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# Fleet Scheduling of Service Vessels used in a more exposed Norwegian Aquaculture Industry

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# Preface

This thesis is written by Henrik Ramm and Alexander W. Berge and is our master thesis at the department of Marine Technology at the Norwegian University of Science and Technology. The purpose of this master thesis is to investigate how fleet scheduling of service vessels in the Norwegian aquaculture industry can be improved, and demonstrate how optimization models can be used in order to create robust fleets in a more exposed aquaculture industry.

People reading this report should have basic knowledge about the Norwegian fish farming industry, simulation using Simulink, optimization, and the programming language MATLAB.

All group members have contributed with a fair share of the work during this report. And all the work has been performed with both group members contributing.

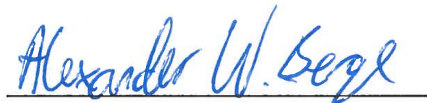
We would like to give a special thank to our supervisor, Professor Bjørn Egil Asbjørnslett for guidance and feedback during the semester. We would also like to thank our co-supervisor Inge Norstad with help and guidance when formulating our optimization model.

Finally we want to thank the EXPOSED centre, Marine Harvest and SalMar for providing weather data used in the models. In addition, we would like to thank contributors from the Norwegian aquaculture industry for providing information regarding their daily operations.

The Norwegian University of Science and Technology, June 23, 2017



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## Summary

This thesis studies a maritime transportation problem for service vessels used in the Norwegian aquaculture industry. We create an optimization model which try to find the most efficient fleet size and mix and associated routes in order to meet a specific demand for maintenance. A simulation model is used to evaluate if the routes are realistic.

The system which is modelled consists of several types of maintenance operations which are common in today's aquaculture industry. These are delousing, cleaning operations, handling of moorings, inspections, change of nets and transfer of personnel. The jobs are typically performed by three different vessel types, 15 m catamarans, 25 m catamarans or 40 m monohulls. In addition to today's industry, the thesis discusses possible future scenarios for service vessels which are handling of waste, sea grass farming and tourism.

The need for better production environment and increased production area have caused fish farmers to move their facilities towards more exposed locations[44]. In order to reduce the risk of delays and increase the operational window for maintenance operations, vessels with better seakeeping abilities are necessary. Such vessels involve increased investment and operational costs.

More advanced vessels increases the demand for more efficient routing. Performing jobs in a suboptimal order will lead to unnecessary costs regarding fuel consumption, salary for crew members and dead time. Furthermore, varying weather conditions increases the need for better planning in order to avoid aborting operations. By investigating how the likelihood of vessels not being able to perform their jobs varies with different weather scenarios, we see how the planning process is affected.

The thesis uses a route generation algorithm combined with a set partitioning model to solve the optimization problem and find optimal fleets and routes for the given scenario. The route generation algorithm finds all possible routes based on constraints regarding vessel type and time windows. The possibility of implementing different weather scenarios is also included.

The weather is based on wave data from a buoy placed outside of Frøya in Sør-Trøndelag.

Different weather scenarios are created by the use of Markov chain simulations. The weather conditions varies between 10 states representing different significant wave heights.

The simulation model evaluates how the routes suggested by the optimization model perform when different weather scenarios are generated. The model created is generic. The vessels used, routes travelled and jobs performed are all defined from an excel sheet which is used as input to the simulation model. By studying results from the simulation model we see how each route performs and how many jobs are executed within their time windows.

The simulation model is run with both calm and rough weather. By including rough weather, the robustness which is defined as number of jobs performed within their given time windows, decreases by 18% compared to the simulation with calm weather.

We test three different approaches which could increase the robustness of the optimization model. These are:

- Including weather constraints in the route generation algorithm.
- Setting a limit regarding how many jobs are allowed on each route.
- Including slack in the route generation algorithm.

The two methods showing most promising results are maximum number of jobs per route and slack. Implementing the methods separately lead to an increase in robustness by 7% and 3%, respectively. The cost increases are only 1% and 2%, respectively. By combining the two constraints we are able to increase the performance by 8% compared to not including any constraints. However, we see that even with these additional constraints included some of the routes are quite exposed to delays and additional actions might be necessary.

Further work regarding this topic should be directed towards better modelling of the real life scenarios. In order for the method to be more attractive to the industry, the algorithms used need to be more effective in order to be able to solve larger problem instances. In addition, the models need to represent the daily operations of the vessels in a more realistic way.

# Sammendrag

Denne oppgaven omhandler en studie av et maritimt transportproblem for servicefartøy i den norske oppdrettsnæringen. En optimeringsmodell lages for å finne den mest effektive flåtestørrelsen og tilhørende ruter for å imøtekomme et spesifikt behov for vedlikehold. En simuleringsmodell brukes til å vurdere om rutene som er foreslått er gjennomførbare.

Systemet som er modellert består av flere typer vedlikeholdsoperasjoner som er vanlige i dagens oppdrettsindustri. Disse er avlusing, vaskeoperasjoner, håndtering av fortøyninger, inspeksjoner, skifte av not og transport av personell. Jobbene utføres vanligvis av tre forskjellige fartøystyper, 15 m katamaraner, 25 m katamaraner eller 40 m énskrogsfartøy. I tillegg til dagens industri diskuterer oppgaven mulige fremtidsscenarioer for bruk av servicefartøy som involverer håndtering av avfall, oppdrett av tang og tare, og turisme.

Behovet for bedre produksjonsmiljø og økt plass har ført til at fiskeoppdretterne flytter sine anlegg mot mer utsatte områder [44]. For å redusere risikoen for forsinkelser og øke operasjonsvinduet for vedlikeholdsoperasjoner, er det nødvendig med fartøy med bedre sjøegenskaper. Slike fartøy innebærer økte investeringer og driftskostnader.

Mer avanserte fartøy øker behovet for mer effektiv ruting. Å utføre jobber i en suboptimal rekkefølge vil føre til unødvendige kostnader relatert til både drivstofforbruk og lønn til dekksmannskap. Videre øker varierende værforhold behovet for bedre planlegging for å unngå å måtte avbryte operasjoner. Ved å undersøke hvordan sannsynligheten for at et fartøy ikke er i stand til å utføre en jobb varierer med forskjellige værscenarier, ser vi hvordan planleggingsprosessen påvirkes.

Opgaven bruker en rutegenereringsalgoritme kombinert med en matematisk optimeringsmodell for å løse optimeringsproblemet og finne optimale flåter og ruter for det antatte scenariet. Rutegenereringsalgoritmen finner alle mulige ruter basert på begrensninger angående fartøystype og tidsvinduer. Muligheten for å implementere forskjellige værscenarier i rutegenereringen er også inkludert.

Været er basert på bølgedata fra en bøye plassert utenfor Frøya i Sør-Trøndelag. Ulike

værscenarier opprettes ved bruk av Markov chain simuleringer. Værforholdene varierer mellom 10 tilstander som representerer forskjellige signifikante bølgehøyder.

Simuleringsmodellen evaluerer hvordan rutene foreslått av optimeringen presterer når ulike værscenarier genereres. Modellen er generisk og fartøy, ruter, og vedlikeholdsjobber er alle definert fra et Excel-ark som brukes som input til simuleringsmodellen. Ved å studere resultatene fra simuleringsmodellen ser vi hvordan hver rute presterer og hvor mange jobber som blir utført innenfor deres angitte tidsvinduer. Slik kan vi evaluere sannsynligheten for forsinkelser.

Simuleringsmodellen kjøres med både pent og dårlig vær. Ved å inkludere dårlig vær, reduseres robustheten som defineres som antall jobber som utføres innenfor de angitte tidsvinduene, med 18% sammenlignet med pent vær.

Vi tester tre forskjellige tilnærminger som kan øke robustheten til optimeringsmodellen. Disse er:

- Inkludere værbegrensninger i rutegenereringsalgoritmen.
- Angi en maks grense for hvor mange jobber som er tillatt per rute.
- Inkludere slakk i rutegenereringsalgoritmen.

De to metodene som viser mest lovende resultater er maksimalt antall jobber per rute og slakk. Implementering av disse metodene hver for seg fører til en økning i robusthet med henholdsvis 7% og 3%. Kostnadsøkningene er henholdsvis 1% og 2%. Ved å kombinere de to metodene øker robustheten med 8% sammenlignet med resultatet uten noen tilleggsbegrensninger. Vi ser imidlertid at selv med disse ytterligere begrensningene er det noen av rutene som fremdeles er nokså utsatt for forsinkelser, og det kan være nødvendig med ytterligere tiltak for å unngå forsinkelser.

Videre arbeid med denne oppgaven burde rettes mot bedre modellering av operasjonsprofilene til fartøyene. For at metoden skal være mer attraktiv for industrien, må algoritmene som brukes være mindre tidkrevende for å være i stand til å løse større probleminstanser. I tillegg må modellene representere den daglige driften av fartøyene på en mer realistisk måte.



# Nomenclature

AGD - Amoebic Gill Disease

AHTS - Anchor Handling Tug Supply

AUV - Autonomous Underwater Vehicle

cat - Catamaran

DES - Discrete event simulation

EAC - Equivalent Annual Cost

KPI - Key Performance Indicator

LCC - Life Cycle Cost

LNG - Liquefied Natural Gas

m - Meter

mono - Monohull

NOK - Norwegian Kroner

RONC - Remotely Operated Net Cleaner

ROV - Remotely Operated Vehicle

TOC - Total Operational Cost

TSP - Traveling Salesman Problem

VRP - Vehicle Routing Problem

VRPTW - Vehicle Routing Problem with Time Windows



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# 1 Introduction

The Norwegian fish farming industry has had a remarkable growth the last decade. The need for increased food production has caused Norwegian salmon to become a major export industry, delivering approximately 14 million meals of salmon everyday[29]. The growth in the aquaculture industry along with the technological development, has created a market for service vessels designed for maintenance of fish farms along the coast of Norway.

A look into the key figures from selected service vessel companies show a large increase in revenue. Two of the biggest companies in Norway, AQS AS and Frøy Akvaservice AS, have had an increase in operational revenue of 200% [39] and 160% [40], respectively from 2013 to 2015. Out of today's 51 service vessel companies, 26 have been established after 2010. These companies operate a total of 261 vessels, where 133 have been delivered after 2014 [26].

The need for better production environment and increased production area have caused fish farmers to move their facilities towards more exposed locations[44]. In addition to better growth conditions caused by increased flow of water, this reduces unwanted environmental impacts on the Norwegian coastline. Examples are increased amounts of salmon lice and spread of diseases. However, the farming companies who have placed production facilities at more exposed locations, report of increased difficulties maintaining a regular production [42]. The exposed locations have stronger currents and winds, and bigger waves, increasing the structural loads on the facilities and complicating regular operations.

A series of incidents the last years resulting in injuries, and increased danger of damage on equipment as a consequence of more exposed fish farms, have lead to bigger and more complex service vessels. The increase in complexity of vessels and number of service vessels, cause an increasing demand for efficient routing to avoid dead time and unnecessary costs.

## Background

Norway has for generations been among the best in world regarding ocean space. This is mostly because of our long coastline, competence, long-term thinking, courageous decisions and knowledge about ocean technology. The three big ocean space industries; marine, maritime and offshore are the most complete industries in Norway [47]. The Norwegian ocean space industry has lead to the growth of welfare in Norway for generations and has lead to that the Norwegian industry today is a world leader within numerous ocean space industries.

Ocean farming is a relatively young industry that has had a significant change in technology the last 40 years. From the commercial breakthrough of the Norwegian aquaculture industry in the beginning of the 1970s, where each fish cage only consisted in volume of a few thousand cubic meters, to being the second largest exporter of seafood in the world in 2017. The Norwegian salmon farming industry has increased the production by 4000 tonnes since 1980. After a period of 20 years with very high production growth of salmon in Norway of about 10% each year, the production growth stagnated in 2013. The main reason was due to salmon lice and increasing strain on the Norwegian coastline[35].

The Norwegian government's goal is to increase the production volume from one million tonnes in 2010 to 5 million tonnes by 2050. Sustainable solutions must therefore be developed to reach this target. However, the issues regarding salmon lice must be resolved in order to obtain this goal. New technology often comes from other related industries, like for example offshore and fishery. These industries have for many years been used to the rough working environment in the North sea. This knowledge and competence can be transferred to the ocean farming industry.

As any other nature based industry it is expected that the aquaculture industry should exercise and expand in an environmentally friendly and sustainable manner. Challenges for a sustainable operation varies over time and the main issues in the aquaculture industry in Norway in 2017 are summarised on the next page.

**Main challenges:**

- Mortality and reduced fish welfare due to lice.
- Effects on wild salmon caused by salmon lice from fish farms.
- Escaping of fish from fish farms and genetic influence of wild salmon.
- Spread of diseases .
- Emissions of particular materials.
- Access to raw material for fish feed.

A continuation of ocean farming towards 2050 will most likely involve a significant increase in production of salmon, but also a possible diversification of new species. This may involve several species of fish, seaweed and sea grass, shell and crustacean.

A realistic sustainable growth in ocean farming requires many states of indicators to cover the ecological influence the fish farms have. Increased knowledge and an assessment of ecological effects of ocean farming, together with development of new technological solutions are required to obtain a sustainable growth in the aquaculture industry.

Should the aquaculture industry succeed in achieving the goal of growth, there will be a need for new developments of fish farms to solve the environmental challenges ahead. This requires companies in the industry, that have the capital to invest in research, development and commercialisation of the new systems.

The need for increasing consolidation and professionalism in both the aquaculture industry and supply industry are therefore crucial. A collaboration between the different maritime industries is necessary in order to take advantage of solutions and knowledge other industries have. The offshore industry has great knowledge about offshore construction that the aquaculture industry should take advantage of in order to build fish farms at more exposed locations. With this transition from inland aquaculture to more exposed locations it is important that the design and capability of service vessels keep up with this development. The increased complexity of vessels and tougher working environment make fleet scheduling important in order to reduce delays and make sure the necessary maintenance operations are performed in an efficient way.

**State of art**

Very little research has been conducted regarding logistics of service vessels in the aquaculture industry. The existing research mainly consist of design of vessels and risk analysis.

SINTEF carries out a research project to investigate the existing vessel designs, and come up with solutions on how to improve the designs. The project is based on an identification of the most critical operations in today's industry involving service vessels. Based on the results they come up with two designs for service vessels which should decrease risk and increase operability during maintenance operations.

Berge & Ramm 2016[3] perform a literature study regarding the service vessels used in the Norwegian aquaculture industry. Based on the information found, a simulation model is created to see how a set fleet of service vessels are able to handle a certain amount of demand for maintenance. An increase in operational limit for the vessels is tested in order to see how the fleet capacity increases in the simulation model.

No research has been done regarding optimization within logistics of service vessels. The problem remains to be solved to evaluate fleet performance and create a decision support tool for better fleet scheduling.

**Objective**

This thesis aims to study a maritime transportation problem for service vessels used in the aquaculture industry. Based on information gathered during the work with the project thesis written the fall of 2016, we will create an optimization model which will try to find the most efficient fleet and associated routes in order to meet a specific demand for maintenance. The optimization model will be tested on a hypothetical scenario, which will be based on a more exposed industry. The aim for the optimization model is to demonstrate how such a method can be utilised in order to increase fleet efficiency and how mathematical models can be used in order to improve the planning process.

In order to evaluate the fleet created with the optimization model we will create a simulation model where rough weather will be included. By doing this we wish to gain insight into how bad weather may create delays and how likely it is for delays to happen. We also wish to use



the results from the simulation model to analyse how additional constraints can be added to the optimization model in order to reduce the probability for delays to occur.

### **Structure**

This thesis is structured as follows. Chapter 2 presents the system which we try to model. This consists of the service vessels used in today's industry and the maintenance operations required. In addition, possible future operations for service vessels are discussed. Chapter 3 examines the problems which we analyse. Some of the main difficulties faced by the farmers today and the service vessel owners are discussed. Chapter 4 presents research done within the fields of optimization regarding maritime transportation problems in addition to research within discrete event simulation. We present related articles and their findings. Chapter 5 describes the methodology, consisting of optimization and simulation, and theory related to the models. We also present the software used in the thesis. Chapter 6 discusses the operability of the service vessels used in today's industry. We present weather data obtained from the areas where the vessels operate, and figures displaying the likelihood of vessels being able to operate for two different weather scenarios. Chapter 7 presents the optimization model and the hypothetical scenario created. It also discusses potential strategies for increasing robustness. Chapter 8 describes the simulation model and its architecture, before chapter 9 presents results from scenarios tested in the optimization and simulation model. Chapter 10 discusses the results found in chapter 9 and their credibility, based on limitations and assumptions. In chapter 11 we make a conclusion regarding our findings and summarise our work. Chapter 12 discusses possible further work.

