composition.

Chapter 4

Literature Review

This upcoming chapter will provide a literature review of some of the already existing literature and contributions within the field of optimization found relevant for this study. The problem for this thesis is to come up with an optimization model to be used within the aquaculture industry that may contribute to making tactical planning decisions. The main aim is to look at the areas of application of the model, focusing on the tactical planning decisions regarding optimal routing of wellboats and fleet composition. The latter is mostly with regards to determining an optimal fleet size and composition which can handle a certain demand of wellboat operations in a specific area within a given time frame.

The problem involves the routing of wellboats servicing different types of demands in the aquaculture industry, operating with full shiploads of smolt or salmon. The operations are carried out by picking up and delivering a demand at respective pickup and delivery locations, before moving on to the next task and its demand. All tasks are to be serviced while providing the most optimal routing of the fleet of wellboats at minimum cost. The aim for this literature review is therefor to study relevant papers, models and solution approaches, that hopefully can contribute as to how to model and solve the problem at hand. As the problem involves routing and scheduling, pickup and deliveries, and fleet composition, relevant literature will mainly be searched for within those areas of optimization problems.

Vehicle routing are fundamental tactical planning decisions that often are used as the underlying structure for further strategic planning, as in Fleet Size and Mix Problems (FSMP). With this problem looking into both fleet composition and routing decisions, it is of interest to look at the relation between them and the combined fleet composition and routing in maritime transportation. A small portion of this chapter is therefor dedicated to look into fleet composition and papers that have contributed within this area as well. However is the primer focus on the tactical planning decisions and previous papers related to routing and scheduling.

The upcoming chapter will introduce some central terms and planning problems in maritime transportation, before presenting the relevant papers found on the field.

4.1 Maritime planning problems

Maritime transportation planning problems can be classified according to the planning horizon into strategic, tactical and operational problems (Christiansen et al., 2013). Strategic planning is associated with the determination of long-term decisions such as ship design, network design and fleet size and mix decisions. Tactical planning on the other hand is concentrated towards the medium-term decisions, focusing more on routing and ship scheduling in maritime transportation. There is normally a significant overlap between these levels of planning, where tactical information often is necessary in order to be able to make the strategic decisions. This especially accounts for fleet size and mix decisions, where these models often require and include routing decisions. The higher amount of and the better the information is regarding the shorter-term decisions, the better the position to make good, solid longer-term decisions. It is therefor of great interest to look into the routing and optimal use of wellboats, in order to come up with a corresponding optimal fleet composition. At a operational planning level, the decisions are short- term and made on a day-to-day basis. The resort to short-term operational planning is mostly due to either high uncertainty in the operational environment, very dynamic situations or the short-term impact of the decisions made.

The problem for this thesis falls mainly into the category within the tactical planning level, and additionally under the term *industrial* operation. In maritime transportation, it is often distinguished between three modes of operations: liner, tramp and industrial. Industrial shipping is categorized as a mode of operation where the operator usually owns the cargoes shipped and the vessels used for transportation, trying to minimize the costs while operating the fleet and transporting the cargo. This corresponds well with the problem for this thesis, where a farming or a wellboat company tries to minimize the costs while operating a fleet of wellboats.

The following section is devoted to relevant literature and decision models found on tactical planning problems, with a special focus on ship scheduling and routing problems, as well as Vehicle Routing Problems (VRP). In the literature, it has been done multiple studies within these areas, but the number of papers on operation research (OR) within the field of aquaculture is however quite limited. One approach is therefore to look over at the offshore industry and the routing and scheduling of supply vessels. From this industry, one can try to find some similarities and try to incorporate these into the aquaculture industry and the routing of wellboats.

4.2 Vehicle Routing Problems (VRP)

Vehicle routing consists of deciding the order in which the associated pickup and delivery locations should be visited by each vehicle in a given fleet. Vehicle scheduling on the other hand specifies the exact time at which each location should be visited. These two latter expression are tightly intertwined and usually calls for simultaneous optimization. Such optimization problems are often handled by generalizations of Vehicle Routing Problem with Pickup and Delivery (VRPPD). The problem of routing wellboats can be associated with the VRPPD, where the pickup and deliveries at the different customers, or facilities, are performed with a fleet of vessels. The VRPPD is a generalization of the classical VRP, which belongs to a larger family of Pickup and Delivery Problems (PDP). Since the first article was published by Dantzig and Ramser in 1959, the VRPs have been subject to numerous research studies, and several variations of the basic problem have been put forward (Cordeau et al., 2007). The classical VRP is a generalization of the Traveling Salesman Problem (TSP), and involves servicing a collection of customers with one or more vehicles, and routing these vehicles in the most optimal way while satisfying the customers demands. Each route starts and ends in a given central depot.

The pickup and delivery problem (PDP) is a planning problem where a set of routes has to be made and serviced by a fleet of vessels in order to satisfy given transportation requests (Savelsbergh and Sol, 1995). The requests consist of a specified quantity demand to be transported, as well as the associated locations of where to pick up and deliver the load. Each vessel servicing a route has a given capacity available, and a start and an end location. Each requested load has to be transported by a vehicle from start- to end location without any transshipment at other locations. As stated in Berbeglia et al. (2007), the PDP can be classified according to a three-field scheme consisting of structures, visits and vehicles. The *structure*-field indicates the number of origins and destinations of the commodities, and separates between *many-to-many* problems (M-M), *one-to-many-to-one* problems (1-M-1), and finally *one-to-one* problems (1-1). *Many-to-many* indicates that each vertex can operate as both source and destination for each commodity, while for *one-to-one* problems each commodity has a given origin and destination port. *one-to-many-to-one* implicates that some commodities are initially available at one depot and destined to many customers, while other commodities are initially available at the customers and destined to the depot. The *visit*-field provides information about whether pickup and/or delivery operations are performed, denoted as either PD, P-D or P/D. PD indicates a combined pickup and delivery at a vertex, P-D that the operations may occur combined or separately, and P/D that each vertex either has a pickup or delivery request, but not both. Lastly, the *vehicle*-field gives to number of vehicles used in the solution.

Applying this scheme to the problem at hand, it can be classified as a *one-to-one* problem with P/D and multiple vehicles. Since there only exists a one-to-one correspondence between the pickup and delivery locations, the problem has to be a n-commodity problem. Two important problems classified within this category are the Dial-a-Ride Problem (DARP) and the VRPPD, where the latter correspond to transportation of objects. The VRPPD consists of routing a fleet of vehicles in order to satisfy a set of customer requests (Berbeglia et al., 2007). Associated with each request is the quantity demand and the pickup and delivery locations. Only one vehicle is to service each demand, and the pickup location must be visited before the delivery locations. The VRPPD often include restriction on the time for when service at each location can begin by a vehicle. This leads towards a slightly more general variant of the problem, called the VRPPD with Time-Windows (VRPPDTW). With VRPPDTW, if a vehicle arrives at a service operation before the beginning of its time window, the vehicle must wait until it opens before beginning its service.

Desrosiers et al. (1995) describes the significant advances made in time constrained routing and scheduling, and provides an overview of the models and algorithms developed. This paper point out the importance and relevance of the optimal algorithms based on Dantzig-Wolfe decomposition/column generation schemes as a solution methodology. As an example, Dumas et al. (1991) has performed a study on pickup and delivery problem with time windows (PDPTW), presenting an exact algorithm to solve PDP's using a column generation scheme with a constrained shortest path as a sub-problem.

Similar and extended versions of the VRPPPD is also presented in Fernndez Cuesta et al. (2017), presenting two models, a multi-Vessel Routing Problem with Pickup and Deliveries (mVRPPD) and a new Vessel Routing Problem with Selective Pickups and Deliveries (VRPSPD). The paper introduces these models with the aim to improve the current practice in offshore oil and gas logistics. The first problem aims to choose which orders to pick up and deliver, and which ones to leave behind at the expense of a penalty cost. The mVRPPD, the problem of most relevance to the problem at hand, require that all orders are mandatory, also removing the penalty term. The study and both models showed potential savings, the mVRPPD more than the VRPSPD, at the expense of larger operational changes.

The problem at hand shares similarities with some of the papers previously mentioned, and the problem resembles as mentioned to a one-to-one n-commodity problem, leading towards a VRPPDTW to be looked at for multiple vehicles.

4.3 Ship Routing and Scheduling Problems

The ship routing and scheduling problem in industrial shipping involves a ship operator in possession of a fleet of ships, who optimally tries to assign cargoes to the available ships in the fleet, simultaneously as determining the underlying routes and schedules for each ship. Each cargo is associated with a loading and unloading port, a quantity, and possible time windows for when the loading operations must start. This type of problem does not include one central depot, but each vessel can begin and end at arbitrary ports or positions at sea, unlike with a VRP with one central depot. On the other hand, does the problem share several similarities with the multi-vehicle Pickup and Delivery Problem with Time Windows (mPDPTW) (Fagerholt et al., 2010).

There has been published up to this day four surveys of research on ship routing and scheduling problems, with the purpose to provide a comprehensive source to research publications on the topic. The first survey dates back to 1983 (Ronen, 1983), which discusses the differences between vehicle and ship routing and scheduling and the reasons for lack of attention to ship scheduling in the past. These reasons can shortly be summarized to be mainly due to a conservative shipping industry, a large variety in problem structures and the high uncertainty found in the maritime environment due to e.g. weather conditions and service times. As stated by Ronen (1983), most of the published research in ship routing and scheduling has until that date been performed in industrial operations carrying bulk commodities, such as oil and ore. This still applies today, where these commodities usually are shipped in full shiploads from their loading port to their corresponding destination port. Such a problem is previously studied by Brown et al. (1987), and later extended in several ways. A similar generalized problem is presented in Christiansen et al. (2007), considering an arc flow formulation of the industrial ship scheduling problem with full shiploads. As the problem studied in this thesis deals with transportation of full shiploads of smolt or salmon, this kind of routing and scheduling problem with full shiploads can be seen as highly relevant to look further into. The objective of such problems is to minimize the sum of costs related to operating the fleet while ensuring all cargoes are transported from their loading ports to the corresponding unloading ports. For the problem discussed in Christiansen et al. (2007), it is assumed a fixed fleet with sufficient capacity to serve the committed cargoes during the planning horizon. The fixed costs are disregarded as they do not change with a fixed fleet size, and do not influence the routing and scheduling. This problem extends to multiple cargoes onboard, as well as flexible cargo sizes and multiple products. With respect to the problem addressed in this thesis, the wellboats are only to operate with full shiploads, these extensions are not found relevant for the problem and will not be looked further into.

One natural extension to this problem is imposing time windows for when the loading and unloading operations may occur. It is differentiated between hard and soft time windows. As stated in Fagerholt (2001), in scheduling problems with hard time windows, each customer has a time window within which service must begin. Introducing soft time windows instead, one allows the service to begin outside the time windows as well. This may however require an appropriate penalty, often called an inconvenient cost. The paper by Fagerholt (2001) dealt with a ship scheduling problem that was considered a multi-ship pickup and delivery problem with soft time windows (m-PDPSTW). The motivation behind introducing soft time windows instead of hard ones, was that by allowing controlled time window violations, it could possibly lead to better schedules and possible reductions in transportation costs. The objective of the problem was to determine the schedules for each ship in the fleet to perform, and which cargoes to be serviced by spot carriers, in order to minimize the transportation and inconvenience costs. The problem was formulated and solved as a set partitioning problem, where the columns represent the candidate schedules that are generated. In this paper, a schedule is defined as the visiting sequences as well as the time for start of service at each node. The generated candidate schedules introduced the most promising schedules, only considering the schedules with high capacity utilization for the set partitioning problem.

Another paper concerned with making more robust schedules, is the paper by Fagerholt and Lindstad (2007) introducing the topic of ship scheduling with multiple time windows. This paper looks into the issues of the large amount of time that is spent on loading operations in maritime shipping, and thereby the extensive time spent staying idle at a port due to ports being closed for service at night and during weekends. Therefor, this paper investigates the possibility of making more robust schedules, hindering ships of staying idle in ports. This problem was also solved as a set partitioning problem, finding the feasible schedules *a priori*. The computational results showed more robust schedules, but at the expense of increased transportation costs.