## 2 System description

We will in the following chapter present the real life system which we are going to model. This system consists of service vessels, aquaculture facilities and the regular maintenance operations which need to be performed on these facilities. We will also discuss how the future of this system might look like, by presenting developing trends seen in the industry.

### 2.1 Maintenance operations

This thesis focuses on the use of service vessels to perform maintenance operations on fish farming facilities involving the use of fish cages. There are many different maintenance operations that require the use of service vessels and we will in this section present the operations included in our model.

#### 2.1.1 Cleaning of nets

One of the most common operations is cleaning of nets. The nets are cleaned using a remotely operated net cleaner (RONC). This machine uses high pressure washers to remove the fouling. The nets are cleaned approximately every 10th day at most. The demand for cleaning varies depending on water temperature and weather conditions, like strength of currents. The demand is usually at its highest during late summer and lowest during winter. Each cleaning operation varies in duration depending on weather condition, amount of fouling, and size of net, but average duration is around three hours[8]. When cleaning operations are performed, the service vessel usually cleans the whole facility before moving on to another operation.

#### 2.1.2 Delousing

Delousing has recent years become one of the more regular operations carried out at salmon farming facilities. Due to strict limits imposed by the Norwegian Food Safety Authority

(Mattilsynet) regarding number of lice on each salmon, the salmon farmers have to perform regular delousing operations in order to be allowed to continue production. These limits state that each salmon is only allowed to have 0.5 sexually mature lice on average. During spring season the limit is reduced to 0.2 for six weeks, because this is when newborn wild salmon travel from the rivers, out the fjords and into the ocean. The newborn salmon have not yet developed the ability to withstand lice and are therefore very fragile. The salmon farmers have to count lice, and as of 2012, send in weekly reports at least every 14th day, and every 7th day when the sea temperature is over 10 degrees celcius [49]. If the amount of lice is above the limit, reducing measures have to be carried out. We will in the following present some of these measures. This presentation is based on a report published by Nofima May, 2017 [33].

#### **2.1.2.1 Medical delousing**

Medical delousing involves the use of pharmaceutical substances which effectively kills the lice. This has been, until quite recent, the most commonly used delousing method. It is effective and in addition it has a low death rate for the salmon. However, since the lice have a very short life span and new generations of lice are born very often, the lice have become resistant to these pharmaceuticals and the effectiveness of this delousing method has dropped significantly [6]. Due to this problem the delousing techniques have started to shift from medical to mechanical. In 2016 the number of medical delousing operations decreased with 41% while the number of non-medical delousing operations increased with 535% compared to 2015 [57].

#### **2.1.2.2 Mechanical delousing**

Mechanical delousing methods involves handling of the salmon and mechanically removing the lice from the salmon. The salmon is pumped on board a vessel where the lice is usually hosed and/or brushed off. This method is environmentally friendly, has a big capacity and is quite effective, but often leads to high death rates among the salmon as a direct consequence

of the treatment, in addition to salmon being injured [33]. Especially the outer skin layer of the salmon can be affected, making the salmon more susceptible to infections. In addition the salmon has to be starved before treatment which is expensive.

### **2.1.2.3 Thermal delousing**

Thermal delousing involves the use of lukewarm water which makes the lice fall off the salmon. The salmon are pumped on board the ship where they are exposed to lukewarm water for about 20-30 seconds before being pumped back into the fish cage. The method is environmentally friendly, has a large capacity and is easy to perform, however the death rate is quite high. In addition the warm water has a negative effect on the health of the salmon making them more susceptible to diseases. The salmon also has to be starved before treatment.

### **2.1.3 Handling of mooring**

Handling of moorings are also one of the more common operations. The net cages are usually kept in place by a mooring frame which make sure the cages stay together. The whole frame is kept in place by additional mooring lines and anchor lines attached to the seabed. The moorings have to be checked regularly to make sure that the fish cages are kept in place. If discrepancies are found, the moorings need to be tightened or replaced. Inspections of moorings are usually done using ROV's, but can also be done using divers. Handling of moorings often requires heavy lifting and thus vessels with stronger cranes and better stability. These operations are therefore often performed by 25 m catamarans. Handling of mooring is usually done for the whole facility and the operation takes about two days, depending on the size of the facility [43].

### **2.1.4 Change of net**

Change of net is not performed as often as delousing and cleaning of nets, but it is one of the more complicated operations. A survey performed by SINTEF during the project

"Servicefartøy 2010" stated that change of net was one of the top five most critical operations performed at the farming facilities. This is due to the heavy lifts required which are very exposed to waves. Change of net is done after the salmon is slaughtered. Before a new generation of salmon is deployed into the nets, they have to be cleaned. This is usually done by unstrapping the net from the floating collar, lifting it up and transporting it to a cleaning facility on land. Here it is either cleaned, or if found to be too damaged, replaced by a new net. Change of net takes about 2-5 hours per net [43].

### **2.1.5 Cleaning of floating collars**

Cleaning of the floating collar is one of the easier operations. This is done by the use of a small barge which travels around the whole collar. The collar is lifted up with the assistance of a service vessel, while the barge hoses down the collar and removes fouling. This operation takes about 2-3 hours per collar [43].

### **2.1.6 Transportation of personnel**

Crew needs to be transferred from shore to the salmon farming facilities. As an example, the new facility owned by SalMar which is going to start production during September 2017 will have a crew of four people working on shift for two weeks at the fish cage. This means that every two weeks, crew needs to be transported to and from the facility. This is naturally a quite easy job and does not require technically complex vessels. However, the vessels need to be stable to avoid seasickness, ensure secure transfer of crew from the boat to the facility, and avoid having to wait for calmer seas. The duration for crew transfer naturally depends on the distance from shore.

### **2.1.7 Inspection of anchor lines**

This is one of the more seldom operations. Anchor lines need to be checked every second year [37]. This operation is similar to inspection of moorings and can be done by the use of ROV or divers. If discrepancies are found, the anchors need to be repositioned or replaced.

Inspection of anchor lines takes minimum around 4 hours, but the duration increases with the size of the facility [43].

## **2.2 Service vessels used for maintenance work**

The service vessels used in the maintenance work required to ensure optimal growth conditions for the salmon and avoid losses in revenue, mainly consist of 15 m catamarans, 25 m catamarans and some longer monohulls used for delousing operations. 15 m catamarans are by far the most common vessel, but we see today an increasing demand for larger vessels due to the shift from inshore facilities to more exposed locations. The operational profiles of the vessels vary depending on the vessel type as explained below. For further information regarding service vessels, the reader can look in our project thesis in appendix C, section 2.3.

### **2.2.1 Catamarans**

The catamarans in general have a 12 hour work day[8]. Although the distance back to harbour is usually quite small, often not more than half an hour, the catamarans often stay out by the fish farming facility over night. This is preferred by the service companies as it saves time and fuel. The small 15 m catamarans however, have quite small fuel capacities and need to refill once a week on average. The larger catamarans can run without having to refill for around one month on average, but are usually in harbour at least once a week to refill necessary equipment or food and water.

### **2.2.2 Monohulls**

The large monohulls have a more continuous operation profile than the catamarans, with longer work days. Both Frøygruppen and AQS have 24 hour operation of their delousing vessels, and delousing operations are performed both day and night[8]. The vessels can run between 1-2 months before refilling fuel, but are usually in port more often depending on

what kind of equipment they need for delousing. AQS use hydrogen peroxide for delousing which needs to be refilled after around 3 delousing operations depending on the size of the fish cages and the container capacity of the vessel. For that reason, their main vessel AQS Odin needs to go back to harbour around every second day. Refilling of containers is usually done at night and takes around 4-5 hours[37]. Frøygruppen on the other hand uses a machine called Thermolicer which uses lukewarm water for delousing. This does not need any refilling and their vessel Frøy Fighter can operate continuously for several weeks before harbouring to refill supplies and fuel[43].

### 2.2.3 Developments in the design of service vessels

The newly started service company Laponie Aquaservice believes that the service vessel industry are falling behind in the development when it comes to the size of the fish farms. The founders have 35 years of experience in the field and say that they are familiar with the challenges and possibilities in this industry. Service vessels are too small for the operations they are supposed to perform when the fish farms have grown to a size of up to 200 meters in circumference. The founders have developed a service vessel that is innovative and flexible for cleaning the nets, but also for other tasks. The vessel is built by the modular principle, which means it easily can install other types of equipment, such as delousing and feed equipment [28]. It will with simple adjustments be able to do delousing, towing, sorting of feed and stand-by operations. The new vessel will also reduce the risk at sea according to the company.

Laponie Aquaservice's service vessel will change the nets every three to six months. The operation will be carried out the side of the fish cage and the plan is to replace the flushing of nets which have lead to a flourishing of amoebic gill disease (AGD). To be able to clean and change the nets at the locations and not on land will reduce the costs for the owners, it will become more efficient and be better for the environment, according to Laponie.

The newly started company believes that their new service vessel will become a great offer to an industry that struggles with high operating expenses. The service vessel will be ready

for operation in the beginning of 2018 and is 40 meters long. It is informed to be a service vessel with good bollard pull and lots of deck space in order to be able to do most tasks.

## 2.3 Future scenarios

The aquaculture industry today is in rapid change and the industry screams after innovation and new technology. The Norwegian directorate of fisheries created in November 2015 a new initiative where companies can apply for funding for projects related to considerable innovation. Since they started the program they have received 59 applications, the most recent on the 18th of may 2017. 5 have been approved, 13 have been declined and 39 are still under evaluation [13]. Out of the five concessions that have been given, two are concerned with offshore fish farming while the other three involve closed fish cages. All 5 concepts involve floating structures which will require the assistance of service vessels to a varying extent. Naturally the two concepts involving offshore fish farming will require the most technological vessels, since they are exposed to a rougher environment. However, both companies behind these concepts claim that they will need very little maintenance from service vessels, since most operations will be autonomous. More information regarding these concepts can be found in appendix C, section 2.5. We choose however to have some scepticism regarding this claim and assume that service vessels will be needed to some extent.

### 2.3.1 Delousing

Delousing will in the future with eventual offshore placed facilities still be necessary. This is because salmon lice will always be present in open facilities and the salmon can get injuries and infections from too many lice. The salmon are especially exposed to diseases and infections in the early stages of their life. The industry has stated until recent that salmon lice does not effect the quality of the farmed salmon, and is a danger primarily to wild salmon. However in 2016 there were reports of facilities where the amount of salmon lice was so large that the farmed salmon were severely injured by the lice. The lice had eaten its way into the bone structure of the salmon [6]. Hence the lice have become a problem



for the farmed and not just the wild salmon [57]. This is also because the increase in use of mechanical methods for delousing have lead to an increase in the death rate for farmed salmon. The mechanical methods causes a lot of stress on the salmon and they become more susceptible to diseases.

The demand for delousing using service vessels in more offshore placed farming facilities is not easy to assess. The companies involved in the latest projects regarding exposed aquaculture, claim delousing with assistance from service vessels will not be necessary. This is due to both a decreased demand for delousing when the facilities are placed further offshore, and that delousing can be performed on the facility without the use of external service vessels. This may be true, but the existing inland facilities will continue to need this assistance in the years to come. The change to production techniques that can eliminate the need for delousing operations will take time, and for now no such techniques are commercially available.

### **2.3.2 Handling of waste**

Sludge and other types of emission from salmon farming have caused conflicts in the local societies, problems for inshore fishermen and have lead to an excessive fertilisation in the fjords.

A Norwegian concrete company called Norcem wishes to use the emission as a replacement for coal at the concrete factories. However, this presumes that there will be a transition from open to closed fish farms where sludge will accumulate. The production water and waste need to be carried out in pipes in order to avoid the waste being spread to the fjords [41]. Since the planned transportation method involves pipes and not vessels, we do not expect this problem to involve service vessels and it will not be further discussed.

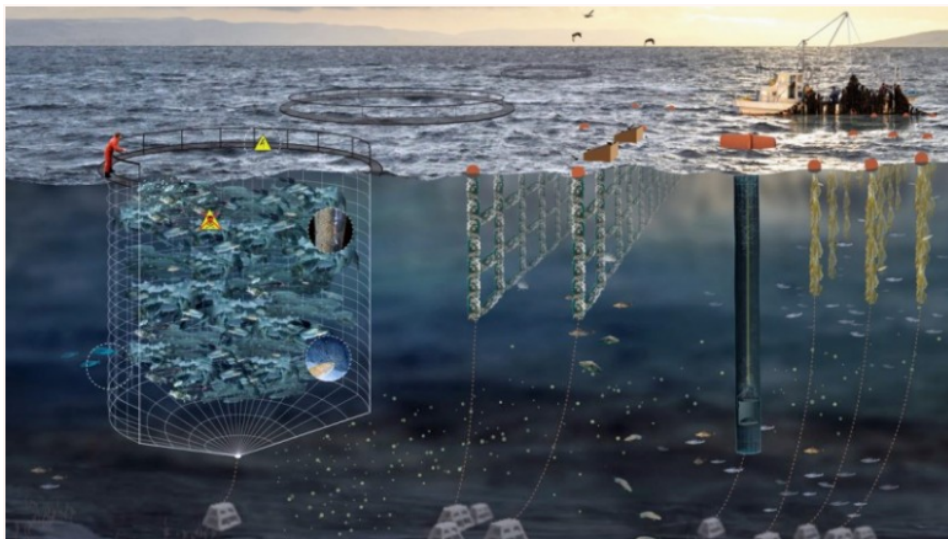
### **2.3.3 Sea grass farming**

The interest for a more environmental way to produce sea weed as an alternative to the raw material production has increased both in Norway and in the rest of the world. Macroalgae

can be a new and useful raw material for provision of food and health products, forage and fish feed, production of biochemicals and bio-materials, fertiliser and bio fuel[4]. The possibilities for innovation and business development based on a general utilisation of the cultivated raw material which macroalgae represent are enormous. However, a development of technology for an efficient cultivating and utilisation of the raw material is crucial to be able profit from macroalgae production.

Approximately sixty percent of the forage that salmon consumes will come out as excrement. Salmon fertiliser is a good nutrient for macroalgae [34]. The production can reduce the environmental load and take advantage of the biomass production within areas that is already used for ocean farming.

Several large salmon production companies have now started to look into the possibility of combining the production of salmon and macroalgae. Production of wild macroalgae was in 2015 about 200.000 tons. A report written by SINTEF Fiskeri og havbruk, states that in 2050, Norway has the potential to produce 20 million tons, which may create a yearly value added of 40 billion NOK [48]. Scientist Aleksander Hånda from SINTEF Fiskeri og havbruk, states that around 10 million tons can be produced in areas where they have ocean farms facilities. He also states that they need new technological developments and methods to make it industrial interesting [34].



**Figure 1:** Showing how the production of macroalgae can be a part of the aquaculture [23].

Figure 1 shows production of macroalgae near a fish farm. The production of macroalgae may be a new possibility to use maintenance vessels. This will highly depend on what kinds of equipment and vessel type that is needed. Maybe a multipurpose vessel will be able to do both the harvesting of macroalgae and maintenance in the future.

### **2.3.3.1 New vessel design for sea grass farming**

Møre Maritime AS received in the beginning of 2017, 8.7 million NOK from Forskningsrådet (the scientific council) to develop a vessel and technology for industrial sea grass farming in Norway. The project will be a part of Forskningsrådet's focus towards a collaboration between the ocean space industries [17]. This shows that the expectations towards an increased production of sea weed and sea grass in Norway can open new possibilities for the Norwegian service vessel industry.

In collaboration with several technology companies in the fishery industry, ocean farming, agriculture, and offshore industry, Møre Maritime will develop a vessel, technology and outfitting to deal with the industrial production, harvest and storage of sea grass.

### **2.3.4 Other work tasks during low season**

During low season the service companies may experience an overcapacity in their fleet. Therefore, they may have to try and find alternative operations for their vessels.

Fish farming facilities have recent years become quite attractive tourist attractions. Due to this there have been created own designated fish cages for tourism. One example is a facility in Vesterålen, where a visit to the facility is usually a part of a bigger tour to experience the local nature [24]. Owners of the facility say that the interest is biggest during the summer months, but the number of visitors during the winter season have increased the last two years. The visitors are usually either tourists, politicians or students on school trips to learn more about the aquaculture industry. These visitors will need transportation from land to the facilities and service vessels may provide assistance in this work. The increased effort regarding tourism is also beneficial for the industry as a way of improving its reputation.

## 3 Problem description

In the following chapter we will present in more detail the problem which we are going to analyse. We will present the main challenges and why this is a problem.

### 3.1 Exposed aquaculture

The advantages of placing salmon farming facilities at more exposed locations are many, but there are also many challenges involved with this change. The stronger currents, increased wave heights and stronger winds complicate the daily operations and maintenance work often has to be postponed due to bad weather [42].