The volume of research papers on ship routing and scheduling has over the last decades increased tremendously. During the later decades, best represented through the two latest surveys on the topic in Christiansen et al. (2004) and Christiansen et al. (2013), the focus and interest has shifted more towards maritime transportation due to the increased industrialization and seaborne trade. Both surveys focus on the trends and the research done within each their respective decades. One study presented in Christiansen et al. (2004) was by Fagerholt (1999), a study to determine the optimal fleet of liners and the optimal routes of the respective vessels. The solution method consisted of three phases; generation of feasible single routes, combination of these into multiple routes, before solving a set partitioning problem. Christiansen et al. (2013) is the latest of the literature surveys and reviews the research done on ship routing and scheduling and related problems in the new millennium, and additionally provides four basic models within this domain. While full shiploads are central in a lot of the earlier surveys, this survey focuses on the more general case of multi-stop routes and that associated model. This review also puts a focus on the increased research interest in offshore logistics, such as routing and scheduling of offshore supply vessels (OSVs). Hence, due to possible similarities between the offshore and aquaculture industries, it is found applicable to look at some of these research papers.

Some of the papers found within this area is Aas et al. (2007), Fagerholt and Lindstad (2000), and Halvorsen-Weare et al. (2012) which all look into the routing and scheduling of supply vessels in the offshore industry. Aas et al. (2007) provides a real-life routing problem for supply vessels serving a number of offshore installations. The paper considers a single vessel routing problem with pickups and delivery extended with capacity restrictions at the installations. The paper introduces a mathematical formulation of the problem, with the purpose to look at how these capacity restrictions affects the routing of the supply vessels, aiming towards creating efficient routes.

Fagerholt and Lindstad (2000) presents a study carried out to evaluate and determine an optimal routing policy to supply a given number of offshore installations in the Norwegian Sea from an onshore depot by supply vessels. One of the main purposes of the study was to investigate the cost effect of having the installations closed at night. Six alternative operating scenarios were created by varying the opening hours of the installations and the needed frequency of service. For each of these scenarios, through route generation and an integer programming model, it was determined which vessels to operate and their coherent weekly schedules. The policy showed great results, potential cost savings of 7 million dollars, and was implemented by Statoil. A quite similar problem as the one above is presented by Halvorsen-Weare et al. (2012), with the objective to determine an optimal fleet composition and weekly schedules for the respective supply vessels in the fleet. Both the problem and the solution method is quite similar to Fagerholt and Lindstad (2000), and both papers also discusses to issue of robustness of the solutions and how this can be handled. One way to deal with rough weather conditions and to ensure more robust schedules, is according to both papers through introducing slack. This slack can be defined as the time the vessel is staying idle in port after completion of one voyage, before preparing for a new. Both papers are concerned with the problem of assigning vessels to weekly schedules. For the problem at hand, the issue is rather to look more into routing, the fleet composition to handle the demand, and which vessels to assign to which routes. Though, is the aspect on robust measures something to possibly consider.

With this study considering both routing and fleet composition, Hoff et al. (2010) has been read in order to gain a better understanding of the relation between them and the combination of the two. The review gives a description of the industrial aspects of combined fleet composition and routing in both maritime and road-based transportation. The survey focuses on planning that combines routing and fleet composition, and describes how the problem began as a classical VRP, and extended towards a Fleet Size and Mix Vehicle Routing Problem (FSMVRP) that accommodates a heterogeneous fleet and takes vehicle costs into consideration in addition to travel costs. The review presents an arc flow oriented mathematical model of the FSMVRP. The formulated model differs from the classical VRP by including the composition of the vehicle fleet in the problem definition, also to be included in the total cost function to be minimized.

4.4 Relevance

As indicated previously in this literature review, there are considerably less research done within the field of ship routing and scheduling than within vehicle routing. This research is also mostly concerned with the solution approaches, discussing exact methods and algorithms. The problem at hand shares similarities with some of the papers previously mentioned, and resembles to a one-to-one n-commodity problem, leading towards a PPDTW to be looked at for multiple vehicles. With this study addressing a problem in aquaculture that has to a very little degree been dealt with before, it encounters difficulties classifying the problem and establishing an associated model. Though will the arc-flow model in Christiansen et al. (2007) be further used, with the attempt to adapt it to the aquaculture industry, with contributing influence from the optimization area of VRPPDTW due to shared similarities. Problems as the ones studied here are usually computationally hard to solve, and the solution approach is to attempt on removing a lot of the calculations out of the optimization solver and into Excel.

The problem at hand revolves around the fact that there are tasks with associated demands in the industry that needs to be serviced by a fleet of wellboats. Each task is represented as a ”super node”, where the pickup and delivery occurs between to geographical nodes within that super node. Left for the routing problem is then to determine the optimal sequence in which the task should be done. Time windows will be applied for when the service can begin at each ”super node”, and not for each pickup or delivery location. Hence is the focus on the completions of the whole task, with both loading and unloading included, but the time window set for when the loading operation of each task can begin.

Chapter 5

Mathematical Formulation

This chapter presents the mathematical model created as a contributory tool for primarily tactical decision making, related to the optimal use and routing of wellboats in the aquaculture industry. The model is presented as an arc flow formulation of an industrial ship scheduling problem with full shiploads, with similarities to a VRP-PDTW. The model is made with the possibility to both decide upon the optimal use and routing of wellboats, as well as look into the needed fleet size and composition in order to meet a certain demand in the industry.

The chapter first presents a description of the logic behind the model together with the modeling assumptions, before moving on to the mathematical formulation. The complete mathematical model is presented in compact form in Appendix C.

5.1 Modeling assumptions

The mathematical model to be presented in this chapter is to a large degree based on the arc flow formulation found in Christiansen et al. (2007). The model is kept as it is with very few alterations, only possible due to the extent of pre-processing work performed in Excel beforehand. A whole section is therefor dedicated to this pre-processing alone, discussed later in Chapter 6. The pre-processing contributes to minimizing the model size, making it more generic and easier to solve and adapt to various scenarios.

Instead of the standard use of pickup and delivery nodes, where each node represent either a pickup node or a delivery node, these nodes are gathered into so-called ”super nodes”. These ”super nodes” each represent a complete operational task in the model, including loading at the pickup node, transit to and unloading at the delivery node, as well as sailing to the pickup node of the next task. Each task is connected to two geographical nodes, representing the pickup and delivery nodes, indicating where and between which locations the operations are being executed. The use of "super nodes" is illustrated below in Figure 5.1.

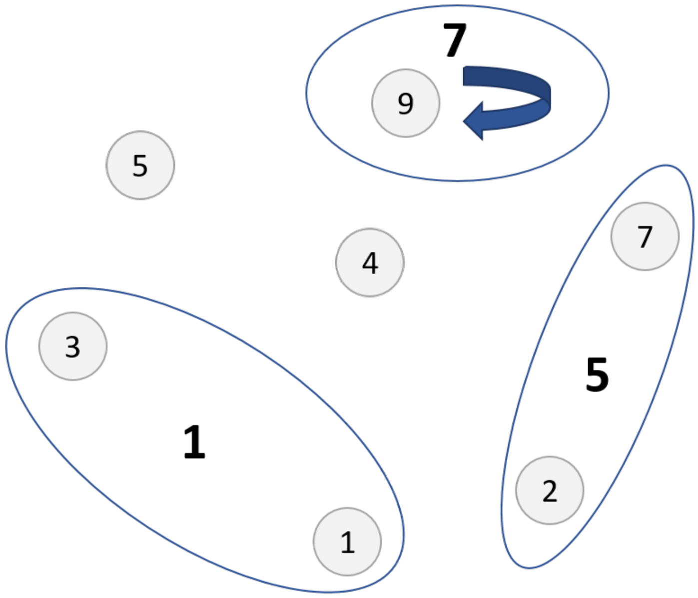

Figure 5.1: Illustration of the operational tasks with pickup and delivery nodes gathered into "supernodes".

A complete task is displayed in the figure above as everything contained within a blue circle. The small grey circles represent the geographical nodes, while the bold black letters represent the tasks. To be able to solve the problem in this manner, a distance matrix is needed to connect the tasks and the geographical nodes. This connection and all related tasks calculations is handled in the pre-processing in Excel, and discussed further in the next chapter.

It is for this study assumed full shiploads, meaning that the ship is loaded to its capacity in a loading port, and transporting the cargo directly to its unloading port. The same goes for the case where the capacity of the ship exceeds the demand, and the ship is not completely filled up. The wellboat can in other words only transport one cargo at a time, and not mix or split cargoes between different locations.

The time-use related to perform each task includes the time it takes to perform the task itself, the transit time to the next task, and may also include other optional time elements related to the operation. Smolt release and salmon harvest only occurs one time each during a salmon production cycle, and will rarely occur simultaneously at a location within a smaller time frame. Therefore, only one operational task is assigned each location within a given time frame. Lice treatment on the other hand might occur multiple times. However, it is not found health beneficial for the fish to be treated more than three times during its life time, and it will therefor be assumed only one lice treatment per cycle for this study. The lice treatment will therefor, like the other two tasks, be assumed to be a quantity demand. A standard restriction is to require that the capacity of each vessel assigned to a task is greater than the quantity demand of the given task. The wellboat demands in aquaculture are for most tasks greater than the vessel loading capacity. This means that a task will require multiple visits in order to be completed. Hence, must the loading capacity of the vessel for the respective task multiplied by the number of trips be greater than the total quantity demand of the task. The loading and unloading of fish must be executed once for every trip necessary to complete the task. This constraint and calculations are handled in Excel, and thereby taken out of the optimization model in Xpress.

Each task is to be done within a given time frame, requiring the operations to happen within applied time windows. These time windows are assumed hard time windows, meaning that the loading operation has to start within the time window, and there is no possibility to operate outside it. If a vessel arrives before the time window is open, the vessel must eventually wait until it open in order to begin the operation. All tasks are for this study assumed to be compatible in the sense that all tasks can be executed in any order or sequence. Though will certain sequences require additional time-use and costs due to change of operation, here in the form of transaction time and costs. All tasks related to lice treatment require the wellboats to return to base for refill of chemicals when empty. The operating conditions, such as weather or equipment issues, are disregarded.

Depending on the use of model, multiple associated costs are related the use of the wellboats, both fixed and variable costs. Though, when looking at tactical decision making, the fixed cost of the fleet can be disregarded as it has no influence on the planning of optimal routes and schedules (Christiansen et al., 2004).

5.2 The mathematical formulation

In this following section the mathematical formulation is presented. First will the sets and indices, together with the parameters and the used variables, be presented and described. Furthermore, will the the objective function be given, followed by the applied restrictions in the model. Lastly will both the objective function and the restriction be commented at the end of the formulation.

Sets and indices

Let N^T = {1,2....,n} be set of tasks indexed by i, and let N = {0,1,....,n+1} be the set of nodes also indexed by i. Task i is represented as a node which includes both the loading and the unloading locations of task i. This is illustrated in Figure 5.1, where the loading and unloading locations of the different tasks i are assigned geographical nodes and are connected through a distance matrix in Excel. The geographical nodes are to be separated completely from the nodes mentioned in this model. Further, let V = {1,....,v} be the set of vessel types in the fleet indexed by v. o and d are two artificial nodes indexed by v, representing the origin and destination nodes of vessel type v, respectively. If a vessel is not used, then the vessel will go directly from $o(v)$ to $d(v)$. The number of tasks is n, while the total number of nodes is $n+2$, including both artificial nodes i=0 and i=n+1. The set and indices are summarized below.

Set	Description	Index	Range
N^T	Set of tasks	i, j	{1,2,...,n}
N	Set of nodes	i, j	{0,1,...,n+1}
V	Set of vessel types	v	{1,...,v}
$\{o, d\}$	Origin and destination nodes	v	{0,n+1}

Parameters

Let T_{ijv} represent the calculated operation time for vessel type v from arrival at the loading location for task i until the arrival at the loading location for task j. This parameter includes the sum of the time spent by vessel type v loading and unloading the demand at task i, the transit time between the geographical nodes related to task i, and transit time from the unloading location of task i to the loading location of task j. Also included in this time parameter is the time addition due to washing and disinfection when switching between different type of tasks. A time addition will also be included if it is found necessary to sail back to home base for refill of chemicals in relation to lice treatment.

Let $[T_{iv}^{MIN}, T_{iv}^{MAX}]$ denote the time window associated with the loading location of task i, related to all vessel types v. The parameter T_i^{MIN} represents the earliest time for start of service, while T_i^{MAX} is the latest time. If wanted, it is possible to change the number of each vessel type v to be included in the fleet of wellboats. The number of available vessels of vessel type v is given by V_v^A. The cost parameter denoted as C_{ijv} represent all the possible costs that are related to the operation of vessel type v between the tasks i and j. Included in this parameter are the variable costs related to sailing, here represented by the fuel costs, in addition to the transaction costs. The parameter can if wanted also include fixed costs and investment costs if the model is to be used with other purposes. Calculations of all parameters are executed in Excel, also facilitating to changing and adapting the parameters after purpose and use. All parameters are summarized below.