Due to the increase in number of exposed locations, the demand for more complex vessels has increased. In order to reduce the risk of delays and increase the operational window for maintenance operations, vessels with better seakeeping abilities are necessary. Naturally such vessels come at a higher cost, with both increased investment and operational costs.

#### 3.1.1 Efficient fleet scheduling in a more exposed industry

This thesis aims to treat the problem of creating an efficient fleet for a specific demand for maintenance. This problem consists of designing a fleet composition which can handle uncertainties regarding weather conditions in a cost efficient manner. We will treat both the problem of selecting a fleet and finding the most efficient routes to minimise the costs involved. These costs consists of many factors which will be further explained in section 7.2.

Maintenance of aquaculture facilities is today a highly stochastic business with very short planning periods. The industry as of today is dominated by experience and very little integrated decision support systems. There is little use of condition based maintenance and hence maintenance operations are planned shortly before they are needed. This makes it difficult for the operators of service vessels to schedule the use of their vessels in an efficient manner. The biggest service vessel company in Norway, Frøygruppen, operates today a fleet

of 48 service vessels [25]. Naturally, operating such a big fleet requires a lot of planning and there is much room for cost reductions from more efficient fleet scheduling.

The industry today is to a bigger extent than before, a mix of facilities placed near shore at sheltered locations and facilities placed at more exposed locations. This is a challenge for owners of service vessels because they have the choice of investing in cheaper vessels which are sufficient for the inshore locations or investing in vessels which can do operations in rougher conditions as well. These vessels are likely to be overqualified for operations inshore and thus suboptimal from a cost perspective. Since we are focusing on a more exposed aquaculture industry, we will try to design a fleet which can do both in a most cost efficient way while covering the given demand for maintenance. The ship owners can also choose to invest in more flexible vessels which can be used for many different kinds of operations. These vessels do however come with a higher price tag, and an evaluation of cost versus benefits needs to be done.

The trend of placing facilities at more exposed locations does not only increase the demand for more complex vessels, but it also increases the demand for more efficient routing. Performing jobs in a suboptimal order will lead to unnecessary costs regarding both fuel consumption and salary for crew members. One will in addition perhaps not be able to perform as many jobs during the same time period.

The main goal is to design a fleet which will be robust and avoid delays as much as possible. In order to do this we need to be able to test the fleet against unforeseen events and rough weather conditions. We will therefore treat the weather included in the models in such a way that the probability of aborting an operation because of bad weather is reduced. By doing this we wish to demonstrate how planning can be done in a better way to achieve these goals.

We will also investigate how the operability of selected vessel types varies depending on weather scenarios. By doing this we want to see how different weather conditions affects the planning process.

## 4 Related research

The optimization model used in our thesis is based on published articles found in various journals and knowledge obtained through several years of study at the Norwegian University of Science and Technology. Here we will present the present state of research performed in the fields of maritime transportation problems and articles related to this topic.

### 4.1 Maritime Transportation Problems

There are no published articles yet regarding maritime transportation problems in the aquaculture industry. Due to this fact we will focus on articles from the shipping and offshore supply industry where optimization algorithms have become increasingly popular the last decade[5].

Optimization has been used within maritime transportation for many years, and there exists numerous examples of cost reductions from implementing the results obtained from optimization models. In the following we will present articles treating similar problems to ours and discuss their conclusions and findings.

Halvorsen-Weare et al. (2010)[18] have addressed a supply vessel planning problem and created a voyage based solution method for finding the optimal fleet composition. Their method involves a two stage process first generating all possible routes for a given vessel and then finding the optimal set of routes. A computational study shows how the solution method can solve a real life problem given by Statoil, resulting in the optimal fleet composition of offshore supply vessels and their corresponding weekly schedules. The schedules suggested have been implemented by Statoil which report of significant cost savings.

Halvorsen-Weare & Fagerholt (2011)[19] have continued the work regarding the supply vessel planning problem treated by Halvorsen-Weare et al. [18] and analysed the effects of including the value of robustness in their solutions. The same two step approach is used, but the objective function is expanded with a profit associated with robust solutions. This is done

in order to increase the preparedness for unforeseen events. Several different approaches are tested in a simulation model and compared in a computational study. Results show that some potential improvements are possible when different measures for robustness is considered in the model. We will use a very similar approach to this in our thesis regarding the combination of optimization and simulation.

Christiansen et al. (2013)[5] summarised all research performed on ship routing and scheduling during the new millennium and discovered that the number of published articles regarding this topic about doubles every decade. Problems regarding liner network design, maritime inventory routing and maritime supply chains have especially received an increased amount of attention since the potential cost savings are huge.

Pantuso (2013)[38] have summarised the current research regarding maritime transportation problems, and treated the fleet renewal problem using stochastic programming. Pantuso has chosen to model the problem with an increased number of uncertain parameters instead of using deterministic values based on expectancy and thus tried to decrease the gap from theory to real life situations. Pantuso has divided his PhD thesis into four separate papers, each treating different problems. The first paper is a summary of the current research regarding maritime fleet size and mix problems and a suggestion to where more attention should be given due to unresolved issues regarding these problems. One of the conclusions were that existing research focuses too much towards the composition of new fleets instead of fleet renewal. The second paper treats a case regarding uncertainty in fleet renewal. The problem addresses how to adjust the fleet size to meet the changing demand in the shipping industry. A stochastic programming model is presented which is tested on a real life case and proven to give better results than existing deterministic models. The third paper presents a solution scheme for hierarchical stochastic programs especially directed towards fleet renewal problems. The fourth paper discusses which uncertainty is relevant in stochastic fleet renewal problems. From a decision making perspective it demonstrates how to numerically evaluate which uncertainties are more important to capture in the optimization model. Using this model one can evaluate which information is more important to gather early in a decision making process regarding maritime fleet renewal.

## 4.2 Discrete Event Simulation

The applications of DES are endless, but some of the most common areas are health care, the airline industry, supply chain management, production management, assembly lines etc. DES has also been used in the shipping industry especially for terminal logistics, but there are also papers on DES being used in fleet evaluation. There are no published articles regarding DES in the aquaculture industry and the related research therefore consists of simulation models from the shipping and offshore supply industry.

Darzentas and Spyrou (1996)[7] have developed a simulation-based decision aiding tool for ferry traffic in the Aegean Islands. The sources of uncertainty include demand variance and weather conditions. Using the simulation model, the authors have compared several combinations of different vessel types, harbour layouts, routes, passenger and vehicle demands, and even the establishment of new ports. The main measures of efficiency include the fraction of covered demand, the maximum number of ships queueing in ports, as well as vehicle and passenger delays.

Shyshou et al. (2009)[46] have created a simulation model for the fleet sizing problem in offshore anchor handling operations. StatoilHydro wanted a decision support tool that would enable them to evaluate the impact of different future spot rates on the cost-optimal number of AHTS vessels on long-term hire. The problem is highly stochastic because durations of anchor handling operations vary and depend on uncertain weather conditions. Moreover, future spot rates for anchor handling vessels are extremely volatile. The study has received considerable attention and acceptance among the planners at StatoilHydro.

Erikstad and Ehlers (2014)[10] have created a simulation model for arctic LNG transport to identify market opportunities and possible mitigation strategies for increased transport system utilisation, given seasonal surplus capacity due to change in ice conditions. The problem consists of transporting LNG from a liquefaction plant located offshore of Kharaseyev with limited storage capacity. To avoid costly production stops the fleet of LNG vessels has to be large enough to make sure the max storage capacity is never reached. The results from the study indicated a high payoff from renegotiating the initial fixed schedule contract to



allow for a higher degree of seasonal variations in the LNG deliveries. Flexible contracts that implies seasonal deliveries to the UK would help ensure continuous production and deliveries in winter season.

Maisiuk and Gribkovskaia (2014)[31] have developed a discrete event simulation model to work as a decision support tool in the planning problem arising in servicing offshore gas and oil installations. Deciding on the fleet size in the offshore supply industry has a strong economic effect as the day rates for these vessels are massive. Especially avoiding having to hire vessels from the spot market is preferable as this is very costly. The simulation model takes into consideration uncertain weather data and future spot rates and simulates if a hired vessel is able to finish a planned voyage before the next voyage starts. If not, another vessel must finish the job. The simulation model has been validated and tested on real data and received considerable attention from marine planners in the oil and gas industry.

Muhabie et al. (2015)[32] have investigated the possibility of using DES to improve the planning of installation of offshore wind farms. The installation process is highly affected by weather conditions which means planning ahead is crucial for the lead time. By comparing simulation results with both historical weather data and probabilistic weather data they have analysed the correlation between the results and found a good agreement.

## 5 Method

In this chapter we will present our methodology for treating the problem at hand. This includes theory behind the models, as well as the mathematical formulations used to solve the problem.

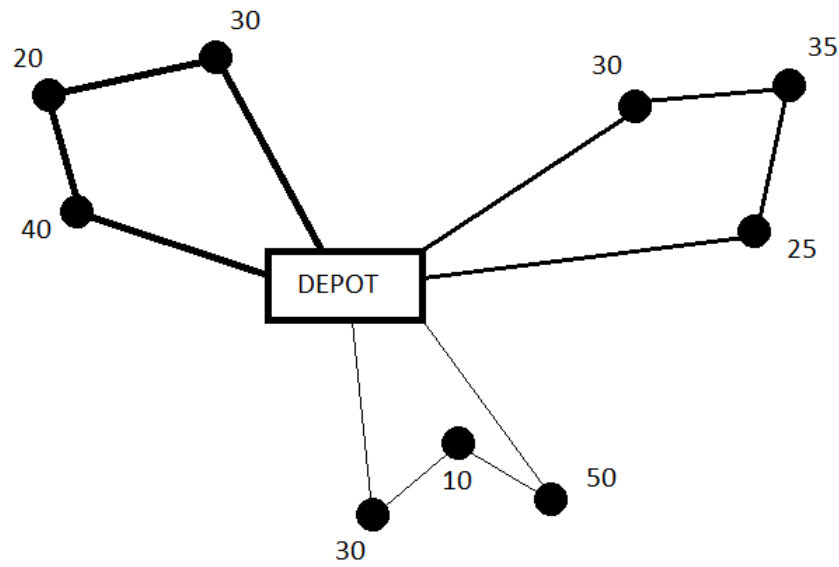
We will attempt to create an optimization model for the routing problem with a heterogeneous fleet performing a set of different tasks. Especially the cooperation between vessels of different sizes and the mix of inshore and offshore placed aquaculture facilities will be of interest. The optimization model will be used in combination with a simulation model in order to test the robustness of the solutions generated by the optimization model.

### 5.1 Optimization

Optimization is the science of making the best decision or making the best possible decision. The expression "best" indicates that we have a defined objective and "possible" indicate that we have a set of restrictions defining what feasible decisions we can make. The field of optimization belongs to the field of applied mathematics and encompasses the use of mathematical models and methods to find the best alternative available. The objective is defined through an objective function that depends on decision variables. The objective can be minimised or maximised [30].

### 5.2 Vehicle routing problem (VRP) with time windows

A Vehicle Routing Problem (VRP) is the problem of assigning routes to a set of vehicles starting from a depot such that each customer in the network is visited once. The VRP is a generalisation of the Travelling Salesman Problem (TSP) which is the problem of finding the shortest route such that all nodes in a network is visited exactly once. The vehicle routing problem has a set of constraints that need to be included in the formulation of the problem. Each vehicle can only travel one route and each customer, often called node, must be visited



**Figure 2:** Figure showing example of VRP with three routes and given demands at each customer. Each route must start and end in the depot. Different line thickness indicate different routes.

exactly one time. An illustration of the vehicle routing problem can be seen in figure 2.

There are many variations of the VRP. The most classic one involves a homogeneous fleet of vessels and a given set of customers, each with a given demand for some product. The vehicles have a given capacity and shall distribute the product to the customers such that their demand is met. Each route must start and end in the depot. The goal is usually to minimise the total distance travelled, but it could also be to minimise the number of vessels used. This is often more practical when there is a cost connected to deploying a new vessel.

In our thesis we will look at another variation of the VRP called VRP with Time Windows (VRPTW). This is similar to the classic VRP, but in addition to demands, the customers have associated time windows defining when the customers can be visited. This reduces the number of possible solutions compared to the classic VRP. The vehicles are allowed to wait at a customer in case of early arrival, but arriving after the time window has closed is not allowed. This is a more practical way of modelling the reality as customers usually have preferences to when they want to be visited.

The VRPTW can be modelled as follows [53]:

**SETS:**

$N$  - Nodes/Customers.

$V$  - Vessels.

**INDICES:**

$v$  - vessel.

$i$  - node/customer.

$j$  - node/customer.

**PARAMETERS:**

$C_{ij}$  - Cost of driving from node  $i$  to  $j$ .

$Q$  - Capacity vessels.

$D_i$  - Demand at customer  $i$ .

$T_{ij}$  - Time it takes to travel from node  $i$  to  $j$ .

$T_i$  - Duration of service at node  $i$ .

$T_i^S$  - Start of time window at node  $i$ .

$T_i^E$  - End of time window at node  $i$ .

$M_{ij}$  - Big M.

**VARIABLES:**

$x_{ijv}$  - 1 if vessel  $v$  travels from node  $i$  to node  $j$ , 0 otherwise.

$t_{iv}$  - Start of service at node  $i$  for vessel  $v$ .

$t_{jv}$  - Start of service at node  $j$  for vessel  $v$ .

$$\min \sum_{v \in V} \sum_{i \in N} \sum_{j \in N} C_{ij} x_{ijv} \quad (1)$$

s.t.

$$\sum_{v \in V} \sum_{j \in N} x_{ijv} = 1, \quad i \in N \setminus 0 \quad (2)$$

$$\sum_{j \in N} x_{ijv} - \sum_{j \in N} x_{jiv} = 0, \quad v \in V, i \in N \quad (3)$$

$$\sum_{i \in N} x_{0iv} \leq 1, \quad v \in V \quad (4)$$

$$\sum_{i \in N} \sum_{j \in N} D_i x_{ijv} \leq Q, \quad v \in V \quad (5)$$

$$t_{iv} + T_i + T_{ij} - t_{jv} + M_{ij} x_{ijv} \leq M_{ij}, \quad v \in V, i, j \in N \setminus 0 \quad (6)$$

$$t_{iv} \in [T_i^S, T_i^E], \quad v \in V, i \in N \setminus 0 \quad (7)$$

$$x_{ijv} \in \{0, 1\}, \quad v \in V, i, j \in N \quad (8)$$

The objective function (1) minimises travelling costs while the constraints represent the following.

(2) - Make sure each node except the depot is visited exactly one time.

(3) - Flow balance constraint. Each node must have one entering and one leaving arc, travelled by the same vessel.

(4) - Each vessel can only leave the depot one time. If we want to use all vessels in the fleet

the inequality can be replaced by an equality.

(5) - Each vessel can only carry as much cargo as its capacity.

(6) - Sequencing constraint. The start of operation at node  $j$  can not start before the sum of the starting time at node  $i$ , service time at node  $i$  and travelling time from node  $i$  to  $j$ . The constant  $M_{ij}$  is chosen large enough such that if  $x_{ijv} = 0$ , the inequality is always fulfilled. The constant could be set to a random large number, but if we want to make the formulation tighter,  $M_{ij}$  should be chosen as small as possible. Therefore we can choose  $M_{ij}$  as

$$M_{ij} = \max\{t_{iv} + T_i + T_{ij} - t_{jv}\} = T_i^E + T_i + T_{ij} - T_i^S \quad (9)$$

Constraint (6) can therefore be reformulated as:

$$t_{iv} + T_i + T_{ij} - t_{jv} \leq (T_i^E + T_i + T_{ij} - T_i^S)(1 - x_{ijv}), \quad v \in V, i, j \in N \setminus 0 \quad (10)$$

(7) - Start of operation at node  $i$  must start within the given time window at node  $i$ .

(8) -  $x_{ijv}$  is binary.

It is common to add subtour eliminating constraints to a classic VRP model, but because of constraint (6) this is not necessary in the VRPTW.

### 5.3 Route generation method

The model described above could be solved in one step, using the given formulation as input to a commercial solver. However, with increasing problem sizes, the number of variables and constraints become extremely large which can make the problem very time consuming to solve even for powerful computers. To avoid this problem we can instead solve the problem in two steps using the route generation method. This method generates all possible routes upfront, and then solves the VRPTW using a set partitioning model. A set partitioning model partitions the nodes into feasible subsets which here represents routes. Each subset, or route, consists of a subset of nodes and each route has a given associated cost. The goal

is then to find a partitioning such that all nodes are visited while the total cost is minimised [30].

The advantage of this technique is that we now have one variable for each route instead of one variable for each arc, reducing the number of variables considerably. Subtour eliminating constraints are also avoided since this is taken care of in the route generation. The mathematical formulation is then much easier to solve for a commercial solver. It is also quite easy to implement practical constraints such as time constraints, ship capacities, ship compatibility and so on, into the route generation. The disadvantage is of course that all feasible routes must be generated upfront which can be time consuming [11].