C_{ijv}	Cost for operating vessel type v between task i and j.
V_v^A	Number of available vessels of type v in the fleet.
T_{ijv}	Time it takes for vessel type v from arrival at task i until arrival at task j.
T_i^{MIN}	Earliest time for start of service on task i.
T_i^{MAX}	Latest time for start of service on task i.
M	Big M used to linearize the time constraints.

Variables

In the mathematical formulation, the binary flow variable x_{ijv} determines which type of vessel services a particular task. The variable is equal to 1 if vessel type v services task i just before task j, and 0 otherwise. The time variable t_{iv} represents the time at which the service begins at the loading location of task i with vessel type v.

x_{ijv}	1 if the vessel sails from node i to j, 0 otherwise.
t_{iv}	Time before vessel v starts the service on work task i.

Objective function

$$minimize \quad z = \sum_{i \in N} \sum_{j \in N} \sum_{v \in V} C_{ijv} x_{ijv} \tag{5.1}$$

Subject to the following constraints.

$$\sum_{v \in V} \sum_{j \in N} x_{ijv} = 1, \qquad i \in N \tag{5.2}$$

$$\sum_{j \in N \setminus \{d(v)\}} x_{o(v)jv} = 1, \qquad v \in V \tag{5.3}$$

$$\sum_{i \in N} x_{ijv} - \sum_{i \in N} x_{jiv} = 0, \qquad j \in N \setminus \{o(v), d(v)\}, v \in V \tag{5.4}$$

$$\sum_{i \in N \setminus \{o(v)\}} x_{id(v)} = 1, \qquad v \in V \tag{5.5}$$

$$x_{ijv}(t_{iv} + T_{ijv} - t_{jv}) \leq 0, \qquad v \in V \tag{5.6}$$

$$T_{iv}^{MIN} - t_{iv} \leq 0, \qquad i \in N, v \in V \tag{5.7}$$

$$T_{iv}^{MAX} - t_{iv} \geq 0, \qquad i \in N, v \in V \tag{5.8}$$

$$x_{ijv} \in \{0, 1\}, \qquad (i, j) \in N, v \in V \tag{5.9}$$

$$t_{iv} \geq 0, \qquad i \in N, v \in V \tag{5.10}$$

The objective function

The objective function (5.1) minimizes the costs related to operation of the available fleet of wellboats. This function only consists of one term, having gathered all the related costs into this term through calculations in Excel. The term multiplies all the included flow variables x_{ijv} by the associated cost coefficients, and sums it up to a value to be minimized.

The restrictions

Constraints (5.2) ensure that all tasks are serviced, while constraints (5.3)-(5.5) describe the flow along the sailing route used by vessel type v. Constraints (5.4) ensure node balance by requiring that all arcs in towards a node, also must leave this node. This accounts for all nodes except the artificial nodes $o(v)$ and $d(v)$. Constraints (5.3) ensure that vessel type v only services and leaves the artificial origin node once, while constraints (5.5) ensure that vessel type v only arrives and services the artificial destination node once. Constraints (5.6) describe the compatibility between routes and schedules. These constraints ensure that the time when arriving at task j must be greater or equal to the time the service starts at the previous task i, plus the time it takes to complete the service and then get from the the unloading location of task i to the loading location of task j with vessel type v. Constraints (5.6 are linearized by the use of Big M, as shown in Equation (5.11).

$$t_{iv} + T_{ijv} - t_{jv} - M_{ijv}(1 - x_{ijv}) \leq 0, \tag{5.11}$$

where Big M is calculated as:

$$M_{ijv} = max(0, T_i^{MAX} + T_{ijv} - T_i^{MIN}$$

The time-window constraints are given by constraints (5.7) and (5.8). The starting time t_{0v} for each vessel type v is set equal to zero. Finally, the mathematical formulation involves binary requirements on the flow variables (5.9), as well as non-negativity constraints for the time variables (5.10).

Not all constraints are listed and used directly in the model, but handled in the pre-processing phase in Excel. This accounts for the constraints regarding sufficient capacity of vessel type v to service the demand at task i. If applied directly in this model, a new variable had to be introduced controlling the amount of cargo onboard the vessel, and constraints requiring that the demand is no greater than the capacity.

Chapter 6

Computational Study

The following chapter will provide a computational study presenting an implementation of the mathematical model described in the previous chapter. This chapter will first introduce the necessary input data and assumptions, as well as the logic behind the building and structuring of the modelling and implementation. The aim is to make the model itself the most compact and generic as possible, taking a lot of the heavy calculations and restrictions out of Xpress by pre-processing the data in Excel. Thus, will Section 6.2 of this chapter be dedicated entirely to the pre-processing phase executed in Excel to give an indication of the extent of work that has been done before the optimization process in Xpress. This chapter will further introduce multiple demand scenarios, looking into the applicability of the model, together with results and comments on the performance of the model. The results may give an indication of preferred fleet composition of wellboats, as well as routing decisions of the respective wellboats in various scenarios.

Software specifications

The mathematical model is implemented and solved in Xpress-IVE, a software using *Mosel* as a modelling language. The model is written in Mosel Version 3.10.0, and implemented in Xpress-IVE 1.24.08 64 bit. The input data used in Xpress was processed and compiled into a data file in Excel Office 365 ProPlus Version 1707, and read as a text file in Xpress.

6.1 Model structure and assumptions

As stated in the problem description, the problem for this study is to look into the areas of application for the optimization model to be used for fleet composition and routing in the aquaculture industry. These areas of application may be versatile, and can either be the need to look into optimal routing decisions, or the interest of finding the best fleet composition of wellboats short-term scenarios. An attempt is made in order to make the problem as realistic and close to the real-world problem as possible. A lot of assumptions are made with regards to both data and operation of the wellboats, that again may cause misleading results. Nevertheless, the intention of solving this problem is to look at its applicability, and not receiving in-depth and exact solutions to the problem.

As mentioned, the mathematical model described in the previous chapter, is maintained with very few alterations to it. This is only due to the extent of work that has been done in Excel, which will be further discussed and described later in this chapter. The only data used as input in Xpress is the data containing information regarding the number of nodes, number of vessel types and how many of each type, as well as time-use and costs related to the operation of the vessels. The rest is handled in Excel. The reason for solving the problem by moving most of the data processing out of the optimization model, is to minimize the model itself, making it more generic and easier to solve and adapt to various scenarios. The different spreadsheets in Excel, and the logical connections between them, are made to facilitate the possibility to change parameters, such as task or vessel related data, without imposing big, if any, alterations to the layout in Excel or to the model in Xpress.

The total cost and time-use related to the operation of the fleet of wellboats consists of multiple terms. In the underlying real world problem, these terms are a lot greater and more extensive than used within this study. As mentioned previously, this study is used to look at the applicability of the optimization model, and not to find exact and in-depth solutions to any problem. However, is it of highest interest to find and use data that are most similar and close to the real world, which hopefully will give a more correct result and impression of the area of use. Several assumptions made regarding the cost elements are based on information obtained through conversations with supervisors or co-students.

6.1.1 Locations and demands

As previously stated, for this study the problem area is limited down to the Sør-Trøndelag and the area around Hitra and Frøya. This is again to simplify the investigation and verification of the applicability of the model, as well as minimizing the need for bigger collection of data. The problem size is only set and made as an example in order to give an indication of how this optimization problem can be used within the industry. To further simplify the problem the 53 listed locations surrounding the islands of Hitra and Frøya have been gathered into so-called ”super locations”, as shown in Figure 6.1. This reduces the problem size down from 53 to 10 nodes, disregarding the origin and destination node. Each ”super location” contains 3-8 farming locations, and is marked with a dashed line and a large bold number in black. This number also represent the work task i taken into the optimization model. When clustering the locations as done here, the transit distances are all assumed average values. With the transit time being a relatively small part of the total time-use of a wellboat, this assumption will not have a large impact on the final result.

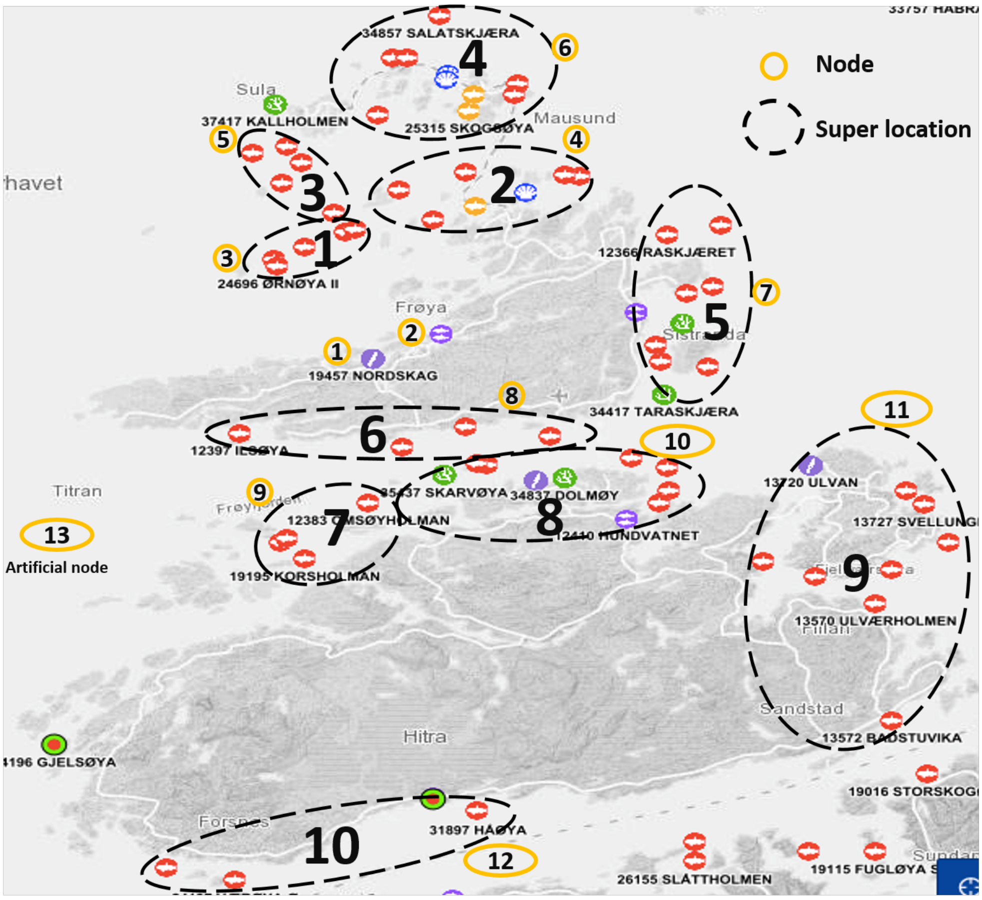

Figure 6.1: The locations around Hitra and Frøya gathered into "super locations". Source: (Fiskedirektoratet, 2017)

Each "super location", with its associated locations and production volumes, is listed in the Excel-file attached in Appendix B. This file is made with the possibility to regulate which locations and how many of its licenses to be included in the total service demand. When all locations and licenses are included, the total production volume of a "super location" corresponds to the MAB. The total service demand at a location also depends on the service task in question, taking into consideration the equivalent weight of the salmon at the time of service. Meaning, the total demand is calculated based on the amount of fish allowed within the cage and multiplied by the weight of the salmon at the time. For smolt transportation, lice treatments, and salmon harvest, the salmon weights are for this study assumed 0.1 kg, 2.0 kg and 5.0 kg, respectively.

For this study, it is assumed only one task per super location within a given time frame. This is due the time span between smolt release and harvesting, where it rarely occurs having to perform both operations within one production cycle. Lice treatment on the other hand might occur multiple times. However, it is not found health beneficial for the fish to be treated more than three times during its life time, and it will therefor be assumed only one lice treatment per cycle for this study.

As illustrated in Figure 6.1, the problem is reduced to ten "super locations", with the red marks representing each of the contained farming locations. Additionally, the problem consists of one smolt facility and one processing plant, assumed able to provide with sufficient capacity to deliver and receive the respective amounts of fish, respectively. The measured distances from these facilities out to the farming locations, are the shortest distances from the closest located smolt or processing facility out to the surrounding farming locations considered. Not included in the figure, is the home base assumed situated in Trondheim port. For later case studies, an additional "super location" will be added to illustrate offshore aquaculture and to look into the effects of moving the industry into such environments. Here the demand will be larger, and the distances increased.

6.1.2 Cost and operational data

The total cost related to the operation of the fleet of wellboats consists of multiple cost elements. In the underlying real world problem the cost elements are a lot greater and more extensive than used within this study. For eventual further use of the model, more correct and accurate data can be used or added to obtain more exact results. However, it is of highest interest to use data that is the most similar and close to the underlying real problem, to hopefully give a more correct outcome and impression of the applicability of the model.

The cost elements related to the use of ships can be divided into fixed and variable costs. The variable costs are the voyage dependent costs, which mainly consist of the sailing costs, including fuel costs and port charges. With fuel costs being the larger element in the variable cost, this element has been the bigger focus, and port costs will for this study be disregarded. The fixed costs on the other hand are voyage independent, and are more related to crewing costs, and vessel expenses in the form of maintenance and repair. With the primarily focus on tactical routing decisions, the most influencing cost factors are the variable costs. As the routing decisions are mainly based on the sailing time and the eventual applicable time-windows, fixed costs will rarely interfere or affect the routing decisions. Therefore, will fixed costs, as well as the investment costs mentioned previously in the problem description, primarily not be included in the calculations. Nevertheless, both of these terms are added in the Excel-calculations giving the opportunity to include these cost elements in the model if desirable. When going into the more strategic decision making, these elements are highly relevant. Though for a wellboat, it assumed that the crewing will be quite the same for the different vessel types, and only a slight difference in maintenance and repair costs.

To estimate the fuel costs related to the operation of wellboats, assumptions regarding the fuel consumption and fuel price are made. The fuel consumption of wellboats is assumed to range between 300-400 depending on size. The operation mode is disregarded, and the same fuel consumption will be used for both transit and task operations. The assumed fuel consumption for the different vessel types are listed below in Table 6.1. For simplicity, all vessel types are assumed to use the same type of fuel, with the same associated fuel price. The fuel price per liter of marine gas oil (MGO) is rounded up to roughly 10 NOK per liter (CircleK, 2017).

Table 6.1: Voyage specific costs - fuel costs

Vessel Type	**Fuel Consumption [L/h]**
1	300
2	350
3	400

Fixed unit costs are added for each vessel leaving the origin. The aim is to minimize the number of vessels being used, favoring that most vessels choose to sail directly from the home base to the artificial node. The fixed costs are shown in Table 6.2, and are also added with the purpose to differentiate between the vessel types. The assumed costs indicate larger costs related to the larger vessels, which would favor the use of smaller vessels if possible. The costs are set quite random and unrealistic, but are easily adjustable. These costs are also set slightly higher than the different transaction costs, so that it will be preferred to continue operation if possible, instead of initiating a new vessel. It is desirable with the smallest fleet possible to handle the required transportation demand.

Table 6.2: Fixed unit costs

Vessel Type	Fixed unit cost [NOK]
1	50000
2	75000
3	100000

A similar table can be made representing investment costs and assumed fixed costs in the form of crewing and maintenance in Table 6.3. The investment costs where mentioned in the problem description, while the fixed costs are, as with the unit costs, more or less pure assumptions.

Table 6.3: Investment costs and fixed voyage cost

Vessel Type	Investment cost [mNOK]	Fixed cost [mNOK/month]
1	150	0.6
2	200	0.8
3	300	1.0

The transition costs mentioned in the problem description are unlike the other cost elements, strictly dependent on the routing sequence. A transition cost matrix is given in Table 6.4, with assumed costs for the different task transitions. These costs are assumed and sized with the attempt to actually affect the results and the routing decisions. If these values would have been too big or too small, it will not affect the routing decisions, which is the aim. The values are also made up with the attempt to favour continuing with the same type of task.

Table 6.4: Transition cost matrix

	FT	LT	ST
FT	20000	25000	35000
LT	30000	20000	45000
ST	5000	5000	0

When it comes to the execution of the operational tasks and related time-use, Table 3.3, 3.4 and 3.5 are used as reference. These tables represent the time-consuming factors, where the manoeuvring and preparation element is disregarded for this study. The task duration is strongly dependent on the type of vessel and its capabilities, in addition to the size of the location and its demand. Related to each vessel type is a lot of essential vessel information such as vessel speed, cargo hold, and loading capacity. These parameters have a great influence on both time-use and cost.

The speed is a central parameter that will affect the time spent on the sailing legs between the different locations. Though with the transit time only being a small proportion of the total time-use, the speed will not have the greatest impact. The time spent on the service tasks itself on the other hand, constitute the larger proportion of the total time-use. In the underlying real problem, the service time is affected by many parameters, such as vessel size and capacities, weather conditions, and available equipment and man-force. For this study, the service time will be mainly affected by the transportation volume and the loading rate, disregarding the rest. The transportation volume and the corresponding loading capacity will have an impact on the time-use, by indicating how many trips that are necessary to make by one vessels in order to execute the whole service task. The larger the transportation volume, the fewer trips needed, and less time spent sailing. The higher loading rate, the faster the wellboat is capable of executing the loading- and unloading- operations.

The vessel capabilities used for this study are listed below in Table 6.5, and are based on average values from the list of Norwegian wellboats attached in Appendix B.

Table 6.5: Vessel capabilities for each vessel type

Vessel Type	Speed [km/t]	Transport volume [m^3]	Loading rate [t/h]
1	20	1000	150
2	20	2000	300
3	20	3500	350

All parameters and values used are primarily set as a foundation to be able to solve the problem, but can easily be changed to look for affects in routing decisions. The vessels are assumed to be able to operate throughout the day, day and night, disregarding possible weather conditions. For longer time periods used in the model, some days or weeks have to be subtracted from the available hours due to maintenance and similar tasks. For the shorter time periods, the amount of available hours is disregarded.

6.2 Data pre-processing in Excel

As it is advantageous to keep the mathematical model in Xpress the smallest and most concise possible, pre-processing of data is executed in Excel. This is done by transforming the raw data, both through logical connections and calculations, and adapting it to data files suited for Xpress. The Excel-file can be found as an attachment in Appendix B. This section will present and discuss the different spreadsheets, tables and data pre-processing that are concluded within the Excel-file, in order to provide with a better understanding of the work that has been done and removed from Xpress.

The Excel spreadsheets
The attached Excel-file includes multiple spreadsheets providing essential data regarding the wellboats, the operational tasks and the farming locations and their production volumes. The most central spreadsheet, *WorkTasks*, holds the information about the work tasks, the wellboat data, and the main calculations of cost and time-use. Other essential data is provided in the spreadsheets *Production volumes* and *SeasonalChanges*, providing the main spreadsheet *WorkTasks* with necessary information regarding the demands.

All relevant calculated information contained in this spreadsheet, is summarized in the *Data*-spreadsheet made to simplify the comparison between the different tasks and vessels. All data is compiled into the *DataFile*-spreadsheet, a layout ready to be copied and used as a text-file in Xpress.

6.2.1 The data

The *WorkTasks*-sheet contains both the most information, as well as the most intricate connections and logical functions. The data is divided into and gathered within numerous tables, such as vessel data, work-task information and a distance matrix. Though most information is directly listed in the tables, some data is also connected either to other spreadsheets or through calculations and logical Excel-function. The most essential tables are the tables containing vessel data and work task information. Sections of these tables with the most relevant parameters are displayed and shortly described in the following section.

Based on the list of the Norwegian fleet of wellboats and the size categories both set in the system description (2.3, 3.8), a table is made with relevant vessel data. A section of this table is displayed below in Table 6.6, quite similar to Table 6.5.

Table 6.6: Vessel data

VesselType	Speed[km/h]	CargoHold [m^3]	LoadCapa [t/h]	FleetSize
1	20	1000	150	n
2	20	2000	250	n
3	20	3500	350	n

As the model and the data file would have been to extensive to run with each individual vessels on the list, the vessels are categorized into three vessel types. This also gives the opportunity to vary the number of each vessel type, and thereby easily regulate and adapt the fleet size. This way, the fleet size can either be set beforehand, or adapted according to the varying demands, though manually.

A given fleet, consisting of a varying number of each of the three wellboat types, is set to handle the demand of wellboat operations. The work tasks and associated information is listed in a work task table. A section of this table is given below in Table 6.7. The numerated work tasks and nodes are corresponding to the numeration in Figure 6.1.

Table 6.7: Work task information

WorkTask(i)	Type	Demand[t]	StartGeo	EndGeo	TaskDist[km]
0		0	0	0	0
1	FT	25740	3	1	8
2	FT	10530	5	1	12
3	FT	24960	4	1	13
4	FT	31200	6	1	22
5	ST	437	2	7	16
6	ST	265	2	8	8
7	LT	7072	9	9	2
8	LT	5928	10	10	2
9	FT	33540	11	11	26
10	FT	17160	12	12	60
11		0	13	13	0

The data represented in Table 6.7 contains information about the operational tasks of the wellboat. The table includes the task-number, what type of task, the demand, the geographical start- and end node related to each task, and finally the sailing distance between the geographical nodes. As previously mentioned, the tasks are represented as "super nodes", as shown and explained in Figure 5.1. To be able to solve the problem using "super nodes", a distance matrix is needed in order to connect the tasks to the geographical nodes. A smaller distance matrix is given below in Table 6.8, representing a simplified problem area.

Table 6.8: Distance matrix - simplification with 5 nodes in addition to an artificial node, d

	0	**1**	**2**	**3**	**4**	**d**
0	0	140	140	126	116	0
1	140	0	4	8	13	0
2	140	4	0	12	11	0
3	126	8	12	0	10	0
4	116	13	11	10	0	0
d	0	0	0	0	0	0

The table found in the Excel-file also includes relevant data such as corresponding time-use, possible time-windows and the MAB of each super-location with the percentages to be used out the total production volume. Data on locations and production volumes is presented in its own spreadsheet *ProductionVolumes*, containing all the locations listed under Hitra and Frøya found at BarentWatch (2017). The locations are grouped into "super locations", including information about the location-ID and production volume of each location, as well as the total MAB of each "super location". Further does the table include the number of licenses held within each location, and the possibility to regulate the number of licenses and locations to be included in the final demand at the super-location.

The table is made with the possibility to regulate itself depending on which task to be done, as well as between which geographical locations related to the task. Meaning, by taking into account which task that is listed in the second column, either "ST","FT" or "LT", the demand to be operated on will automatically regulate itself and return the corresponding production volume at the time. The volume is dependent on the current fish weight at the locations, which for this study are assumed specific values for each operation, but can be regulated in the spreadsheet in Excel. The final amount of demand to be operated on will be regulated according to Equation 6.1 below. The demands listed in the table represent a case where 100 % of the locations and licenses contain fish to be handled.

$$Demand(i) = ProductionVolume * \%ContainingFish * \frac{FishWeight(i)}{MABWeight} \quad (6.1)$$

MSD, fish weight and other task related values for the respective tasks are listed as shown below in Table 6.9.

Table 6.9: Task data at the time of operation/service

TaskType	**MSD[t/m^3]**	**Fish weight[kg]**	**TaskDist[km]**	**MaxDemand[t]**
ST	0.05	0.1	-	-
FT	0.15	5.0	-	-
LT	0.10	2.0	2	2000

As can be seen from the table above, two extra column are added for information only regarding lice treatment. Lice treatment operations occur at sea, close, but at a certain distance away from the farming location. This distance is for this study given a value of 2 km. The latter column in the table contains information about the maximum demand that can be treated before the vessel has to return to a base for refill of treatment chemicals.

6.2.2 Calculations

When calculating the essential data to be compiled into the data file, and to get into the logic of the excel-file, one needs to consider Figure 5.1, Table 6.7 and the distance matrix all together. A simplified version of the calculation table in Excel is given below in Table 6.10, with arbitrary numbers made up to give an impression of how the calculation process works. These numbers will change in correspondence with alterations to the data involved, and will thereby also automatically change in the *DataFile*-spreadsheet.

Table 6.10: Simplified version of the calculation table in Excel - arbitrary numbers.

Indices			**TotTime**	**TotCost**
i	**j**	**v**		
0	1	1	6.3	68900
0	2	1	5.8	67400
0	3	1	6.3	68900
0	4	1	6.0	68000
0	5	1	0.0	0
1	2	1	2042.7	24000
1	3	1	2042.6	51950
1	4	1	2043.1	51800
1	5	1	2038.0	30000
2	1	1	763.0	50450
2	3	1	763.2	51050
2	4	1	763.7	52550
2	5	1	758.6	29250
3	1	1	2047.4	66200
3	2	1	2047.7	66950
3	4	1	2048.1	68300
3	5	1	2043.0	45000
4	1	1	870.9	74000
4	2	1	870.8	74750
4	3	1	870.4	74600
4	5	1	866.2	52800

The terms *TotTime* and *TotCost* constitute multiple contributing terms in Excel, which together make up the total time-use and the total cost related to the respective indices involved. Thus, all the terms and data falling under these head-terms are dependent on the involved indices, and takes into consideration which task to execute first with index i, which following task to sail to next, j, and by which vessel, v. With these dependencies, the data automatically changes if one of the indices changes.