After all feasible routes are generated, the set partitioning problem can be solved with the following formulation assuming a homogeneous fleet.

**SETS:**

$R$  - Feasible routes.

$V$  - Vessels.

$N$  - Nodes.

**INDICES:**

$v$  - vessel.

$r$  - feasible route.

$i$  - node.

**PARAMETERS:**

$C_r$  - Cost of travelling route  $r$ .

$A_{irv}$  - 1 if route  $r$  for vessel  $v$  services node  $i$ , 0 otherwise.

**VARIABLES:**

$x_{vr}$  - Binary variable. 1 if vessel  $v$  travels route  $r$ , 0 otherwise.

$$\sum_{v \in V} \sum_{r \in R} C_r x_{vr} \quad (11)$$

s.t.

$$\sum_{r \in R} x_{vr} \leq 1, \quad v \in V \quad (12)$$

$$\sum_{v \in V} \sum_{r \in R} A_{irv} x_{vr} = 1, \quad i \in N \setminus 0 \quad (13)$$

$$x_{vr} \in \{0, 1\}, \quad v \in V, r \in R \quad (14)$$

The objective function minimises the total cost of all routes travelled, while the constraints represent the following.

(11) - Make sure each vessel can travel max one route. If we wish to use all vessels in the fleet the inequality can be replaced by an equality.

(12) - Make sure all nodes except depot are visited exactly once.

(13) -  $x_{vr}$  is binary.

As one can see this formulation is quite simple as all practical constraints are taken care of in the route generation. This method will be used to solve the problem at hand in this thesis in chapter 7.

## 5.4 Discrete-time Markov Chains

A discrete-time Markov chain is a stochastic process in which the behaviour at any time is instant and independent of history, and is restricted to constant rates. It is only dependent on the state in which it is at the moment [50].



A stochastic process with  $\{X_n; n = 0, 1, \dots\}$  is a process that takes on a discrete time with finite or countable number of possible values in the state space  $S$ . The set of possible values of the process is denoted by the set of nonnegative integers  $\{0, 1, 2, \dots\}$ . If  $X_n=i$ , then the process is in state  $i$  at time  $n$ . There is supposed that when the process is in state  $i$ , there is a fixed probability  $P_{ij}$  that it will next be in state  $j$ . That is true if we suppose that:

$$P\{X_{n+1} = j | X_n = i, X_{n-1} = i_{n-1}, \dots, X_0 = i_0\} = P_{ij} \quad (15)$$

for all states  $i_0, i_1, \dots, i_{n-1}, i, j$  for all  $n \geq 0$ . This is then called a Markov chain[45].

The value  $P_{ij}$  represents the probability that the process will transition into state  $j$ , if the current state is in  $i$ . A Markov chain consists of  $N$  states. Each row corresponds to a state in the Markov chain. The Markov chain is characterised by the  $N \times N$  transition probability matrix  $\mathbf{P}$  where each row has the sum of 1. The transition probability matrix can be seen in table 1.

**Table 1:** Transition probability matrix

$$\mathbf{P} = \begin{matrix} & \begin{matrix} 0 & 1 & 2 \\ \end{matrix} \\ \begin{matrix} 0 \\ 1 \\ \vdots \\ i \end{matrix} & \begin{pmatrix} P_{00} & P_{01} & P_{02} & \cdots \\ P_{10} & P_{11} & P_{12} & \dots \\ \vdots & \vdots & \vdots & \\ P_{i0} & P_{i1} & P_{i2} & \cdots \end{pmatrix} \end{matrix}$$

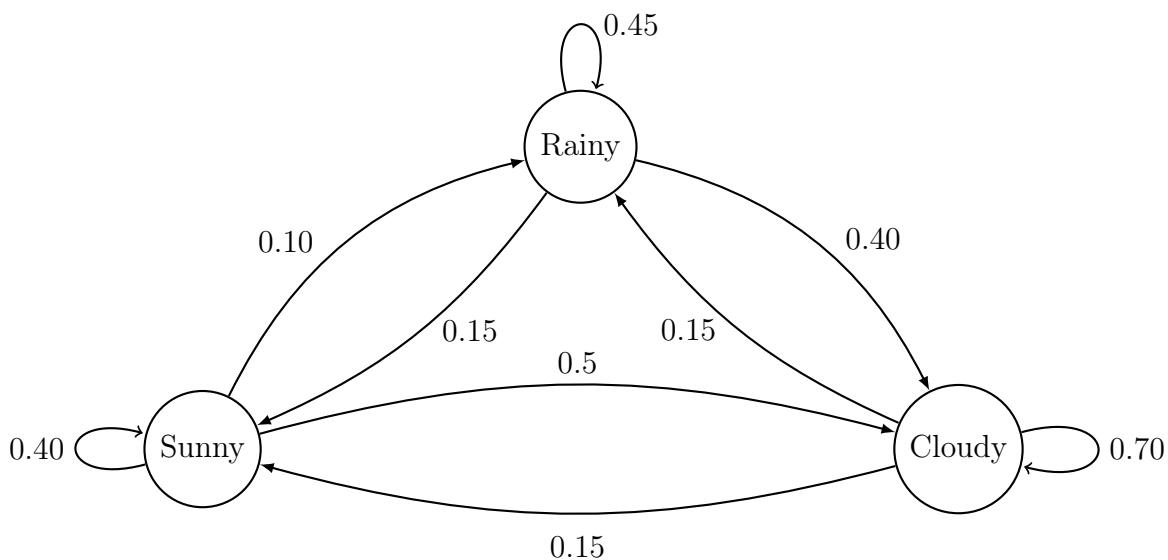
The Markov chain can be in one of the  $N$  states at any given time-step. The transition matrix tells what the probability of the next state at the time-step is  $j$ , when we are in the current state  $i$ .

An example to explain how the transition matrix works is shown in table 2 where the matrix is used to model probability of change in weather in Trondheim.

**Table 2:** Showing an example for change in weather in Trondheim and how to use the transition probability matrix.

$$\mathbf{P} = \begin{array}{c} \text{Rainy} \\ \text{Cloudy} \\ \text{Sunny} \end{array} \begin{pmatrix} \text{Rainy} & \text{Cloudy} & \text{Sunny} \\ 0.45 & 0.40 & 0.15 \\ 0.15 & 0.70 & 0.15 \\ 0.10 & 0.5 & 0.40 \end{pmatrix}$$

To better get a visualisation of how the different states interact within the Markov transition matrix, we can present the matrix as seen in figure 3.



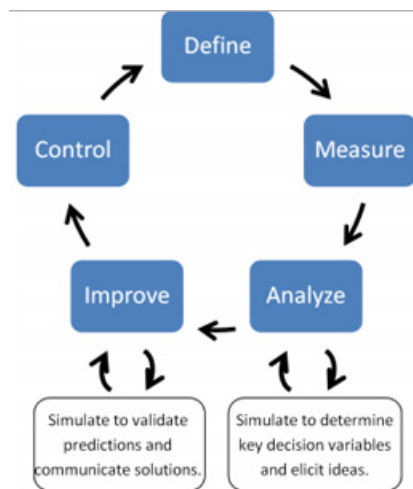
**Figure 3:** A visualisation of the transition matrix in table 2 to better understand how the Markov chain works.

#### 5.4.1 Markov chains Monte Carlo simulation

Monte Carlo simulations model the probability of different outcomes in a process that can not be easily predicted due to the intervention of random variables. The Markov chain Monte Carlo is a technique for generating fair samples from a probability in high-dimensional space, using random numbers drawn from a uniform probability in a certain range [27].

## 5.5 Discrete event simulation

A simulation model will be carried out to investigate the robustness of the optimized routes. The simulation model is made in SimEvent which is used to model and simulate discrete-event systems (DES).



**Figure 4:** Discrete Event Simulation

Discrete event simulation (DES) has been used in operational research for several years in a wide range of industries as a decision support tool. It is a very practical way of analysing the performance over time of a real life system by creating an imitation of the system and then changing parameters to see how the output of the model changes. That way one can test ideas without actually having to build a physical real life object[36]. DES represents individual entities that move through a series of queues and activities at discrete points in time. Models are generally stochastic in nature[55], which means that the output we get from one run is simply one realisation of the model[36]. To obtain a stochastic nature, statistical distributions are used, and state changes occur at irregular discrete time steps[56]. DES is most commonly used on operational and tactical planning levels[56].

## 5.6 Software used in the thesis

The software used in this thesis to help solve our problem are *MATLAB*, *Xpress-Optimizer*, and the simulation tool within the *MATLAB* environment, *Simulink*. *MATLAB* will not be further explained here as we assume the reader has knowledge of this program.

*Simulink* is an application integrated in *MATLAB*. *Simulink* is a block diagram environment for simulation and model-based design. By using *Simulink* we are able to create a roundtrip model with entities representing the service vessels involved in the operations and servers representing the different operations.

*Xpress-Optimizer* is a solver within *Xpress Optimization Suite* which is a development environment for mathematical modelling and optimization. The mathematical formulation of the optimization model can be implemented in the solver by using the high-level programming language *Mosel*. *Xpress-Optimizer* then finds the optimal solution by utilising several integrated solving techniques [22].

## 6 Operability and support

To evaluate the operability of the most common service vessels used in today's industry, we will in this chapter run several Markov chain simulations. This will give an indication on how the vessels are able to deal with various weather conditions. The results obtained can be used as a pointer towards how exposed the routes suggested by the optimization model are to delays. We will also investigate how long bad weather is likely to last in order to see how waiting time is affected.

### 6.1 Statistical weather data from buoy

The weather data used in all models is obtained by a weather buoy owned by Marine Harvest as part of the SFI Exposed run by SINTEF Ocean. The buoy is placed near Sula in Sør-Trøndelag. Due to a confidentiality agreement, the weather data will not be presented explicitly in this thesis.

#### 6.1.1 Markov chain simulation for creating wave heights

In order to create a time series of wave data, we have performed a Markov chain simulation. We present in table 3 the probability distribution created with the data from the weather buoy at Sula. We have decided to split the wave data into 10 sea states. The range for each state is found by taking the max value in the data set and dividing by the desired number of sea states.

**Table 3:** Transition matrix for wave states representing the probability for shifting from one wave state to another.

State	0	1	2	3	4	5	6	7	8	9
0	0.903	0.091	0.006	0	0	0	0	0	0	0
1	0.070	0.797	0.127	0.006	0	0	0	0	0	0
2	0.004	0.165	0.690	0.136	0.005	0	0	0	0	0
3	0	0.009	0.238	0.610	0.139	0.004	0	0	0	0
4	0.001	0.004	0	0.008	0.236	0.606	0.138	0.008	0	0
5	0	0	0	0.017	0.260	0.574	0.149	0	0	0
6	0	0	0	0	0.012	0.249	0.609	0.130	0.003	0
7	0	0	0	0	0	0	0.243	0.614	0.136	0.007
8	0	0	0	0	0	0	0	0.455	0.409	0.136
9	0	0	0	0	0	0	0	0	0.636	0.364

As an example one can see that the probability for going from sea state 0 to sea state 1 in the next time step is 0.091. The table has been created with a data set with measurements from 25.01.2016 to 03.04.2017. The buoy collects new measurements every hour, giving a total of 10113 measurements.

When the transition matrix is created we can simulate new time series by starting in a random sea state and creating a random set of wave states of desired length. The simulated data can be used as input for the optimization model to decide if an operation should be carried out or not. Since the weather is known upfront one can make sure that the sea state is calm enough for the entire duration of the operation before starting a new operation. It is important to emphasise that the data used is only measured for one year. We do not know if this weather is representative for other years or if for example the weather during a season was especially good or bad. The Markov chains used in the rest of the models are therefore only a representation of what the weather may be like.

## 6.2 Simulation using Markov chains

We have decided to simulate two different weather scenarios. One with winter weather, and one when the need for maintenance is at its highest which is usually during late summer and

fall. The winter weather is chosen in order to be able to see how the weather may look like at more exposed locations since the weather during winter is normally worse than the rest of the year. The second scenario is chosen to be able to compare the winter scenario, but also to show what kind of weather the fish farming companies usually deal with today. This scenario will hereby be called high season, and the data measured are from week 26 to 41. Looking at the sites of Barentswatch.no under fish health, one can see that most delousing jobs are performed during this period. This is mostly because the temperature in the water is at its highest during summer and the beginning of autumn[2].

The two scenarios provide different Markov matrices and the probability to enter different wave states are not the same. The Markov chain is run with data from these specific time periods. For the winter scenario that is from December to March. For high season it is from the week 26 to 41. Every simulation will have a random starting state so that we can give a better representation over mean time spent in each state and how the weather changes from state to state.

The Markov matrices for the two simulations can be seen in table 4 and 5. Table 4 shows that if you are in state 0 to 4 it is not very probable to end up in state 5 to 9. However, if you are in state 7 or upwards, the chances of staying in those 3 states are quite high. This is an indicator that if you do have rough weather, it may stay like this for a longer period of time.

**Table 4:** Transition matrix for wave states representing the probability for shifting from one wave state to another. The transition matrix represents a weather scenario when there is most need for delousing

State	0	1	2	3	4	5	6	7	8	9
0	0.915	0.082	0.001	0.001	0	0	0	0	0	0
1	0.086	0.825	0.085	0.003	0.001	0	0	0	0	0
2	0	0.182	0.702	0.113	0.002	0	0	0	0	0
3	0.005	0.027	0.253	0.591	0.118	0.005	0	0	0	0
4	0	0.015	0.015	0.354	0.462	0.154	0	0	0	0
5	0	0	0	0	0.268	0.512	0.220	0	0	0
6	0	0	0	0	0	0.500	0.444	0.056	0	0
7	0	0	0	0	0	0	0.125	0.750	0.125	0
8	0	0	0	0	0	0	0	0.333	0.333	0.333
9	0	0	0	0	0	0	0	0	0.333	0.667

**Table 5:** Winter season: Probability matrix for wave states representing the probability for shifting from one wave state to another.

State	0	1	2	3	4	5	6	7	8	9
0	0.333	0.583	0	0	0.083	0	0	0	0	0
1	0.017	0.778	0.198	0.007	0	0	0	0	0	0
2	0	0.140	0.706	0.152	0.002	0	0	0	0	0
3	0	0.005	0.239	0.611	0.137	0.008	0	0	0	0
4	0.004	0	0.004	0.194	0.626	0.166	0.007	0	0	0
5	0	0	0	0	0.016	0.266	0.565	0.153	0	0
6	0	0	0	0	0	0.500	0.444	0.056	0	0
7	0	0	0	0	0	0	0.218	0.621	0.161	0
8	0	0	0	0	0	0	0.	0.424	0.424	0.152
9	0	0	0	0	0	0	0	0	0.833	0.167

From table 5 one can see that the probability of being in state 0 has decreased drastically from 0.9 to 0.3. Furthermore, the probability of having really rough weather (from state 7 to 9) over a longer period of time is reduced.

**Table 6:** A display of the wave heights for each state in the Markov chain.

State	0	1	2	3	4	5	6	7	8	9
High season [m]	0.29	0.57	0.86	1.14	1.43	1.71	2.00	2.28	2.57	2.85
Winter[m]	0.35	0.70	1.04	1.39	1.74	2.09	2.43	2.78	3.13	3.48

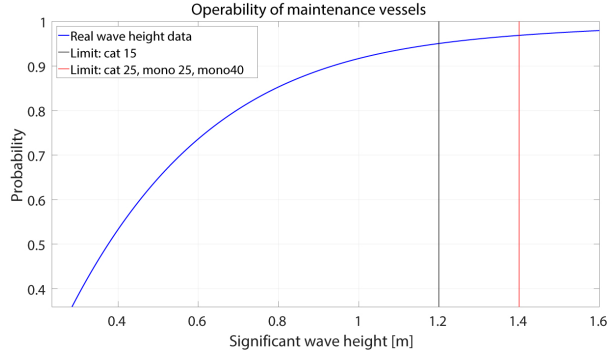
Table 6 shows the interval for each state, thus state 0 goes from zero to 0.29 meters for high season. State 2 from 0.29 to 0.57 meters and so on.

Both Markov matrices are simulated 1000 times to include a high number of possible weather scenarios, and a mean of the simulation will be discussed below.