Logical Excel-functions are used in order to systematically calculate the data to be implemented in Xpress. These functions include Boolean operators and conditional tests, mostly in the form of IF, AND and OR-functions, together with the VLOOKUP-function. These functions are used together to extract the right values from the right tables corresponding to the respective indices involved. The following section will provide more information about the calculated time-use and costs, with the most relevant terms and functions, both through equations and explanations.

Calculation of the total time-use

The total time-use for each operation/arc is taken into Xpress as the value T^S_{ijv}, representing the calculated time ship v uses from the arrival at the loading port for worktask i, until the arrival at the loading port for worktask j. The value of T^S_{ijv} is the total sum of several elements, and includes the time for loading and unloading, sailing between the geographical nodes related to the operation/worktask, and sailing to the starting node of the next operational task. All these elements are taken care of in Excel, removing certain constraints and calculation out of Xpress. The sum is as shown in Equation 6.2, constituting the terms *TaskTime*, *TransitTime* and *TransactionTime*.

$$TotalTime(i,j,v) = TaskTime(i,v) + TransitTime(i,j,v) + TransitionTime(i,j) \tag{6.2}$$

The transit time in the equation above represents the sailing leg from the geographical end-node of worktask i to the geographical start node of worktask j. In Excel, this is done according to Equation 6.3, used to extract the correct value from the distance matrix and divide it by the speed of vessel v.

$$TransitTime(i,j,v) = \frac{Distance(EndGeo(i), StartGeo(j) + 2)}{Speed(v)} \tag{6.3}$$

The transition time is a time contribution due to wash and disinfection operations which is necessary to execute between certain operations. Both the related time and cost additions are listed in respective tables in Excel, and are dependent on what type of task that follows the other. The transition time is extracted from the matrix displayed in Table 6.11.

Table 6.11: Transaction time matrix

	FT	**LT**	**ST**
FT	4	4	4
LT	6	6	6
ST	1	1	1

The time related to actually executing the wellboat operation itself is gathered under the term *TaskTime*, calculated as shown in Equation 6.4.

$$TaskTime(i,v) = LoadingTime(i,v) + TransitTimeTask(i,v) + LiceCons(i,v) \quad (6.4)$$

The actual execution of the operational task includes the loading process at the geographical start node, transit to the corresponding end node of the task, and then a unloading process at this node. The time-use related to the loading operations are for this study assumed to be a result of taking the demand for task i and dividing it by the loading rate of vessel v. The transit time is calculated in the same manner as Equation 6.3, but here looking at the geographical nodes related to the task itself. The last term of Equation 6.4 is a constraint related to lice treatment and the limited access to the chemical H_2O_2. As previously described, a vessel can only carry a limited amount of H_2O_2 to handle about 10 treatments of 200 tonnes each. Hence, Equation 6.7 makes a vessel return to the home base to fill up in case the demand is bigger than 2000 tonnes. One flaw to this constraint is that it only considers the demand at one location and not the sum of multiple lice treatments distributed over several super-locations. Each of the terms in Equation 6.4 can be calculated according to Equation 6.5, 6.6 and 6.7, all listed below.

$$LoadingTime(i,v) = \frac{Demand(i)}{LoadingRate(v)} * 2 * NumberOfTrips \quad (6.5)$$

$$TransitTimeTask(i,v) = \frac{TaskDistance(StartGeo(i), EndGeo(i) + 2)}{Speed(v)} \quad (6.6)$$

$$LiceCon(i) = 2 * \frac{Distance(StartGeo(i), o(v))}{Speed(v)} * (\frac{Demand(i)}{2000} - 1) \quad (6.7)$$

In most mathematical arc-flow formulations there are added capacity constraints making sure the demand of each task is no larger than the capacity of the vehicles. This constraint is handled in Excel through Equation 6.8, making sure the vessels take additional trips if the demand of task i exceeds the capacity of vessel v, and further calculates the extra number of trips necessary to complete the task. The available capacity of the wellboat takes into account the maximum stocking densities associated with the respective task. The equation below will return the number of trips necessary if the demand exceeds the capacity, or otherwise, with a demand smaller than the capacity, return the value 1. All values are rounded up to make sure that the vessels carry out enough trips to cover the total demand.

$$NumberOfTrips(i) = \frac{Demand(i)}{CargoHold(v) * MaxStockingDensity(i)} \tag{6.8}$$

For each extra trip necessary, a time addition will be added to both the loading time due to each extra loading operations, as well as additional transit time for each extra sailing legs. It is added two extra loading operations per additional trip, and *(n-1)* extra sailing legs, here excluding the original trip to the loading port.

Calculation of the total cost

The total cost related to the operation of the fleet of wellboats consists of multiple cost elements. In the optimization model, the only cost related parameter used is the C^S_{ijv}, normally representing the variable sailing and port costs. However, Excel is organized to also be able to include other cost elements added according to preferences. The cost elements included within this study is the main element of fuel costs, in addition to a fixed unit cost for each vessel leaving the home base, and the transition costs related to switching operational task. The elements of investment cost and fixed costs are optional and included if desired.

The cost parameter is represented in the objective function value, where the aim is to minimize the cost while operating a fleet of wellboats, making sure all demands are serviced. A cost element is added for each vessel taken in use. This element is in Excel calculated as in Equation 6.9.

$$TotalCost(i,j,v) = FuelCost(v) + FixedUnitCost(0, j \setminus \{11\}, v) + TransCost(i,j) \tag{6.9}$$

The fuel cost is obtained by extracting the right fuel consumption and fuel price corresponding to the respective vessel type. The fixed unit cost is made sure only is added for all vessels leaving the origin node 0, except for the vessels leaving directly for the artificial node and thereby not being used. The transition cost are obtained in the same way as the transition time, but now referring the Table 6.4.

For the possible additional costs in the form of investment costs and fixed costs, columns are made with prepared formulas ready to take in data, and naturally added and included in the total cost.

A brief example

To catch the essence of the calculations and the entire thought process, this section is summed up with a brief example, using Figure 5.1 together with Table 6.7 and the distance matrix in Table 6.8. Take for example a vessel of type 1 to execute task 1 before task 3, representing the indices (1,3,1) in Table 6.10. This example is illustrated in Figure 6.2. The demand of Task 1 has for this example been reduced to one farming location of 5 licenses of 780 tonnes, containing a total volume of 3900 tonnes.

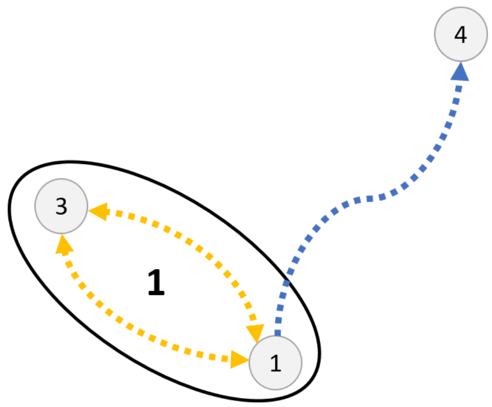

Figure 6.2: Example with vessel type 1 executing task 1 before sailing to the starting node of task 3, node 4.

As illustrated in Figure 6.2, Task 1 includes sailing to the farming location at node 3, loading fish onto the wellboat and sailing transit to the processing facility at node 1 for unloading. With the geographical point being (3,1), it goes into the distance matrix and extracts the correct distance and calculates the transit time according to Equation 6.6. Equation 6.8 will extract the service demand of task 1, and divide it by the product of the transportation volume and MSD to find the number of trips necessary. After executing all trips necessary and unloading the last load of fish at node 1, the vessel sails transit to the starting node of task 3, extracting the distance and calculating the transit time according to 6.3. This is the last time- and cost element included in T^S_{ijv} and C^S_{ijv}, respectively.

The two first indices in (1,3,1) holds the information about the tasks to be done, and the latter about which vessel to use. Thus, reading index i as 1, it goes into Table 6.7, and search for the row with the value 1 in the first column. From there, depending on what calculation to perform, it extracts the corresponding wanted values in the associated columns. The same goes for reading the other indices, though for index v all data is extracted from Table 6.6 with the vessel data. In this case, Table 6.7 shows that both tasks are fish transportation tasks. Therefor will all information related to this type of task be extracted from the associated row and columns in Table 6.9, and transition time and cost from Table 6.11 and 6.4, respectively. All extracted data related to the indices (1,3,1), necessary for further calculations of time-use and costs are listed in Table 6.12.

Table 6.12: Extracted values

Information, (1,2,1)	**Extracted value**
Type of task (i)	Fish transportation, FT
Type of task (j)	Fish transportation, FT
Demand (i)	3900
Fish weight (i)	5 kg
MSD (i)	0.150 t/m^3
StartNode (i)	3
EndNode (i)	1
Start Node (j)	4
Task Distance (i)	8 km
Transit Distance (i,j)	13 km
Transaction time (i,j)	4 hours
Transaction cost (i,j)	20000 NOK
Transportation volume (v)	1000 m^3
Speed (v)	20 km/h
Loading capacity (v)	150 tonnes
Loading rate (v)	100 t/h
Fuel consumption (v)	300 L/h
Fuel price (v)	10 NOK/L
Fixed Unit Cost (0,v)	50000 NOK

The values are extracted for further use in the logical functions and equations to calculate the different time and cost elements. These elements make up the total time-use and costs related to the indices (1,2,1). All elements and total values are shown in Table 6.13 and Table 6.14, for time-use and cost respectively. In the rightmost columns in both tables, the equivalent calculations for vessel type 3 is shown for comparison.

Table 6.13: Calculation of total time-use for vessel type 1 and vessel type 3

Time element	**Time-use [h], V1**	**Time-use [h], V3**
Number of trips (i,v)	26.0	8.0
Loading time (i,v)	2028.0	178.3
Transit time, task (i,v)	10.0	2.8
LiceCon (i,v)	0.0	0.0
Transit time (i,j,v)	0.7	0.7
Transaction time	4.0	4.0
Total time-use (i,j,v)	2042.7	186.8

Table 6.14: Calculation of total cost

Cost element	**Cost [NOK], V1**	**Cost [NOK], V3**
Fuel cost (i,j,v)	31950	13800
Transition cost (i,j)	20000	20000
Fixed unit cost (0,v)	0	0
Fixed cost (v)	0	0
Investment cost (v)	0	0
Total cost	51950	33800
Fixed unit cost (0,v)	50000	100000
Total cost,fixed unit cost	101950	133800

As can be seen from the tables above, vessel type 1 being of the smaller type, it will require the vessel to make a larger number of trips to execute the total demand than for the other vessel types. The time-use for using vessel type 1 is 2043, and significantly higher than for the use of vessel type 3. This is due to the large demand to be handled by only one small wellboat with a transport volume of 1000 m^3 and a loading rate of 100 t/h. With vessel type 3, with a transport volume of 3500 m^3 and a loading rate of 500 t/h, the number of trips would drop to 8 and a total time-use of 132.3 hours.

The total cost related to the operation of vessel type 1 and 3 gives the indication that a bigger wellboat is cheaper to operate than a smaller one. The total costs listed in Table 6.14 are only related to servicing task 1 and sailing to task 3, and does not take into account the fixed unit cost of using the respective vessels. Including this cost, the total cost would for each vessel type increase to 76950 and 108800 NOK, respectively. This would now indicate that the use of vessel type 3 is more expensive than vessel type 1. Though with the time-use of vessel type 1 and eventual applied time-windows, it might not be efficient enough to be considered in a routing solution.

6.3 Scenarios

This section aims to show some of the areas of application for the optimization model. To test the applicability of the model, several scenarios are made, looking at and evaluating the resulting fleet composition and routing within each scenario. The scenarios are made deterministic, and are not in total compliance with the value chain and does not follow a complete life cycle of the salmon. However, the scenarios are made the most realistic possible, testing multiple variation of demands, time steps, tasks and industry changes, with the attempt to see if the results and outcome correspond to the what previously insinuated or predicted by the industry. The model will be tested with seasonal changes, as well as testing the affects on fleet composition and routing due to new additional tasks in the form of alternating lice demands and offshore aquaculture. Lastly will the model also be tested with national levels of demand with the current available fleet of wellboats in Norway.