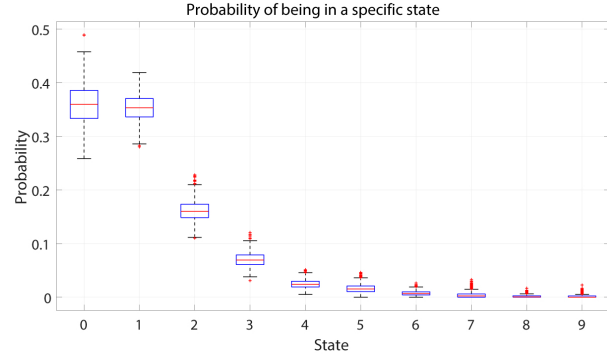
### 6.2.1 Simulation of calm weather based on a high season scenario

Figure 5 displays the mean operability of service vessels used in our models. The figure shows that for the 15 meter catamaran the operability when there is most need for delousing is at approximately 95%. For the 25 meter catamaran and the 25 and 40 meter monohull vessels the operability is at almost 97% of the time period. This indicates that the weather is





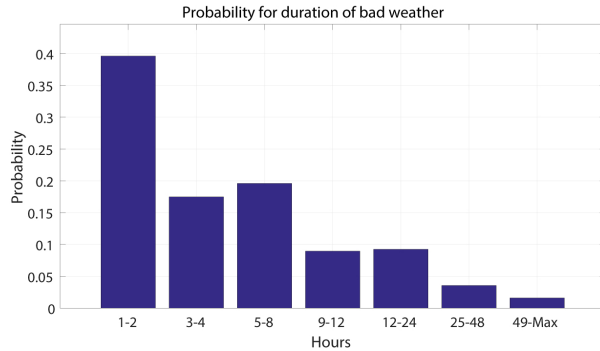
**Figure 5:** Mean operability of service vessels for a weather scenario when there is most need for delousing, week 26 to 41.



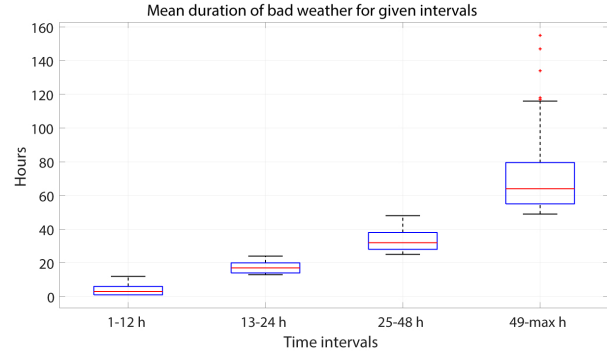
**Figure 6:** Mean probability of being in a specific state for a weather scenario when there is most need for delousing, week 26 to 41.

not the main issue if the service vessels are not able to perform the maintenance as planned. The lack of performing the job may be an indicator of poor planning and tight time schedule. Figure 6 shows the probability of being in a specific state. The box plot gives a good indication on how the probability changes for each simulation. If needed, an explanation of how a box plot works, can be seen in appendix F. The figure displays that the probability of being in state 0 and 1 are higher than all the other states combined. This indicates that the significant wave height is below 0.57 meters most of the time.

Further on it is important to discuss if the wave height at the location is higher than the acceptable limit. Is it likely that the service operation has to be postponed for only a few hours or for days. Figure 7 and 8 give a good signal on that matter.



**Figure 7:** Mean probability for duration of bad weather for a weather scenario when there is most need for delousing, week 26 to 41. The maximum limit of performing the operation is at 1.4 meters Hs.

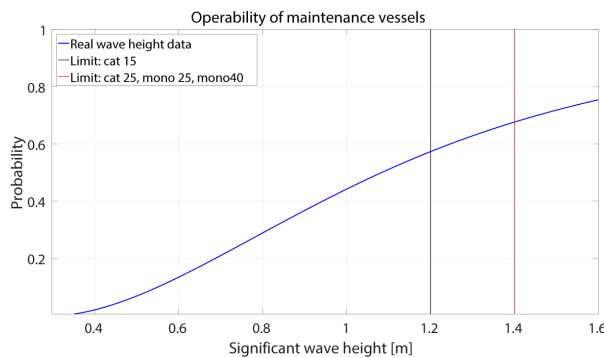


**Figure 8:** Mean duration of bad weather for a weather scenario when there is most need for delousing, week 26 to 41. The maximum limit of performing the operation is at 1.4 meters Hs.

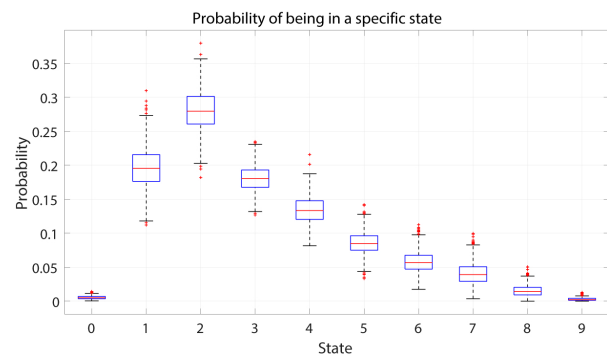
As one can see from figure 7, almost 40% of the time there will only be a delay of up to 2 hours. There is almost a 20% chance that that the delay will last from from 9 to 24 hours. Delays of 25 hours or more only have a probability of 5%. Figure 8 shows the spread of the data in figure 7.

### 6.2.2 Simulation of rough weather based on a winter scenario

The winter scenario gives a lower operability as shown in figure 9. The operability for the 15 meter catamaran has fallen from 95% operability at high season to 58% during the winter scenario. The other vessels experience a decrease from 97% to 68% operability.



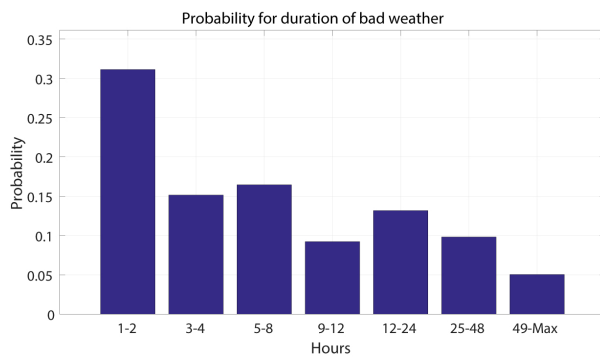
**Figure 9:** Mean operability of service vessels for a weather scenario during winter season.



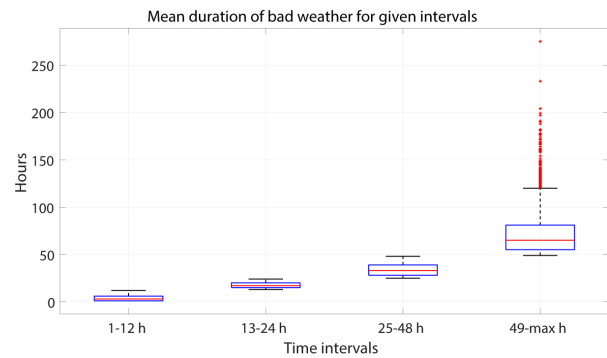
**Figure 10:** Mean probability of being in a specific state for a weather scenario during winter season.

The decrease will affect the planning of routes and jobs and possible strategies to avoid delays will be discussed later in chapter 7.5.

Figure 10 explains why the decrease has occurred. One can see that the probability of time spent in state 0 has dropped from almost 40% for high season to 1-2% during the winter scenario. Here, the probability for state 3 to 8 has increased by almost 100% compared to high season. The time spent in each of the upper range of states affect the duration of bad weather as one can see in figure 11. The mean probability for wave heights over 1.4 meters for more than 24 hours have increased by 50%.



**Figure 11:** Mean probability for duration of bad weather for a weather scenario during winter season. The maximum limit of performing the operation is at 1.4 meters Hs.



**Figure 12:** Mean duration of bad weather for a given interval for a weather scenario during winter season. The maximum limit of performing the operation is at 1.4 meters Hs.

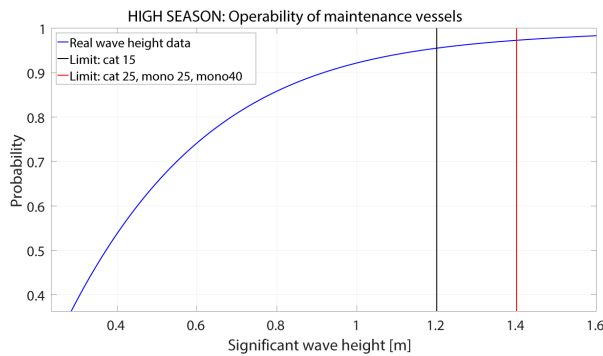
The mean duration for bad weather for given intervals as shown in figure 12, show that the main difference between this plot and the same for high season is that there are several more outliers on the box plot for the interval 49 hours or more. The box plot shows that the longest duration ever during the 1000 simulations for bad weather lasted for almost 270 hours. This is not very likely, but it shows the worst case scenario.

### 6.3 Comparing the simulation with real weather operability

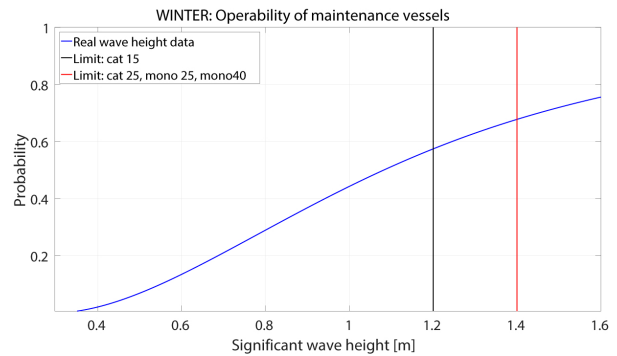
To be able to verify if the simulation is carried out correctly and gives a realistic view on the real weather, the results will be compared with the real time scenario for the year of 2016.

Each Markov chain simulation of the two weather scenarios gives different operability, but the mean of the simulations should give almost the exact same result as the data it was based upon. As seen below, the real weather data are used to verify if the Markov chain can be used in the simulations as a realistic way to simulate the weather.

The real operability of the service vessels in 2016 shown in figure 13 and 14 during the two scenarios show that the mean operability is almost exactly the same as in the simulations. There might be a percentage difference, but the simulations using Markov chains seem to be a good representation of the reality.



**Figure 13:** Real operability of service vessels based on the buoy data from week 26 to 41.



**Figure 14:** Real operability of service vessels during winter season.

## 7 Optimization

As described in chapter 5 we wish to create an optimization model for the fleet scheduling problem. In the following we will present the model and discuss its properties.

### 7.1 Input data to the optimization model

The optimization model uses the data presented in the following sections as input. This data consists of vessel data, data regarding the jobs which need to be performed, costs, and weather data. The weather data used is explained in section 6.1.

#### 7.1.1 Service vessels

In the model we have defined four different vessel types which can perform different jobs. These are 15 m catamaran, 25 m catamaran, 25 m catamaran with the possibility of installing a delousing system and 40 m monohull. The 25 m catamaran with a delousing system is included for the sake of investigating a multipurpose vessel. The main dimensions and speed for the vessels are shown in table 7.

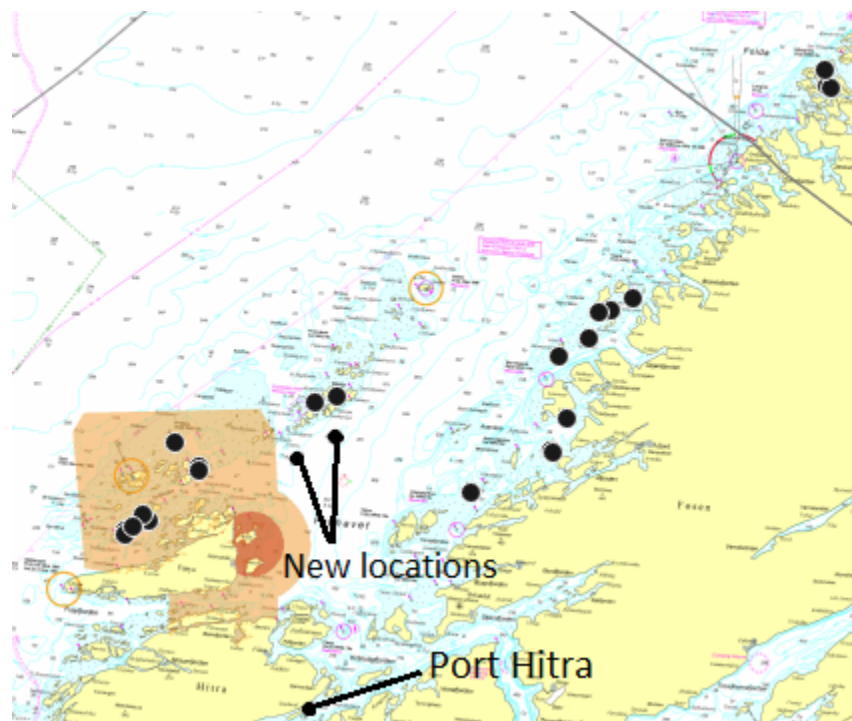
**Table 7:** Main dimensions and speed for the vessel types included in the model. LOA = Length over all, B = breadth, Dhdk = Depth moulded.

No	Vessel type	LOA [m]	B [m]	Dhdk [m]	Cruising speed [knots]
1	Catamaran	15	10	2.5	11
2	Catamaran	25	12.5	4	10
3	Monohull	40	12	4.5	9

#### 7.1.2 Hypothetical scenario for the optimization model

We have created a hypothetical scenario for jobs needed to be performed during a month. The scenario is based on a futuristic industry with both exposed and more inshore placed

aquaculture facilities. We have had to make many assumptions since the industry is changing quite rapidly and it is not easy to tell how the demand for service vessels will develop the next 10-20 years. The scenario created is based on aquaculture facilities located in the coastal areas in Sør-Trøndelag. We have used existing facilities in addition to facilities that do not yet exist. These include Ocean farm 1, owned by SalMar Group and developed by Ocean Farming AS. We have also included an exposed facility that does not exist, but which is included based on the assumption that more exposed locations will be present in the future. All the different locations included in the hypothetical scenario can be seen in figure 15.



**Figure 15:** Locations included in the hypothetical scenario and port Hitra. Black dots mark the different aquaculture facilities. The new locations that do not yet exist are pointed out. Picture from [barentswatch.no](http://barentswatch.no)

In order to reduce the number of feasible routes we have chosen to only include one port located on Hitra. All routes will start and end here. Based on these chosen locations we have created a set of different maintenance jobs which needs to be performed within their respective time windows. The duration of each job is varied depending on the job type, and the size of the facility. Larger facilities often demand jobs to be performed on several fish cages which takes a longer amount of time [37]. An overview of the different job types

**Table 8:** Table displaying different job types and their respective properties.

<b>Job type</b>	<b>Average duration</b>	<b>Time window summer[h]</b>	<b>Time window winter[h]</b>
Delousing	2.5-6 hours pr cage	72	168
Mooring	1 day pr facility	120	96
Inspection of net	4 hours per cage	144	96
Change of net	5 hours per cage	120	120
Cleaning of net	3 hours per cage	48	120
Cleaning of floating collar	3 hours per cage	48	120
Towing	-	12	12
Installation	14-18 days per facility	120	120
Transport of crew	2 hours per cage	8	8
Inspection of anchor lines	1 day per facility	168	168

included and their properties is shown in table 8. Average duration for each job is based on numbers from Frøygruppen and AQS.

The time windows are set depending on the job type. Jobs that are performed often, such as delousing and net cleaning are assumed to have smaller time windows than jobs performed more irregularly such as inspection of anchor lines. Another assumption is that the time windows will vary depending on season. Jobs such as delousing and net cleaning will not have the same urgency during winter, since there is a less demand for these operations at this time of year [8]. This is due to colder water and stronger currents. However jobs such as handling and inspection of moorings are likely to be more critical during winter when the weather is rough. The opposite logic applies for the late summer season when the weather is mild. During this season the time windows for delousing and cleaning operations are likely to decrease while jobs regarding moorings and anchor lines are likely to have increased time windows.

After defining the different job types, we have created a hypothetical demand scenario. In order to decrease the number of possible routes, we have divided the time horizon of one month into four weeks. This is done to reduce the running time of the route generation algorithm. The service demand for week 1 can be seen in table 9. The hypothetical demand created is used as input to the route generation algorithm, and the algorithm finds all possible routes to travel. The routes generated are then used as input to the optimization model,

**Table 9:** Hypothetical demand for maintenance during week 1.

Job nr	Location	Job type	Time window	Job duration [h]
1	Sørøyflesa	Delousing	[0,72]	6
2	Salatskjæra	Inspection of net	[24,96]	5
3	Farmannsøya	Delousing	[48,120]	12
4	Ruggstein	Delousing	[0,72]	6
5	Håbranden	Transfer of crew	[0,8]	2
6	Buholmen	Change of net	[24,144]	5
7	Jektholmen	Cleaning of fl. collar	[48,96]	8
8	Makrellskjæret	Delousing	[24,96]	6
9	Masterholman	Mooring	[0,96]	36
10	New location	Mooring	[0,96]	60

and the optimal routes are found.

The time windows are set to their minimum values presented in table 8 regardless of season, to have a conservative limit. Due to the long duration of some of the jobs we have decided to divide these jobs into smaller jobs in order to avoid the weather criteria being unnaturally hard to comply with. For example, for job nr 10 in table 9 above, the job duration is 60 hours. If this job is treated as one single job, the weather condition needs to be below the set limits for this entire period. This is unpractical since in real life situations it may be necessary to begin an operation one day, but then have to postpone operations the second day due to bad weather. Therefore in order to include this possibility, the job is divided into three separate jobs. This breakdown however, has some flaws which will be discussed in section 10.5.1.

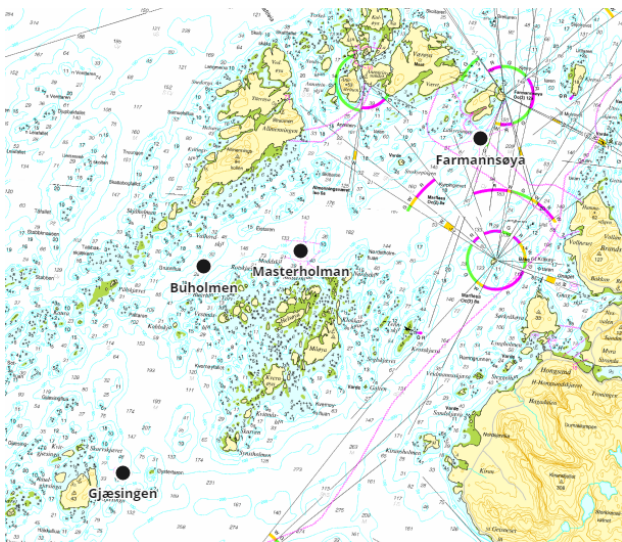
One problem with dividing the time horizon of one month into four separate weeks is that the optimization model will treat each week independently. This means that the fleet size and mix can vary across the different weeks, which is sub-optimal as this may lead to vessels only being used one week. This is a problem because the model does not take into consideration the cost of vessels not being used some of the weeks. Because of this problem we will for each solution generated, evaluate the fleet size and mix for each week. If the fleet size and mix varies a lot we may have to adjust the fleet some weeks to increase the homogeneity of the fleet throughout the whole time horizon.



### 7.1.2.1 Weather-location dependency

Because the facilities we have chosen as input to the model are placed at various locations with different degrees of exposure to weather, we have chosen to adjust the weather data input for each location. The weather data we use as input is from a buoy placed at a location with a high degree of exposure. This must be taken into account when implementing wave limits regarding when it is safe to perform a job. In reality, the wave height at a location will be very dependent on the wave direction. The locations are usually placed in such a way that they are sheltered by islands. This implies that if the waves are coming in from a direction such that the islands are placed directly in front of the production facility compared to the waves, the facility will be shielded by the island. However, when the waves are coming in from a direction such that the facility is not protected in the same extent, the wave height is likely to increase, and the operational conditions are worsened.

Since we use a Markov chain simulation for the wave height it will not be possible to implement this wave direction dependency. This is because we will not be able ensure any correlation between wave height and wave direction. Therefore we have used a very simple approach to take into account the different locations for the production facilities. This is done by multiplying the current wave state from the Markov chain with a reduction factor. For example if the current wave state at the weather buoy is 6, we reduce the wave state at more sheltered locations. How to choose the reduction factors is naturally a problem. In reality these factors will vary with wave direction as explained above, but this is not possible to implement using a Markov chain simulation. Therefore, the factors are chosen only by looking at wave statistics from `barentswatch.no`. From here we can get an impression of the wave heights at the different locations compared to the wave heights at the location of the weather buoy. A segment from the reduction factors can be seen in table 10 along with a figure showing the locations associated with the reduction factors.



**Figure 16:** Locations associated with reduction factors shown in table 10

**Table 10:** Reduction factors from segment of locations.

Location	Reduction factor
Farmannsøya	0.6
Gjøesingen	0.7
Buholmen	0.7
Masterholman	0.7

## 7.2 Capital and operational costs involved in the model

When formulating a mathematical model to optimize the fleet schedule we have many opportunities. There are many ways to attack the problem which can result in many different formulations. One of the first things we need to decide is what the objective function should be. This will decide what we are trying to optimize, hence what we are trying to minimise or maximise. The most common goal is to either maximise profit or minimise costs. Since we are not trying to maximise revenue for a specific company, but rather trying to analyse how a fleet can be utilised in an efficient way it is more practical to focus on cost. When analysing the cost of the operations, there are two different perspectives. The cost for the service company and the cost for the salmon farmer. We will try to include costs from both perspectives.

### 7.2.1 Costs for the service company

The cost for the service company includes investment costs when buying new vessels, operational costs of the vessels and salary for crew. The operational costs of the vessels include mainly fuel cost and maintenance. The investment costs used are based on numbers given

**Table 11:** Investment cost for 3 types of vessels.

Vessel type	Cost [NOK]
15 m catamaran	20 mill
25 m catamaran	43 mill
40 m monohull	60 mill

to us from Frøygruppen and from the vessels AQS Loke and Frøy Fighter.

In addition to the investment costs shown in table 11, equipment for delousing has to be purchased. We have chosen to use the same delousing system as Frøy Fighter which is called Thermolicer. For a more detailed description regarding this system see section 2.1.2. After conversation with Steinsvik AS we were given numbers regarding the cost of their Thermolicer system. One line costs 25 mill NOK. If we use Frøy Fighter, which has three lines installed, as a reference we get a total investment cost of  $60 + 75$  mill NOK for a 40 m monohull delousing vessel. For a 25 m catamaran we assume that we can only fit one line. Thus the extra cost for installing a Thermolicer is 25 mill NOK and the total investment cost for a 25 m catamaran with a delousing system is  $43 + 25$  mill NOK.

We need to calculate the Life Cycle Cost (LCC) of the vessels. In lack of accurate numbers we need to make some assumptions. According to [1] it is common to estimate average total annual operational costs as 5-6% of the investment cost. We use 5% and assume constant annual operational costs. We do not add an extra operational cost for maintenance of the Thermolicer system and assume that this is included in the 5%. In addition we need to select a discount rate  $r$  in order to calculate the present value of the annual operational costs. We neglect the effects of inflation and assume a discount rate equal to the market rate  $p$ . We use the market rate published by Statistisk sentralbyrå (SSB) which is roughly 2.5% as of April 2017. We assume a lifetime of 20 years and get the following formula for total operational cost (TOC).

$$TOC = Inv. Cost * 5\% * \frac{(1+p)^{20} - 1}{p(1+p)^{20}} \quad (16)$$

We assume a selling price after 20 years equal to 15% of the investment cost which is based on examples from [1]. This gives a total life cycle cost (LCC) of:

$$LCC = Inv. Cost + TOC - Selling price = Inv. Cost + TOC - Inv. Cost * 15\% \quad (17)$$

We want to analyse the weekly total cost of using an additional vessel. First we need to calculate the equivalent annual cost (EAC).

$$EAC = \frac{LCC}{\frac{(1+p)^{20} - 1}{p(1+p)^{20}}} \quad (18)$$

If we divide the EAC by the total number of weeks during the year we get:

$$Weekly\ cost = \frac{EAC}{52\ weeks} \quad (19)$$

Based on the equations and numbers presented above we get the weekly costs for hiring an additional vessel shown in table 12.

**Table 12:** Weekly cost for hiring an additional vessel based on vessel type.

Vessel type	Weekly cost [NOK]
15 m catamaran	40 200
25 m catamaran	86 400
25 m catamaran with delouser	117 300
40 m catamaran	213 100

In addition to the investment costs, we also have to take fuel costs into consideration. We have obtained numbers regarding fuel consumption per hour during cruising speed from Frøygruppen and assume a diesel price of 10 NOK/l. The fuel costs can be seen in table 13.

**Table 13:** Fuel consumption and fuel cost per hour during cruising speed for three vessel types.

Vessel type	Fuel consumption [l/hour]	Fuel cost [NOK/hour]
15 m catamaran	100	1000
25 m catamaran	100	1000
40 m monohull	80	800

Another cost to look at is crew salary. Crew salary is considered a travel independent cost and one can assume that the crew cost is included in the operational cost estimated in equation 16. However, it is preferable to include a cost if the crew has to work overtime. We assume that each time the vessels have to wait to perform a job because they arrive before the time window is open, an additional cost for overtime is added. By doing this we make sure it minimises waiting time. Values regarding salaries for deck crew are obtained from SSB [51]. A regular crew member has a salary of 39 700 NOK/month. It is presumed that one week has 37.5 work hours and there are 4 weeks per month the salary will be 265 NOK/hour. A captain has a salary of 59 700 NOK/month. This gives a salary of 398 NOK/hour. By multiplying the salaries with the number of crew members and captains on board each vessel type we get the salary costs seen in table 14. Number of crew members on each vessel type is from Frøygruppen and AQS.

**Table 14:** Salary cost for crew members for three vessel types. Costs in NOK.

Vessel type	Number of crew members	Salary cost per hour overtime
15 m catamaran	3	930
25 m catamaran	4	1195
40 m monohull	7	1990

### 7.2.2 Costs for the salmon farmer

The costs of the maintenance operations for the farmer mainly includes the charter cost of the vessels. We have included this by adding a cost for chartering per hour. The cost is incurred whenever a vessel is performing a job. It is difficult to find chartering rates for the different vessel types, but we were able to get some numbers from Frøygruppen. According

**Table 15:** Chartering rates for service vessels.

Vessel type	Charter rate [NOK/hour]
15 m catamaran	6000
25 m catamaran	12000
25 m catamaran with delouser	17000
40 m monohull	30000

to Frøygruppen, the charter rate for Frøy Fighter, is 30 000 NOK/pr hour. Based on these numbers and the known investment costs for the vessels, we have made some assumptions regarding the charter rates for the other vessel types. It is presumed that the rates are independent of the type of job and the rates can be seen in table 15.

In addition to charter rates, delousing of the salmon involves having to starve the fish for some period [33]. In order to reflect this, a cost for the lost growth of the salmon is included. If the delousing operations are delayed, meaning they will have to be starved for an increased amount of time, this cost increases. The slaughtering time of the salmon is assumed to be decided upfront and can not be changed. This will result in salmon not being fully grown when slaughtered. To calculate the loss of the reduced weight, we use a growth factor rate developed by Skretting. This can be found in appendix B. The growth rate is dependant on both sea temperature and current weight of the salmon. It is difficult to say what the sea temperature will be like around the time of slaughter since this will vary, but we assume a sea temperature of around 10 degrees Celsius bases on numbers from `barentswatch.no`. It is presumed that the slaughtering weight is around 4.5 kg [20] which gives a growth rate of around 0.5%. This gives the cost of the delayed delousing as:

$$Cost = \left( 4.5[kg] - \frac{4.5[kg]}{(1 + Growth\ rate)^{Hours\ delayed}} \right) * Salmon\ amount * Salmon\ price\ per\ kg \quad (20)$$

The salmon amount is set depending on how many fish cages are deloused. For each delousing operation we have defined how many cages need to be deloused and assumed that there are 200 000 salmon in each cage. This is the maximum limit set by the fishery directorate in Norway [12].

### 7.3 Route generation algorithm

When using a two-step approach for creating the optimization model we first need to generate all feasible routes. This is done by creating a script that adds more jobs to a route as long as it is feasible. The route generation process can be described by the algorithm seen in table 16. In addition to the elements described in the algorithm, some additional inputs are added. It is presumed, that the 25 m catamaran with delousing equipment can not perform other jobs while the Thermolicer is on board the ship. Therefore, if the 25 m catamaran first performs a delousing job and then wishes to perform a job involving for example anchor handling it must first travel back to harbour and remove the delouser. It is presumed

**Table 16:** Algorithm for route generation.

---

*Route generation algorithm*

---

```

create Set of vessel types
create Set of jobs needed to be performed
create Set of jobs performed
for all Vessel types
  for all Jobs
    find possible first jobs to add to route
  if Job is feasible
    add job to route, and update time. Add job to set of jobs performed and
    remove job from set of jobs needed to be performed
  while Set of jobs needed to be performed is non-empty
    for all jobs in set of jobs needed to be performed
      if Ship type is compatible with job type
        if Time window for job  $i$  is open
          if Sea state is within operational limit
            add job  $i$  to route and update time. Add job to set of jobs performed and
            remove job from set of jobs needed to be performed
          end if Sea state is within operational limit
        end if Time window for job  $i$  is open
      end if Ship type is compatible with job type
    end for all Jobs in set of jobs needed to be performed
  end while Set of jobs needed to be performed is non-empty
end for all Jobs
end for all Vessel types

```

---

that the process of removing the delouser takes 8 hours. Another input is the fact that vessels need to be cleaned when travelling into another production zone. The Norwegian coastline is divided into different production zones and the vessels need to be cleaned in order to prevent the spread of diseases when crossing into another zone [43]. One of the selected locations is placed in another production zone than the rest of the facilities and any job performed here involves dry docking of the vessel in order to clean the hull. The dry docking of the vessel is set to last for 24 hours and includes transport to harbour, cleaning and the process of lifting the vessel in and out of the water.

The MATLAB script for the route generation algorithm can be found in appendix H.

### 7.3.1 Constraints imposed on the route generation algorithm

The route generation algorithm is limited by a set of predefined constraints defining which routes are feasible which will be further explained in the following section.

#### 7.3.1.1 Vessel - job compatibility

The first constraint which is easy to handle is compatibility between vessel type and job type. Naturally, not all vessels can perform all the different job types and in table 17 we

**Table 17:** Vessel - job compatibility.

Job type	15 m catamaran	25 m catamaran/ with delouser	40 m monohull
Delousing	0	1	1
Maintenance of mooring	0	1	0
Inspection	1	1	1
Net change	1	1	0
Cleaning of net	1	1	0
Cleaning of cage collar	1	0	0
Towing	0	1	0
WASSP	1	1	0
Installation	0	1	0
Crew transfer	1	1	1
Inspection of anchor lines	1	1	1



can see which vessels that can perform which jobs. In reality, many of the maintenance jobs performed require the use of several vessels. We have assumed that in such cases our service vessels are assisted by vessels stationed at the facility. The farmers usually have one or two vessels of their own to perform smaller operations.

The table is based on information from the vessels AQS Loke, AQS Odin, Frøy Server and Frøy Fighter. The 40 m monohull is based on Frøy Fighter and AQS Odin. They are both vessels specialised for delousing and can therefore not perform many other tasks. We assume they are equipped with ROV's and can also perform inspections and crew transfers. The 25 m catamaran is based on AQS Loke. This vessel is specialised for anchor handling and heavy lifts, but can also perform delousing operations. However the delousing equipment needs to be removed in order to perform other jobs as discussed in section 7.3. This is thus the most flexible vessel and can perform most operations defined in the table. 15 m catamarans are the most common vessels in today's aquaculture industry. They are however not suitable for delousing as they can not fit the large machines needed for the operation. They are in addition not as equipped with cranes as the 25 m catamarans and can not perform the same heavy lifts and towing operations.

### **7.3.1.2 Time windows**

The next constraint to analyse is time windows. The jobs which need to be performed will have time windows associated to them, describing when the jobs should preferably be performed as discussed in section 7.1.2. The time windows are treated in such a way that if a vessel arrives at a job after the time window has ended, the job can not be performed. If the vessel arrives at the job before the time window opens, the vessel has to wait.

### **7.3.1.3 Operational limits for the service vessels**

The route generation also takes into account operational limits set by the current weather condition and weather forecast. Based on the paper "Servicefartøy 2010" by SINTEF [21], the operational limits are set based on significant wave height. These limits are 1.4 m

significant wave height for the 40 m monohull and 25 m catamaran, and 1.2 m for the 15 m catamaran. When setting these limits we have assumed that the vessel can position itself during the operation in such a way that its stability is maximised. The operational limit will actually vary with the wave direction. The catamarans are most stable when the waves are coming in from a 90 degree angle, while the monohulls at zero degree angle. The operational limits are the same for all job types except transfer of crew. For this operation we have used the offshore wind industry as reference. The limit for transferring crew to the monopiles used for the wind turbines is 1.5 m significant wave height [58]. However in this case the monopiles are stuck to the seabed while the ship is moving with the waves, creating a large relative movement. This will not be the case for us, since we assume that we use floating structures. Therefore we will not have the same relative movement and we set the limit for crew transfer to 1.6 m significant wave height. It should be mentioned that including transfer of crew in the fleet scheduling problem is perhaps not realistic as the vessels used are far too complex to be used for such simple operations, and these jobs will probably be performed by simpler and faster vessels. However for the sake of demonstrating that this job is likely to be necessary in the future of the aquaculture industry, it is included.