The different scenarios does not interact or stand in correspondence with each other or other scenarios. The aim of running different scenarios is to test the effect of alterations in the demand for wellboat operations on the fleet composition and routing, and thereby again testing the area of use for the optimization model. Testing the model with different scenarios and data, will hopefully give an indication of what the model is able to contribute with, as well as the shortcomings of the model. In addition to the fleet composition and the resulting routing decisions, the solution time and gap will also be noted to evaluate how well and efficient the model is run.

The aquaculture is to some extent quite unpredictable, and the model is run both with and without hypothetical time-windows. These time-windows are made with the idea of a certain pressure to complete the wellboat tasks within a given time frame, with respect to both optimal conditions and critically. Three variants of time windows will be applied, gradually narrowing the time window down. One variant is without time windows, another with time windows of two weeks, and lastly time windows narrowed down to one week, represented with the numeration 1, 2 and 3, respectively. Lice treatment is always given the time window of the whole month, if not stated otherwise.

As the scenarios are run with variations of these time windows, an overview is given in Table 6.15 with the numerations for further use in the different scenarios. Meaning, if a run is named with one of the numerations below, the corresponding time windows is used.

Table 6.15: The applied time windows

Numeration	Notation	TW	Meaning
1	No TW	FT,ST,LT: 0-720	No time windows applied
2	TW 2	FT:0-336 ST:168-504 LT:0-720	Time windows of two weeks applied
3	TW 1	FT:0-168 ST:168-336 LT:0-720	Time windows of one week applied

A max sailing time is set for each vessel type and given the same value as the maximum starting time for service at the artificial end node. For this study, this value is equal for all vessel types. Hence is it the same time as the total time step, which for nearly all scenarios are set to one month. All input files used in Xpress for the following scenarios are attached in Appendix B.

6.3.1 Seasonal demands

The demand for wellboat operations follows the production cycle of salmon and the seasonal changes in the industry. The variation in demand for each operational task is listed previously in Figure 3.1, 3.2 and 3.3, and all related data is listed in the Excel-file attached in Appendix B. Data related to the seasonal changes are taken from Fiskedirektoratet and BarentWatch (2017), using the year of 2015 as a reference point due to its high demands that year. The numbers taken into the optimization model are adapted the best way possible to correspond to the seasonal data, with respect to the total demand summed up at each "super location", by regulating the involved locations and licenses. In some cases, in order to make the service demands correspond to the seasonal data, the type of task related to each "super location" has to change. For each seasonal scenario, the "super locations" and its node numbers related to each type of task is listed behind the respective task in each table.

For this case study it is differentiated between spring demand, fall demand, and low season demand. These seasonal periods are tested in order to see the preferred use of wellboats within each period, and based on the outcome find the best composition adapted to operate throughout all seasons. For each season, the model has primarily been run in Xpress with ten available vessels of each vessel type. These are slightly over sized initial fleets, but set to evaluate the preferred choice of vessels. Different variations of available vessel types are additionally run in order to observe which other options and combinations the possibly could work, and which ones that does not.

Spring demand

The spring demand of wellboats is for this study assumed the demand over the spring months of March, April and Mai, using the data presented below in Table 6.16. These months are central for smolt release, as well as harvesting, while the demand for lice treatment is quite low compared to the higher lice levels in the late summer months.

Table 6.16: Average spring demand in tonnes

	March	**April**	**May**	**Avg**
ST: 5,6	540	700	850	700
FT: 1-4,9,10	24000	19500	15500	20000
LT: 7,8	1100	3000	2750	2500
TOT	25640	23200	19100	23200

Fall demand

The fall demand constitutes the average demand in the months of August and September, and is shown in Table 6.17. The demand in these months differs from the spring demand as it here requires a lot more lice treatment, and considerably less fish transportation. As the spring and fall release of smolt are pretty evenly spread for continuous production, the fall demand for smolt release is quite equal to the spring release.

Table 6.17: Average fall demand in tonnes

	August	**September**	**Avg**
ST: 5,6,10	600	900	750
FT: 1-4,9	8500	6750	7500
LT: 7,8	7000	6000	6500
TOT	16100	13650	14750

Low demand
In the aquaculture industry there are, as with many other industries, periods of lower demands. According to the data found, there periods occur both during mid-summer around June and July, as well as during winter time around November and December. The average demands during the winter months are used below in Table 6.18. Due to poor initial living conditions for smolt at this time of the year, the demand for smolt release is close to 0. The demand for lice treatment and fish transportation is quite similar to the spring season, but considerably less.

Table 6.18: Average low demand in tonnes

	November	**December**	**Avg**
ST:5,6	110	0	55
FT:1-4,9,10	5000	5250	5125
LT:7,8	2500	1500	2000
TOT	7610	6750	7170

These numbers can be taken into the model, either using the average values to be serviced within a time step of a month, or each month represented with its demand to be serviced within a time step of the respective number of months. Since a routing policy also needs to handle demands peaks, it usually is of no practical use to determine an optimal routing policy for the average demand. However the average month is used for the upcoming seasonal scenarios, but also tested with the month with the highest demand for verification. The time step used is a month containing 30 days.

Running the model with the data representing the respective seasonal demands for wellboat activities, the outcome can be displayed as below in Table 6.19. Bear in mind that the distinctive nodes might represent different tasks within the different seasons, as listed in the previous tables. VT represents the vessel type, and OFV the objective function value.

Table 6.19: Fleet composition and routing decisions with average seasonal demands

Season	Fleet composition			Routing decisions	OFV [NOK]
	VT 1	VT 2	VT 3		
Spring 1	0	0	2	VT3: 0-10-4-2-9-1-8-7-11 VT3: 0-6-5-3-11	558 200
Spring 2	0	0	2	VT3: 0-10-4-1-2-9-6-5-7-8-11 VT3: 0-3-11	561 600
Spring 3	0	1	2	VT2: 0-2-4-11 VT3: 0-9-2-4-6-5-7-8-11 VT3: 0-10-1-3-11	652 475
Fall 1	0	0	1	V3: 0-9-4-1-2-3-5-6-10-7-8-11	348 600
Fall 2	0	0	1	V3: 0-9-4-2-1-3-6-5-10-7-8-11	348 600
Fall 3	0	0	1	V3: 0-9-1-4-2-3-5-6-10-7-8-11	348 600
Low 1	0	1	0	V2: 0-10-9-3-2-1-4-6-5-7-8-11	334 750
Low 2	0	1	0	V2: 0-10-1-9-3-4-2-6-5-7-8-11	334 750
Low 3	0	1	0	V2: 0-10-3-1-2-9-4-5-6-7-8-11	334 750

Each of the seasonal demands are run with all the variants of time windows, narrowing it down from no applied time windows to one week. As can be seen from the results above, with higher demands it naturally tends to require more vessels of bigger sizes. During the demand peaks around spring time, it requires at least two vessels of type 3, with an additional vessel of type 2 when introducing the most narrow time windows. The two other season scenarios represent lower demands for wellboat operations. Clearly, the need for vessels will be reduced, and without time windows one vessel of type 3 will be able to handle the demand throughout the fall season. During the low demand season the necessary vessel size is reduced to a vessel type 2, indicating that there is necessary to initiate a bigger vessel for such a demand. With less demand, the time-use will decrease and so will the corresponding operational costs related to running the fleet. Narrowing down the time window implies equal or higher costs due to more limited routing options.

With the data and the constraining time windows used, the results indicate that it in most cases is beneficial to use the large wellboats. Based on the outcome from each run, an optimal fleet would probably consist of at least two wellboats of type 3, and an additional wellboat of type 2. This is the minimum of vessels required, and one should probably invest in one or more in case of higher or more critical demands. Varying the available number of each vessel type, shows that except from low season demands, servicing all required demands is not possible without the use of at least one wellboat of vessel type 3. This is due to its loading capacity, as well as its higher loading rate, using significantly less time performing the operations than the smaller sized vessels. The smallest vessel type is rarely included in any solution, using too much time for most operations to even manage the demand within the time frame. Though, for the low demand scenario, removing the option to choose the two bigger vessel types, it showed that three wellboats of type 1 could service the required demand, but naturally at a higher cost. The data used clearly affects the results, but gives here an indication of the appropriate fleet composition and routing decisions. The routing itself follows the anticipated sequence, continuing with the same type of task if possible. Multiple variation can be done to both the available fleet, the demands and the time windows, which will change the routing and possibly, if narrow enough time windows, the fleet composition. Narrowing the time windows even more, or timing the different demands in a more critical manner, will most likely require more wellboats to be used.

6.3.2 Future demand situations

In Chapter 3, some plausible future aspects were mentioned and discussed. These future aspects are of high interest to look further into and investigate for the associated resulting alterations to fleet composition and routing. The main topics related to future demands is the area scarcity, the lice situations and the introduction of post-smolt. All of the scenarios falling under this section requires alterations to the set up in Excel, having to expand the problem in order to take into account the new tasks or associated locations. This expansion is either in the form of extra geographical nodes, extra tasks, or production volumes greater than what already exist to look at the future demand. The alterations in Excel are not significantly hard or time-demanding to make, but some time-use has be accounted for.

Offshore aquaculture

To solve the problem related to area scarcity in the aquaculture industry, as well as contribute with higher production volumes, the industry is in the process of moving the production farther offshore. Furthest in this process is Salmar with Ocean Farm 1, which now has reached its position at Frohavet, as illustrated in Figure 6.3.

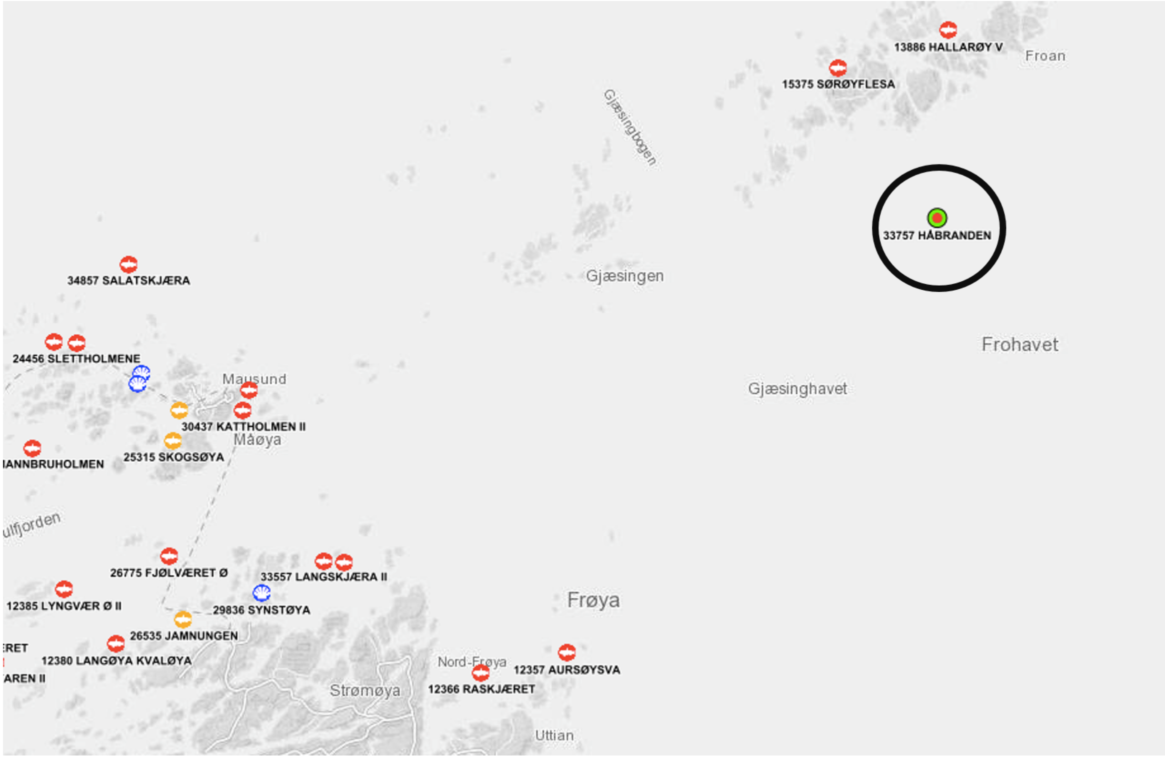

Figure 6.3: Illustration of the location of Ocean Farm 1 at Håbranden in Frohavet

The structure is facing some routine checks before possible smolt release and salmon production can begin. Post-smolt is used at a weight of 250 grams. Using this location as a standard, its data is listed below in Table 6.20, together with calculated demands and average distance.