### **7.3.2 Assumptions in route generation algorithm**

The route generation includes some assumptions in order to make the algorithm easier. We have assumed that the vessels are operated continuously throughout the whole route travelled. For the larger jobs with long duration, we have included some extra time for sleeping in the job duration. However, this leads to the problem of the wave height having to be under the set limit during these sleeping hours as well. For the smaller jobs we have not included any extra time for rest, which means if a vessel performs several shorter jobs in a row, the crew will have no time to rest in between jobs. This is naturally a false assumption, and should be improved.

Another assumption is that the vessels are able to finish their route before the seven days during a week are over. If this is not the case, the routes during the next week will be affected by this, but this is not included in the model. An easy way of dealing with this

would be to implement a maximum limit regarding the duration of a route, but this was not done. However, all routes proposed by the optimization model are checked to comply with this criteria.

## 7.4 Set partitioning model

After all feasible routes are generated, we can use the routes as input to the set partitioning model and solve the VRP. After all feasible routes are generated in MATLAB, we store the routes generated in a data file and export the data file to Xpress MP where the set partitioning model is solved. The set partitioning model can be formulated as shown below. In order to make sure that the model is able to find a feasible solution, we add a cost for not being able to perform a job. We connect the cost with a binary variable  $y_i$  which is equal to 1, if job  $i$  is not performed.

### SETS:

$R_v$  - Feasible routes for vessel type  $v$ .

$N$  - Set of nodes.

$V$  - Set of vessel types.

### INDICES:

$r$  - feasible route.

$i$  - node.

$v$  - vessel type.

### PARAMETERS:

$C_r$  - Cost of travelling route  $r$ .

$P_i$  - Penalty for not doing job  $i$

$A_{ivr}$  - 1 if route  $r$  for vessel  $v$  services node  $i$ , 0 otherwise.

**VARIABLES:**

$x_{vr}$  - Binary variable. 1 if vessel type  $v$  travels route  $r$ , 0 otherwise.

$y_i$  - Binary variable. 1 if job  $i$  is not performed, 0 otherwise.

$$\min \sum_{v \in V} \sum_{r \in R_v} C_r x_{vr} + \sum_{i \in N} P_i y_i \quad (21)$$

s.t.

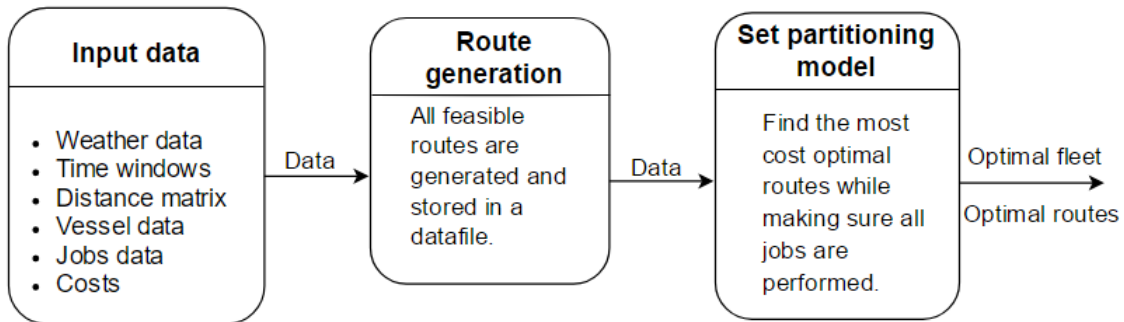
$$\sum_{v \in V} \sum_{r \in R_v} A_{ivr} x_{vr} + y_i = 1, \quad i \in N \setminus 0 \quad (22)$$

$$x_{vr} \in \{0, 1\}, \quad v \in V, r \in R \quad (23)$$

$$y_i \in \{0, 1\}, \quad i \in N \quad (24)$$

The objective function (21) minimises the cost of all routes travelled and adds a penalty cost for any potential jobs not performed. Constraint (22) makes sure all jobs are performed and if not, the binary variable  $y_i$  is set to 1 for job  $i$ . Constraint (23) and (24) state that variables  $x_{vr}$  and  $y_i$  are binary. The script for the set partitioning formulation can be found in appendix I.

Figure 17 shows a flowchart of the total two-step optimization process works.



**Figure 17:** Flowchart for the two step optimization approach.

## 7.5 Possible measures to increase robustness

After solving the vehicle routing problem, the solutions found, will be tested in the simulation model. By using the simulation model one can see how the solutions perform and if delays occur. If there are many delays we will have to consider implementing extra constraints in the route generation algorithm or the set partitioning model and see if this will improve the robustness. We can test different approaches in order to increase the robustness, and also see how they work combined.

### 7.5.1 Length of routes

The routes found will have different lengths. By lengths we mean number of jobs performed during each route. The risk for experiencing delays and also the consequences of delays will increase as the length of the route increases. If a job performed early in the route is delayed, then it is likely that the remaining jobs will also be delayed. In order to try and reduce this risk we will look at constraints regarding the length of routes. If we are able to spread the total number of jobs needed to be performed more evenly across the vessels, then this is likely to increase the robustness of the solution.

### 7.5.2 Slack

Another way to possibly increase the robustness is to implement slack in the route generation algorithm [19]. Slack can be defined as a vessels idle time after finishing a job before it has to be ready to start the next job. By including a slack restriction we can make sure that a vessel must have a given amount of idle time between jobs for a route to be feasible. This will help increase the routes robustness against unforeseen events and bad weather. There are several ways to implement slack. One way is to introduce a unit profit related to the amount of idle time between jobs. However this is not very applicable in our case since we have already introduced a waiting cost for each hour that is spent waiting for a time window to open. Another similar method could be to introduce a profit for each time a vessel waits

a given amount of hours. This will make the model value this idle time and find solutions where this is maximised. However, it is difficult to choose the value of the profit associated with each vessels idle time and again this will contradict the cost related to waiting already included in the model. Another, perhaps more efficient way to do this is to introduce a strict limit which states that all routes must have at least a given number of idle hours between jobs. This will guarantee that a measure of robustness is included in all routes generated.

In order to evaluate the effectiveness of implementing a constraint regarding slack, the new solutions obtained can be tested with the constraint included in the simulation model, and analyse the performance of the routes against the results obtained without the slack constraint included. The effects of the constraint regarding slack will be tested in section 9.4.3.

### **7.5.3 Time windows**

A third way of increasing the robustness is to reduce the time windows. If the time windows used in the optimization model are tighter than the ones used in the simulation model, it is likely that there will be fewer delays. However, reducing all the time windows may completely alter the solutions obtained and create inefficient routes. This method will therefore not be tested as a measure for robustness.

## 8 Simulation

The simulation will take a look at how the result from the optimization will perform when different weather scenarios are generated. The result from the simulation will be an indicator if the optimization model can be executed in a more real life scenario or if the result is too optimistic.

### 8.1 Simulink

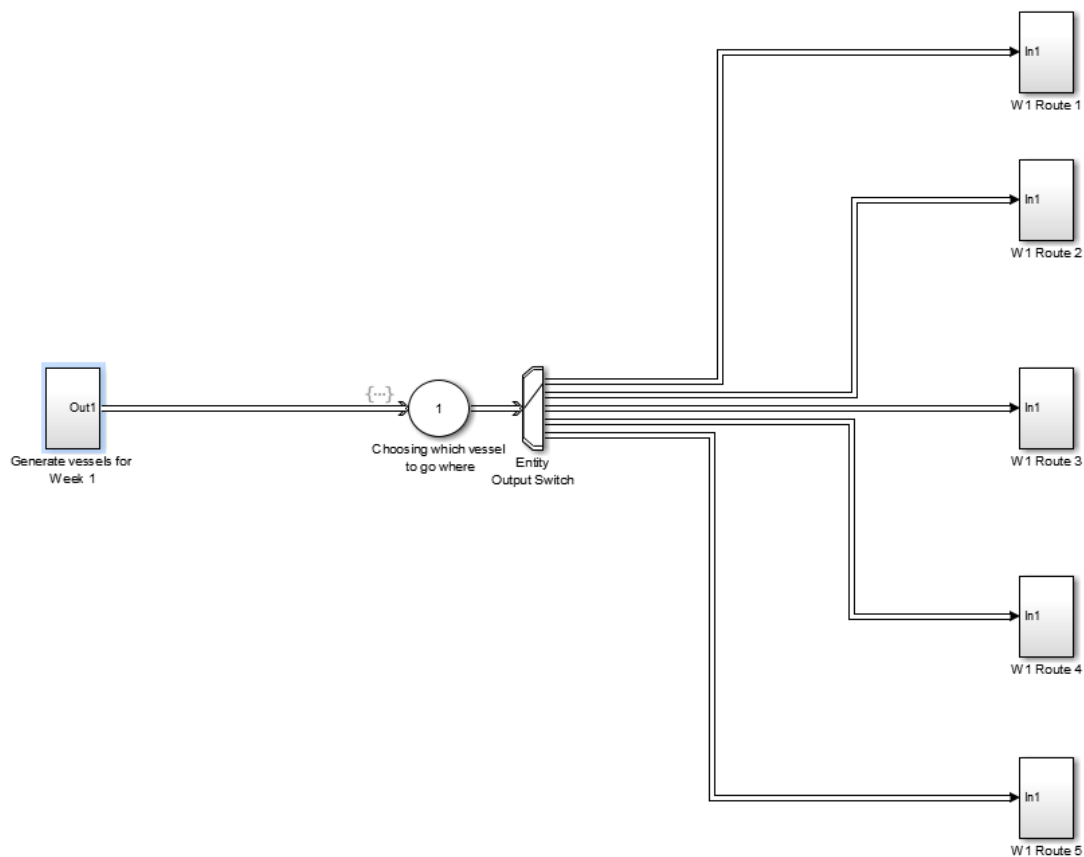
The program used for the simulation is Simulink which is an application integrated in Matlab. Simulink is a block diagram environment for simulation and model-based design. By using Simulink we are able to create a set of routes with entities representing the service vessels travelling through blocks representing either the operations that need to be performed or the sailing time between the operations.

### 8.2 The simulation model

The simulation model created simulates all four weeks in one simulation run, where week two starts after one week, week three after two weeks and so on in order to make sure that the weather is treated in a realistic way. By doing this we make sure the weather state at the start of day 8 will depend on the state at the end of day 7. The model created is a generic model and the model will be able to run ten jobs for each route and five routes per week. The maximum number of jobs and routes included in the model was set after running the optimization script with different parameters and using the results as an indication of how many routes and how many jobs the optimization model could potentially create. The model is therefore usable for most cases and it will not be necessary to make changes to the simulation model for different runs. All changes to the model is carried out from an Excel sheet. Here, the number and types of vessels used and the routes travelled can easily be changed to run a different scenario.

Each model will be run 100 times in order to obtain a good average regarding the starting time of each job and the end time of each route, and thereby a result that can be used to better understand if the optimized solution is realistic. The weather scenarios are the same as those simulated in chapter 6 and the same transition matrices will be used. The weather will change for every simulation and is the main reason that the result will differ for each simulation.

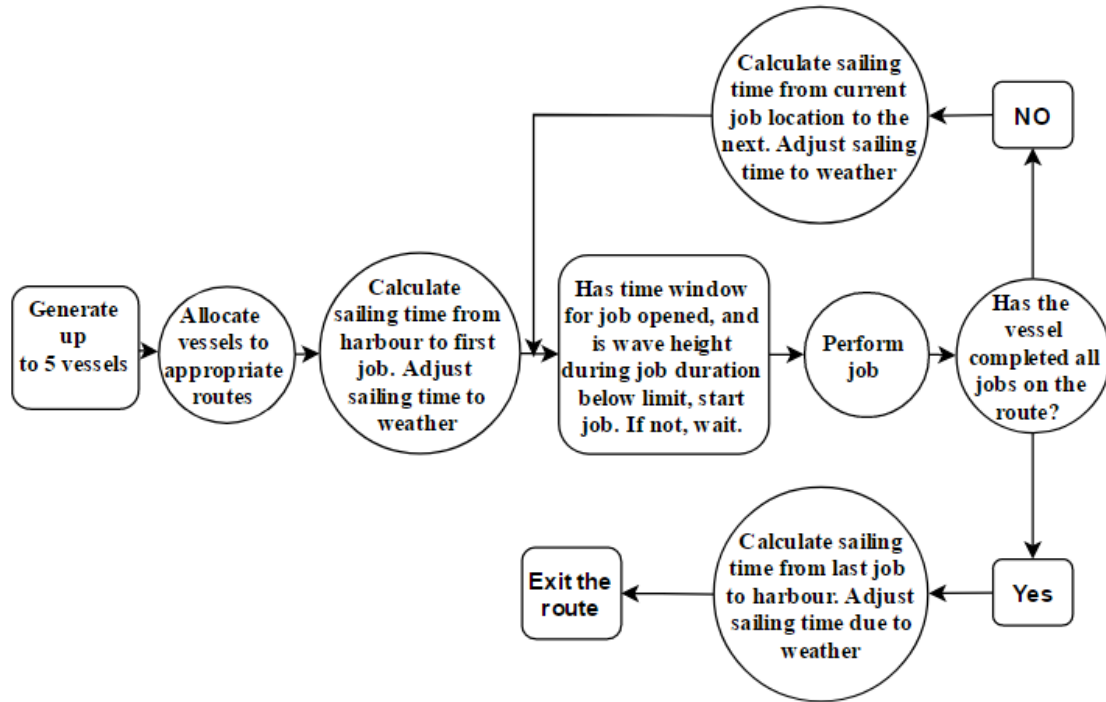
A Matlab script is developed to store every run and plot the outcome in order to be able to interpret the results.



**Figure 18:** Cutout of simulation model. Shows one of in total four weeks in the simulation. Displays five routes for one week.

The simulation model shown in figure 18 displays only one week. The complete model consists of four of these models, but to better show how the model works only one is shown in the figure. In Out1 all the vessels used for that week are generated along with each of the vessel's velocities. It also creates an attribute to tell which vessel that should travel which



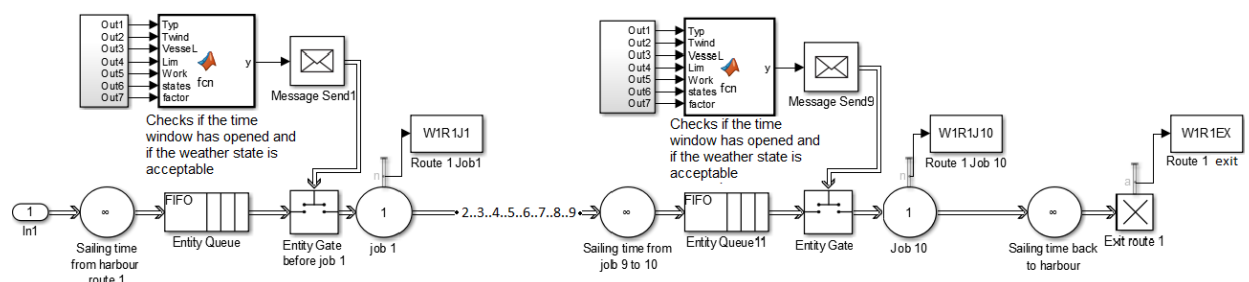


**Figure 19:** Flow chart of one week in the simulation model. Simplified description on how the simulation model works.

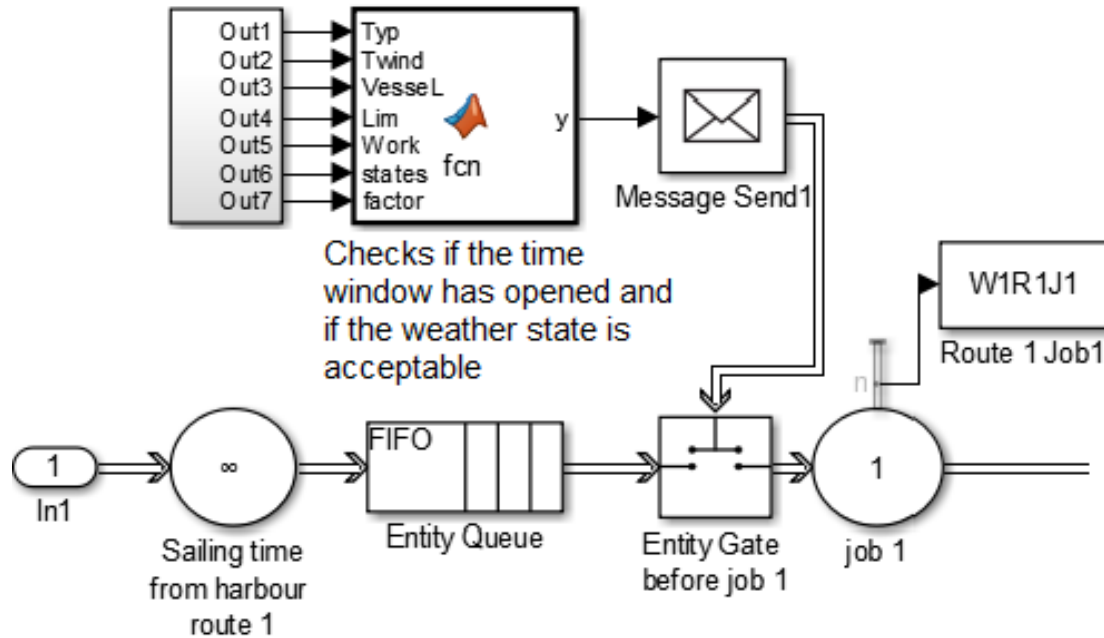
route. The entity server placed in front of the entity output switch uses this attribute to decide which vessel should go to which route. The first vessel generated will go to the first route and so on.