Table 6.20: Ocean Farm 1 data

Data	Ocean Farm 1
Location	Håbranden
Location ID	33757
Production volume [tonnes]	6240
Demand: smolt release [tonnes]	312
Demand: fish transportation [tonnes]	6240
Demand: lice treatment [tonnes]	0
Average distance [km]	46

If proven beneficial, this structure is possibly one of the many offshore cages to come. Initially, for this study, it will be looked into the changes that occur in fleet composition and routing decisions due to the introduction of Ocean Farm 1 and its demand. The demand for smolt and fish transportation will be assumed to be according the total production volume, as shown in Table 6.20, presuming that the whole location must be filled or emptied for fish all at once. The demand for lice treatment is set to 0, due to the assumption of zero lice infestation at offshore locations. The related demand for fish transportation for Ocean Farm 1 will be added to the spring demand previously shown in Table 6.16, while the additional smolt demand is added to the fall demand in Table 6.17.

The introduction of a new location leads to necessary alterations to the structure and the set up in Excel. A new task is added with new associated geographical nodes, which also calls for an additional row and column in the distance matrix. The offshore operation is represented as task 10, replacing the current task with the transportation task related to Ocean Farm 1. The previous demand at node 10 is consequently distributed among the other remaining tasks to maintain the same level of demand during the month. The results of running the offshore scenarios is listed in Table 6.21. Off 1, 2 and 3 represents the spring demand with the additional fish transportation from Ocean Farm 1 within the different time windows, respectively, while Off Fall represents the extra smolt demand during fall season with no time windows/time windows of one week.

Table 6.21: Fleet composition and routing decisions with Ocean Farm 1 included in the spring demand.

Offshore	**Fleet composition**			**Routing decisions**	**OFV [NOK]**
	VT 1	**VT 2**	**VT 3**		
Off 1	0	0	3	VT3: 0-3-11 VT3: 0-5-6-9-1-2-4-7-8-11 VT3: 0-10-11	1 286 550
Off 2	0	0	3	VT3: 0-3-11 VT3: 0-4-2-1-9-7-8-11 VT3: 0-5-6-10-11	1 2331 500
Off 3	1	0	3	VT1: 0-5-6-8-11 VT3: 0-2-1-9-7-11 VT3: 0-4-10-11 VT3: 0-3-11	1 168 500
Off Fall 1	0	0	1	VT3: 0-5-6-9-4-1-2-3-7-8-11	1 020 800

Introducing the new offshore location requires an additional wellboat of type 3 to handle the transportation of salmon from the giant fish farm during spring season. Applying time windows of two weeks does not change the fleet composition, but changes the routing sequences and the distribution of tasks among the involved vessels. However, narrowing the time window down to one week, an additional wellboat of type 1 is added to handle to tasks of smolt transportation. The fall demand on the other hand required more loading capacity, and replaced the wellboat of type 2 with a larger wellboat of type 3. These results may indicate a need to expand the fleet handling the seasonal demands. A wellboat of type 3 should either replace the wellboat of type 2, or be added additionally together with a wellboat of type 1 which can be a suitable asset to handle the smaller demands.

Alterations to the lice situation

The lice situation in aquaculture is a huge barrier for further growth in conventional cages in the sheltered areas along the coast. Different innovative technologies are under development, which can possibly change the lice situation as we know it today. For this case study, it has been looked into the different demands for lice treatment, alternating between high increase and high decrease in demand. The changes are made by increasing or decreasing the percentage of locations in need of lice treatment during a time step of a month. Due to the more natural occurrence of lice during late summer, fall season and August is chosen as the representative month for these scenarios. It will be run four scenarios, one with 0 %, two with 60 % and one with 100 % locations in need for treatment, all regarding the current locations already used to illustrate the demand for lice treatment. These different lice situations are listed Table 6.22.

Table 6.22: Alterations to the demand for lice situation

Alteration	Demand [tonnes]
0 %, no demand at current locations	0
60 % at the current locations, TW1	6500
60 % at the current locations, TW1*	6500
100 % at the current locations	10000

"No demand" and 0% is an alteration that illustrates the situation where the current lice situation is solved, and demonstrated by setting the demand for lice treatment to zero. "Super locations" 7 and 8 are replacing the LT with ST and FT, respectively, distributing the fall demand for these task evenly among them all "super locations".

The second and third alteration is making the lice situation critical at the current locations where the task of lice treatment already is taking place, setting the percentage of locations needing treatment to 60. The two scenarios with 60 %, is run with different time-windows, the first with the standard TW1 and the second with the TW1-window also here applied on the lice treatment tasks. The last scenario involves setting the percentage to 100, with critical need of lice treatment at the involved farming locations. The result of the four demand alterations is shown below in Table 6.23.

Table 6.23: Fleet composition and routing decisions with different alterations to the lice situation.

Scenario	**Fleet composition**			**Routing decisions**	**OFV [NOK]**
	VT 1	**VT 2**	**VT 3**		
0%	0	0	2	VT3: 0-9-3-1-2-8-4-7-6-5-10-11	324 400
60% TW1	0	1	1	VT2: 0-8-11 VT3: 0-9-3-1-4-2-5-6-10-7-11	421 761
60% TW1*	0	0	2	VT3: 0-4-2-8-5-6-10-11 VT3: 0-9-3-1-7-11	475 800
100%	Infeasible				

In the short run, removing the need for lice treatment completely at the two "super locations" does not induce any great differences, though it reduces the cost of operation. Running the two 60%-scenarios however, indicates the need for an extra wellboat. The first scenario required a wellboat of type 2, while the second required one of type 3 when imposing time windows also for the lice treatment tasks. Again does this insinuate that the need for larger and more efficient vessels are needed when narrowing down the time windows. The last scenario was infeasible, as even the biggest wellboats were not capable of completing the necessary demand within the time step.

Post-smolt production

An interesting scenario to eventually look into, would be the introduction of post-smolt. This scenario is not tested in this study, due to lack of information regarding those type of operations and involved locations, as it has not been the focus of this thesis.

However would it follow the same procedure as with the offshore locations, introducing a new task, new geographical nodes, and new demands for wellboat operations.

National levels of demand

In the project thesis leading up to this study, an estimation was made to give an indication of whether there were sufficient amount of wellboats to handle the industry's demand in 2017. Based on that work, it is therefor also of interest to try to verify that estimation by running those data in this optimization model. The data file will change to not include any time-windows, other than a time step of a year. Additionally, will the model be used with national levels of wellboat demands, and the national fleet divided into the same size categories as used previously. The fleet and demands used are shown in Table 3.7 and 3.6. Implementing the data in Xpress resulted as infeasable. This was highly expected, and could easily been previewed in the Excel-sheet. With the operations modeled and calculated as they are in this study, the time-use for each operation clearly exceeds the time frame of a year.

6.4 Resulting comment

This chapter has presented the results of the various scenarios and model runs in Xpress, briefly commenting the result after each run. The used and implemented data clearly affects the results, but gives here an indication of the appropriate fleet composition and routing decisions for each scenario. The routing itself follows the anticipated sequences, continuing with the same type of task if possible. Multiple variation can be done to both the available fleet, the demands and the time windows, which will change the routing and possibly, if narrow enough time windows, the fleet composition. Narrowing the time windows even more, or timing the different demands in a more critical manner, will most likely require more wellboats to be used. Alterations to the available fleet shows that other feasible fleet compositions and routing decisions can be used. Bearing in mind the eventual fixed costs or investment costs related to the vessels used, other solution using cheaper vessel types may be found beneficial when looking at the bigger picture and longer term planning decisions. Further comments and discussion regarding the input data and results is presented in the next chapter.

Chapter 7

Discussion

This chapter will discuss the mathematical model and the modeling approach, as well as the input data and the results of the scenarios presented in Chapter 6.3. The chapter will also discuss the applicability of the model presented in this study, its areas of use as a support tool, as well as its areas of improvement to better represent real-life problems. The model performance is briefly discussed at the end of the chapter.

7.1 Scenarios and input data

In this study, multiple scenarios were made with the intention of evaluating the applicability and areas of use of the model. The scenarios were made deterministic with data mostly based on pure assumptions, as the focus was more on the modeling than on finding exact solutions. Thus, will the results not give an accurate description or representation of the real-life problem. However, the assumptions were made the most realistic possible with the attempt to provide the most correct perception of the reality, and provide as a basis for further development of the decision support tool.

The time-use related to the wellboats and its operations was purely based on the data found on the existing fleet of wellboats, and the associated information given on transport volume, loading capacity and service speed. Hence, were the total time-use related to the operation of the wellboats a direct result of the capacities and capabilities of the vessels. These parameters were set as average values based on the list of the wellboats found, which might have been misleading if not a correct representation of the average vessels. Setting incorrect values to either capacities, demands, fish weights, MST, loading rates and such, could pose major impact on the total time-use and. Disregarding certain features and parameters related to the operations may also contribute to give a misrepresentation of the time-use in the real-life problem. Among others, would probably the time-use related to manoeuvring and preparations at the different locations make up a significant time addition. However is this one of the many alterations one can make in the Excel-sheet if anything is left out or disregarded, and the already existing parameters can be changed after own preferences for further use.

The distinctive vessel types were all initially assigned the same service speed to be used for the scenarios due to the vague information found. This, together with the use of a constant speed throughout all operations, is probably a great source of error. Nevertheless, testing the model with different speeds for the respective vessel types, it was found that the speed did not play a significant role in the total time-use or in the final result. The time spent in transit is a relatively small contribution to the operation time compared to the time spent on the task itself. The transit distances were made average when merging a number of locations into the different "super locations". This again, with the transit time being a smaller contribution, did not have the greatest impact on the model.

The cost elements and the values used for the different scenarios have not been in focus for this study. Other than the investment costs found in relation to the different vessel sizes, most of the costs were pure assumptions in order to have data to be used in the model. With little knowledge on the costs that incurs at the different stages and locations of operation, most cost elements were disregarded for this study. The cost parameters used were however assigned somewhat logical values set in the same order of magnitude and in proportion to each other, such that the different parameters would have an impact on the result. In addition to the service speed, the fuel consumption was also assumed constant, where it might would have been more realistic to model it according to the mode of operation. With the fuel costs being such a central part of the variable costs, it could have had a great impact on the associated cost of operation and again on the final outcome. This could have been taken into account in Excel, by adding different fuel consumption to each mode of operation for each vessel type.

The previous chapter presented the results of the various scenarios and model runs in Xpress, with brief comments of the result after each run. The used and implemented data clearly had an effect on the results, but gave for this study an indication of the appropriate fleet composition and routing decisions for each scenario. The routing itself followed the anticipated sequences, continuing with the same type of task if possible. This is more or less solely due to the transition costs applied when going from one task to another, assigned values provoking the routing sequence. Assigning these costs all the same value, the routing become quite random in the model runs without time windows. As these transition costs were taken out of thin air, this might be quite misleading, and the wellboats could possibly follow a completely different routing policy.

Multiple variation can be done to both the available fleet, the demands and the time windows, which will change the routing decisions, and possibly the fleet composition if narrow enough time windows. The more time available to service the required demands, the higher amount of possible solution are there. The routing is to a large degree based on time-use and which vessels that actually have sufficient capacity to execute the different tasks within the set time limitations. Reducing the time windows, or timing the different demands in a more critical manner, leads to less options and will most likely require more or larger wellboats to be used. The same accounts for increasing the demands, requiring more or larger vessels to handle the demand within the given time frame. Though, with too high demands set, as with the 100 % - lice scenario, the demand becomes too big for one vessel to handle alone within the time frame. Placing the time window related to a larger task late within the time frame, might also lead to an infeasible solution. This suggests and indicates a need for the model to include the opportunity for more than one vessel to operate on a task. Reduced demands on the other hand, shows the possibility of the smaller sized vessels also being able to operate and handle the demands on time, but at a greater cost. These operations tends to be of the smaller kind with less quantity demand, such as smolt transportation. Thus, can it be concluded that the set values for loading capacity and loading rate for the respective vessel types, plays a significant role in the choice of vessels and their routing decisions.

The model is built in a way that can regulate the fleet size, varying the number of each vessel type in the fleet. Alterations to the available fleet shows that other feasible fleet compositions and routing decisions can be found and used, though not optimal. Bearing in mind the eventual fixed costs or investment costs related to the vessels used, other solution using cheaper vessel types may be found beneficial when looking at the bigger picture and the longer term planning decisions.

7.2 The modeling approach and applicability

The modeling approach for this study was an optimization model made as small and generic as possible, by moving a lot of the data pre-processing out of the model itself and into Excel. The layout and data in Excel was attempted set up as systematic as possible, with the data gathered into organized tables, and the extraction and calculation of data performed through logical Excel-functions. The idea behind the Excel-spreadsheets was to provide flexibility, using the same set up to run multiple scenarios and analyses. The set up made for this study is in accordance with the problem size and area, and serve as a basis and illustrative example of how this decision support tool can be used.

With an overview of the farming locations involved in the problem area, the type of tasks, its involved geographical nodes and demands can easily be regulated according to the service task needed at each location at a given time. Meaning, each location can be assigned all service tasks, vary the demand after need, and through geographical nodes and a distance matrix decide between which locations the transportation is needed. As the model and the data file would have been to extensive to run with each individual wellboat characteristic, the vessels were categorized into three vessel types. This also gave the opportunity to vary the number of each vessel type, and thereby easily regulate and adapt the fleet size. This way, the fleet size can either be set beforehand or adapted according to the varying demands, though manually. The vessel data is represented in a table with the average vessel data associated with each vessel type. This table can easily be expanded if more categories is needed or new vessel types are introduced at the market. Further scaling of the problem size can be done by either adding new tasks, locations or geographical nodes in the Excel set-up, and applying the same logical function and process as before. The amount of demand in need of service can be regulated in its own spreadsheet by choosing the amount of licenses within each location to be serviced. This is an easy way of keeping control of and regulating the demands. All alterations and expansions are done in Excel, and no changes will therefor be done to the optimization model.

For simplifications, the problem size of this study got reduced by merging a given number of locations into ten "super locations". Doing so, average distances were used, but as previously mentioned not likely to have had any great impact on the result. However is the accumulated demand represented in one "super location" quite large, and probably unrealistically big to be handled by one vessel within a short time window set for the whole ”super location”. This leads to relatively large demands, which in the scenarios mostly calls for the largest vessels for transportation service, which can be misleading as to what is preferred in the real-life problem. Such high demands may becomes too big for one vessel to handle alone within the time frame, and the model is run to be infeasible. As mentioned previously, this suggests and indicates a need for the model to include the opportunity for more than one vessel to operate on a task. This would probably lead to higher expenses for initiating more vessels, but could make sure the task is done within the time limits. How to provide such a possibility is not looked further into, but one would probably have to introduce some sort of restrictions keeping track of the vessels and the loaded demands. A more realistic way to model the problem would be without so many locations gathered into one ”super locations”, and if the model is capable, with all the locations represented separately with each their own time windows.

All the vessel types are modeled to begin at the time zero, for the sake of simplifying the problem. This should probably be modeled such that the time starts when each vessel actually is needed, without requiring the vessel to start at the beginning of the time step. The modeling and resulting routing is possibly not according to normal practice in the industry today. According to the results, if time, the wellboats are working many consecutive hours without stopping or returning to a base. A solution could be introducing maximum operation time for each vessel within each time period, or also the opportunity for a vessel to sail back to base and reused afterwards. Another restriction to include to better represent the real-life problem, is a constraint requiring the vessel to return to base after the maximum of available chemicals is used for lice treatment. This constraint is taken care of in Excel in the case where the demand for lice treatment at one ”super location” is exceeding the limit for chemicals, by requiring the vessel to make an extra trip back to the base for refill. However, does it not take into account lice treatment at multiple locations. It is for this study assumed that all vessel types can undertake all operations, which to this date is quite correct. For the future however, and especially with regards to the operations offshore, this might not be the case. For such cases, it could be of interest to introduce constraints preventing inadequate vessels from operating offshore, or other inappropriate vessel types to operate on certain tasks.

When it comes to using the model as a tool for deciding upon fleet composition, it is in the simplest manner and in accordance with the routing decisions. It does not include the future aspect of looking at which vessels to invest in, which to sell, or which to rent in for certain tasks. However, does it give an impression of an appropriate fleet size and a composition of vessel types that can handle a given demand. Thus is the model most appropriate for tactical planning problems, looking at medium-term decisions for weekly and monthly periods of time. The optimization model could be of interest for either a salmon farming company or a wellboat shipping company, wanting to reducing the costs of operating their fleet while servicing the farming locations.

7.3 Model performance

The solution time is an essential factor when looking into the performance of the model. As a planner you often need to make fast decisions, which requires a model to be run and to provide an optimal or a close to optimal solution relatively fast. Most of the scenarios run in this study provided optimal solutions with a 0 % gap, with a varying solution time from scenario to scenario. With this model being run with highly assumed and unrealistic numbers, it was not found necessary to solve all problem scenarios to a 0 % gap. However, were there only three scenarios that were not run to 0 and optimal solutions. These included the two least constrained low demand scenarios, as well as the fall scenario without time windows. The latter was run for almost 18 hours, reaching a 7 % gap to the best bound solution. The other two were headed towards using the same amount of time, if not more, and stopped at a 17 % gap. Tendencies showed that the solution time decreased the more constrained the problem got, by either narrowing down the time windows or increasing the demand. All the scenarios run with no constraining time windows other than the time step could run for hours. The only scenario without time windows kept within reasonable solution times, was the spring demand scenario. A theory is that the less constrained the model is with smaller demands to handle, and with more time available to execute each task, the model uses a lot more time to solve the problem.

Chapter 8

Conclusion

In this report, it is presented an optimization model aimed for the aquaculture industry for fleet composition and routing of wellboats. As the aquaculture industry is experiencing remarkable growth and technological development, so is the fleet of wellboats in order to respond to the growth and development. A model aimed for this industry could therefor be of high value as a decision making support tool to make and evaluate decisions regarding fleet composition and routing of wellboats in relation to the future transportation demands and requirements. The model is made deterministic, with the objective to minimize the costs of operating a fleet of wellboats while ensuring all demands are serviced.

The model is presented as an arc flow formulation of an industrial ship scheduling problem with full shiploads, with resemblance to a VRPPDTW. The model formulation is kept quite simple, by moving a lot of the data pre-processing out of the optimization model in Xpress and in to Excel. Doing so, the optimization model is simplified and made more generic and flexible.

To test the applicability of the model and the model performance, the model is run with multiple scenarios. The seasonal scenarios were run with the attempt to evaluate and determine a fleet composition suited for each seasonal demand, before determining a suitable fleet composition adapted to work for all seasons. This resulted in an optimal fleet consisting of at least two wellboats of type 3, and an additional wellboat of type 2. The model was also run with scenarios testing the affects on fleet composition and routing due to new additional tasks in the form of alternating lice demands and offshore aquaculture. These model runs showed a need to expand the fleet set to handle the seasonal demands, which seem quite reasonable given that most of the scenarios implied increased demand for wellboat operations. The routing decisions for each scenario tended to follow the expected sequence, according to the transition costs and time windows set.

Given that most of the time and cost elements used for calculations are mostly assumptions, the results of running the model might be a misrepresentation of the real-world problem. Nevertheless, the aim of solving this problem is not to receive in-depth and exact solutions to the problem, but rather to look at its applicability and give an indication of what the model is able to contribute with. Therefore, more focus has rather been put into the Excel-file and its flexibility to adapt to multiple scenarios. The model has its shortcomings, but can be concluded to be a good basis for further development, to possibly become a contributing decision making tool to be applied in the aquaculture industry.

8.1 Further Work

To the author's knowledge, it does not exist a lot of research nor models proposed for similar problems, which sets its limitations. For further work, it would first and foremost be of interest to model the problem in correspondence with the aquaculture industry, gaining more thorough insight into the industry and its operations. More correct operational data, as well as more accurate time and cost elements used for the calculations, could most likely improve the model and result in a more representative impression of the real-life problem.

For further use of the model, it would also be seen as ideal to break up the "super locations" and set more appropriate demands and time windows for each location. For this study, hard time windows are applied. However, could it be an interesting option to introduce soft time windows and operate with controlled time window violations. This would allow the service to begin outside the time windows, and might lead to better routing and scheduling, and possibly a reduction in transportation costs.

Multiple of the restrictions mentioned in the discussion should be applied for better and more accurate routing decisions in accordance with the real problem at hand. This goes in particular for the lice treatment constraints, as well as introducing the possibility for multiple vessels to work on the same task. With the aquaculture moving farther offshore, the constraints related to preventing certain vessel types from servicing the offshore cages could be interesting as well. With the industry setting stricter regulations to both the wellboats and routing along the coast due to environmental regulation, this could also be an area for further work by differentiating between which vessels to navigate in which zones.

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Appendices

Appendix A

Scope of Work

NTNU Trondheim
Norwegian University of Science and Technology
Department of Marine Technology

MASTER THESIS IN MARINE TECHNOLOGY

SPRING 2017

For stud.techn.

Hanne Hornsletten

Optimization model aimed for the aquaculture industry for fleet composition and routing of wellboats

Background
The Norwegian aquaculture industry is continuously seeking further growth, and aims to almost fivefold today's salmon production within the year of 2050. In order to obtain such a strong expansion of the industry, Norway is today faced with multiple challenges. All depending on how these challenges are met and possibly solved, and the future development of the industry, a corresponding demand for wellboat operations is required. Stricter wellboat regulations, together with the possible future production volumes and tasks, are important aspects when evaluating the future size and composition of the fleet of wellboats. The underlying routing decisions are equally essential in order to enhance the fleet utilization. An optimization model aimed for this industry could be of high value as a decision making support tool to make and evaluate decisions regarding fleet composition and routing of wellboats in relation to the transportation demands and requirements.

Objective
The main objective of this thesis is to propose an optimization model, which can be used for fleet composition and routing of wellboats in the aquaculture industry. The model shall be implemented in a commercial solver to test its performance and its applicability to solve real-life problems.

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

a. Present the real-life system
b. Describe the problem to be modeled
c. Briefly review and present relevant literature
d. Develop a mathematical model, which describes the simplified version of the real problem
e. Collect relevant data necessary for a computational study
f. Implement and solve the mathematical model in Xpress IVE to test the performance of the modeling

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.

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Department of Marine Technology

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

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

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

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

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

Supervision:
Main supervisor: Bjørn Egil Asbjørnslett

Co-supervisor: Inge Norstad (SINTEF)

Deadline: 30.09.2017

Appendix B

Attachments

Included in the attached zip-file:

- Xpress-IVE code for the optimization model
- Excel-file with all relevant calculation spreadsheets for the input files
- Input files for the different scenarios
- Excel-file with the wellboat fleet, size distribution and estimation related to previous work
- Academic poster

Appendix C

Mathematical Model

Sets and Indices

Set	Description	Index	Range
N^T	Set of tasks	i, j	{1,2,...,n}
N	Set of nodes	i, j	{0,1,...,n+1}
V	Set of vessel types	v	{1,...,v}
$\{o, d\}$	Origin and destination nodes	v	{0,n+1}

Parameters

C_{ijv}	Cost for operating vessel type v between task i and j.
V_v^A	Number of available vessels of type v in the fleet.
T_{ijv}	Time it takes for vessel type v from arrival at task i until arrival at task j.
T_i^{MIN}	Earliest time for start of service on task i.
T_i^{MAX}	Latest time for start of service on task i.
M	Big M used to linearize the time constraints.

Variables

x_{ijv}	1 if the vessel sails from node i to j, 0 otherwise.
t_{iv}	Time before vessel v starts the service on work task i.

Objective function

$$minimize \quad z = \sum_{i \in N} \sum_{j \in N} \sum_{v \in V} C_{ijv} x_{ijv} \tag{C.1}$$

s.t.

$$\sum_{v \in V} \sum_{j \in N} x_{ijv} = 1, \qquad i \in N \tag{C.2}$$

$$\sum_{j \in N \setminus \{d(v)\}} x_{o(v)jv} = 1, \qquad v \in V \tag{C.3}$$

$$\sum_{i \in N} x_{ijv} - \sum_{i \in N} x_{jiv} = 0, \qquad j \in N \setminus \{o(v), d(v)\}, v \in V \tag{C.4}$$

$$\sum_{i \in N \setminus \{o(v)\}} x_{id(v)} = 1, \qquad v \in V \tag{C.5}$$

$$x_{ijv}(t_{iv} + T_{ijv} - t_{jv}) \leq 0, \qquad v \in V \tag{C.6}$$

$$T_{iv}^{MIN} - t_{iv} \leq 0, \qquad i \in N, v \in V \tag{C.7}$$

$$T_{iv}^{MAX} - t_{iv} \geq 0, \qquad i \in N, v \in V \tag{C.8}$$

(C.9)

$$x_{ijv} \in \{0, 1\}, \qquad (i, j) \in N, v \in V \tag{C.10}$$

$$t_{iv} \geq 0, \qquad i \in N, v \in V \tag{C.11}$$