The flow chart shown in figure 19 is a simplified explanation of how one week in the simulation model works.

Figure 20 displays that 10 jobs can be executed for each route. If there are only two jobs for a certain route, the entity will go from job two and back to harbour. The duration of the remaining entity servers will then be zero.



**Figure 20:** Cutout from simulation model. Shows one out of five routes per week.



**Figure 21:** Cutout from simulation model. Shows one out of 10 jobs per route.

Figure 21 shows the sailing time from harbour, the duration time for the current job and an entity gate which is connected to a Matlab function block. The script made in the Matlab function block will not let the vessel pass the entity gate if the time window of the next job has not opened yet and if the weather during the time it takes to finish the current job is not acceptable. The Matlab function block takes in the vector of weather states for each time step, the time window for each job, what type of vessel it is, type of job and job duration, maximum wave height the vessels can work in, and a location reduction factor for the wave height. All the parameters come from the excel worksheet and is part of the script to make the simulation as realistic as possible.

### 8.2.1 Running Simulations from Matlab

A Matlab script is created to run one hundred simulations with different weather scenarios. The weather is simulated with the same method as earlier, using Markov chains. The only difference is the probability of starting in a specific state. The probability is based on the simulations for weather and time spent in each state. The probability of being in each state can be seen in table 18.

**Table 18:** Probability of being in each state from 1000 simulations of Markov chains

State	0	1	2	3	4	5	6	7	8	9
High season	0.359	0.354	0.162	0.070	0.025	0.016	0.007	0.004	0.002	0
Winter	0.006	0.197	0.282	0.180	0.133	0.085	0.058	0.041	0.016	0.003

The table shows that for high season the probabilities of starting in state 0 to 3 are most likely. The chance of having good weather in the start of each simulation and then be able to do the maintenance during the first few days of week 1 are therefore quite big. For the winter simulation, the probabilities for starting in state 1 to 4 are most likely. Naturally, the probabilities of starting in state 5 to 9 are higher for winter season than high season and the probability of having to wait for better weather during winter simulation is higher.

Table 19 display how the job duration for each maintenance operation may change. After conversations with the companies, they did not give any exact duration for each job, but rather ranges. Duration varies depending on the weather and the amount of work that needs to be done. To include the varying duration, we multiply a random number within the ranges shown in table 19 with a mean duration.

**Table 19:** Upper and lower range for duration of each job. The range is a stochastic input to the simulation model since the duration of each job may differ from time to time.

Job type	Lower limit [%]	Upper limit [%]
Delousing	100	150
Mooring handling	50	150
Net inspection	75	150
Change of net	50	150
Cleaning of net	75	125
Cleaning of floating collar	75	125
Installation	50	150
Crew transport	75	125
Inspection of anchor lines	50	150

The outputs from the simulation are the start and end time of each job. In addition, the end time of each route is imported into Matlab Workspace. The values are stored for every simulation. To make the simulation time shorter, all data needed for the simulation, all data exported from SimEvent to Matlab Workspace, and what number we are in the loop, are stored in a .mat file. This is to not lose any data when we delete all data stored in Workspace. The information is retrieved when needed. This is done because we experienced that after a certain number of simulations, the simulation time increased exponentially. The clear all command in Matlab deletes all global variables that increases the simulation time. After this new implementation of the clear all command, the simulation time fluctuated between 5 and 8 minutes per simulation.

### 8.2.2 Plotting the results

A separate script is made to plot all results from the simulation. Not all routes will be executed, so it is important to only plot those routes that are being executed. The script is also generic so that we do not have to do any changes if more routes are included in the model during another simulation.

The script can show up to 24 plots. 20 of these are a plot for each route and show if the start time of each job performed is within the time windows given. The last four plots show a plot for each week, where the end time from each route from the optimization model is compared to the simulated mean end time of each route.

## 8.3 Issues faced in Simulink

There are some issues in the simulation model due to operations that Simulink does not support. The first point is that Simulink does not support the random number generator with different seeds. The built in *rand* function in MATLAB will give the same number throughout the simulation, which is not preferred when the point is to generate a random number to ensure a stochastic model. In the simulation model, we generate a random duration for each job within an interval. To solve this issue, we have made a global variable

consisting of a  $1000 \times 100$  matrix with random numbers at the start of the simulation. Each simulation is run with a new column of random numbers from the matrix in order to not be able to get the same random number as the simulation before.

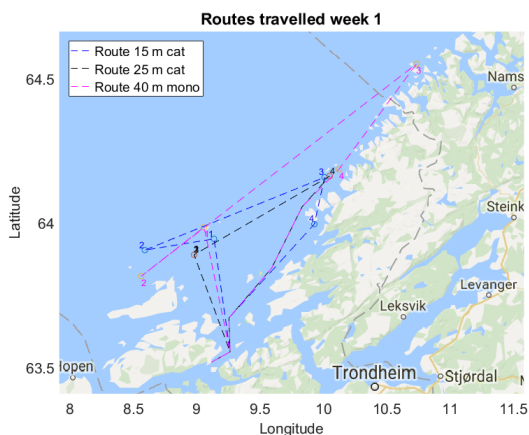
Another issue is that we have assumed that the time for acceptable weather must be as long as the mean time it takes to finish a current job. This means that the vessel can not start doing their job until the weather for the whole time period it takes to finish the job is acceptable. A more realistic approach would be to check the weather continuously and stop during bad weather until the weather is acceptable again. The reason why we are not able to do so is because we can not stop a job when it has already started.

## 9 Results

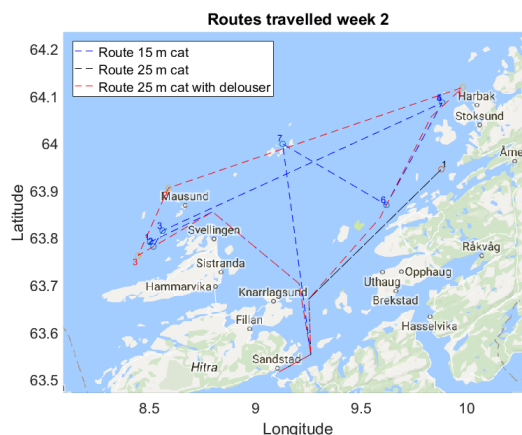
In this chapter the results obtained from running the optimization model with various settings and the results from testing the solutions in the simulation model will be presented. This chapter contains all results from combining the optimization and simulation model and testing how different approaches to increase the robustness of our fleet affect the results. We will for each of the different approaches first present the results from the optimization model, and then test the result obtained in the simulation model. A summary of the most important results and differences will be presented at the end of the chapter in section 9.6.

### 9.1 Optimal routes assuming perfect weather

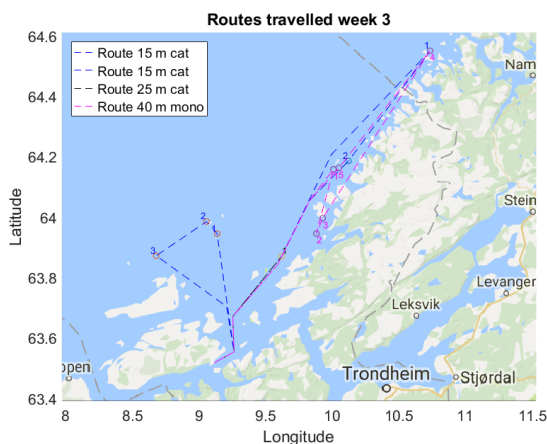
The first routes to be evaluated, are the routes found when we assume that the weather is always perfect. The optimization model is run without any weather constraints included and the optimal routes found with this setting can be seen in figures 22, 23, 24 and 25.



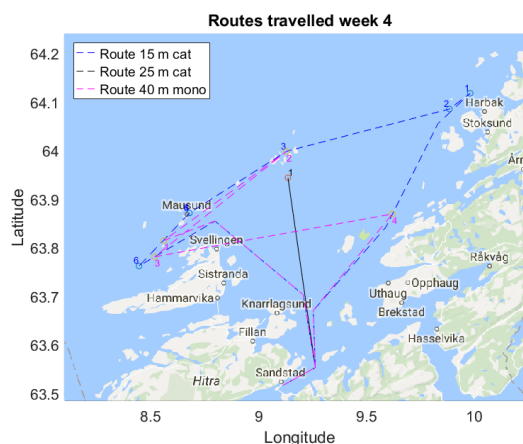
**Figure 22:** Routes travelled week 1 assuming perfect weather for three vessels.



**Figure 23:** Routes travelled week 2 assuming perfect weather for three vessels.



**Figure 24:** Routes travelled week 3 assuming perfect weather for four vessels.



**Figure 25:** Routes travelled week 4 assuming perfect weather for three vessels.

**Table 20:** Vessels used, jobs performed during each route, cost for each route and weekly costs for optimal solution assuming perfect weather. Job numbers indicate which job is done, in which order, for each route. All costs in NOK.

	Vessels used	Jobs performed	Route cost	Weekly cost
<b>Week 1</b>				2 050 890
1	15 m catamaran	5, 2, 6, 7	154 296	
2	25 m catamaran	9, 10, 11, 12	1 159 750	
3	40 m monohull	1, 4, 8, 3	397 081	
<b>Week 2</b>				1 771 720
1	15 m catamaran	8, 10, 3, 6, 5, 2, 7	664 942	
2	25 m catamaran	1	291 438	
3	25 m catamaran with delouser	4, 11, 9	571 431	
<b>Week 3</b>				2 319 520
1	15 m catamaran	9, 5	440 842	
2	15 m catamaran	10, 4, 11	208 296	
3	25 m catamaran	6	488 452	
4	40 m monohull	1, 8, 2, 3, 7	801 962	
<b>Week 4</b>				2 269 280
1	15 m catamaran	5, 7, 9, 10, 11, 8	464 897	
2	25 m catamaran	1	578 792	
3	40 m monohull	4, 2, 3, 6	885 826	
<b>Sum weekly cost</b>				<b>8 411 410</b>

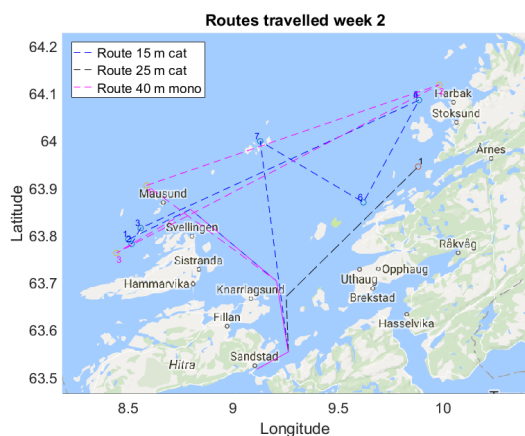
The total cost of the solution can be seen in table 20. The exact value of the numbers is of less importance, as these involve many rough assumptions. Instead the relative difference in numbers when comparing different solutions will be of interest. The cost of the individual routes shown in the table do not include the investment cost of the vessel, while the total cost for each week do include these costs. The numbers used for the jobs performed are the same numbers used in the tables for the hypothetical scenario. For week 1, these are the same numbers which can be seen in table 9 under Job nr and show in which order the jobs are done for that route. Job numbers for the other weeks can be found in appendix D.

Total cost for all four weeks combined is 8 411 410 NOK. As discussed in section 7.1.2, we can see that the fleet size and mix varies across the weeks, and the cost of 8 411 410 NOK does not reflect this. For example the 25 m catamaran with delouser is only used in week 2. If we take this into consideration, the actual cost of this solution is 9 096 964 NOK. Therefore, we run the optimization model again and only allow the setup with one 15 catamaran, one 25 m catamaran and one 40 m monohull to be used. This seems to be the fleet mix which is used most often. Since the 25 m catamaran with delouser only performs delousing jobs in the solution suggested above the result will be very similar with a total cost of 8 448 030 NOK and a difference of only 36 620 NOK. Comparing this with the cost of investing in a new vessel it is easy to conclude that this is a better alternative. We can also test the model with the setting where we only allow the use of three vessels each week as only week 3 requires four vessels. By using this setting the increase in cost is of 55 260 NOK. We have evaluated the weekly cost of investing in a new 15 m catamaran as 40 202 NOK. Thus, the cost of having this additional vessel, 3 extra weeks is 120 606 NOK. By this reasoning the optimal solution is using only three vessels all four weeks, and only vessel types 15 m catamaran, 25 m catamaran, and 40 m monohull. The new solution with the adjusted fleet size and mix can be seen in table 21. We define this as the most cost optimal solution and will test this in the simulation model. Using a 25 m catamaran with delouser instead of the 40 m monohull is also tested, but this gave poor results.

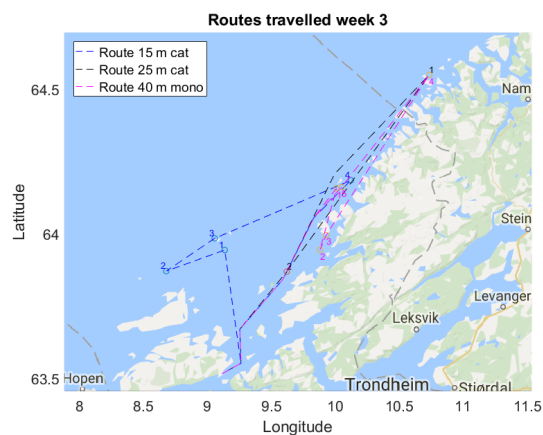


**Table 21:** Vessels used, route description and cost for optimal solution assuming perfect weather with adjusted fleet size and mix. All costs in NOK.

	Vessels used	Jobs performed	Route cost	Weekly cost
<b>Week 1</b>				2 050 890
1	15 m catamaran	5, 2, 6, 7	154 296	
2	25 m catamaran	9, 10, 11, 12	1 159 750	
3	40 m monohull	1, 4, 8, 3	397 081	
<b>Week 2</b>				1 808 340
1	15 m catamaran	8, 10, 3, 6, 5, 2, 7	664 942	
2	25 m catamaran	1	291 438	
3	40 m monohull	11, 4, 9	512 203	
<b>Week 3</b>				2 374 780
1	15 m catamaran	10, 11, 4, 5	501 629	
2	25 m catamaran	9, 6	731 425	
3	40 m monohull	1, 8, 2, 3, 7	801 962	
<b>Week 4</b>				2 269 280
1	15 m catamaran	5, 7, 9, 10, 11, 8	464 897	
2	25 m catamaran	1	578 792	
3	40 m monohull	4, 2, 3, 6	885 826	
<b>Sum weekly cost</b>				<b>8 503 290</b>



**Figure 26:** Routes travelled week 2 with perfect weather and adjusted fleet size and mix.



**Figure 27:** Routes travelled week 3 with perfect weather and adjusted fleet size and mix.

The adjusted routes for week 2 and 3 can be seen in figure 26 and 27.

**Table 22:** Total cost and cost reductions from different fleet compositions assuming perfect weather. All costs in NOK.

Fleet composition	Total cost	Cost reduction	Cost reduction [%]
1	9 096 964	-	-
2	8 865 696	231 268	2.5
3	8 568 636	528 328	5.8
4	8 800 350	296 614	3.3
<b>5</b>	<b>8 503 290</b>	<b>593 674</b>	<b>6.5</b>

1 = No fleet adjustments.

2 = Exclude 40 m monohull.

3 = Exclude 25 m with delouser.

4 = Max one 15 m catamaran, and exclude 40 m monohull.

5 = Max one 15 m catamaran, and exclude 25 m catamaran with delouser.

We can summarise the different results for the different fleet compositions suggested in table 22. In this table the cost of not using vessels all weeks is included. The selected solution is shown in bold.

## 9.2 Simulation of optimal routes created assuming perfect weather

We now wish to test the routes created above in the simulation model and see how they perform. We will run 100 simulations and create plots displaying how the routes perform and how often delays happen. The robustness is defined as the percentage of jobs performed within their respective windows and we use this as a measure of performance for the routes.

### 9.2.1 Simulation with calm weather

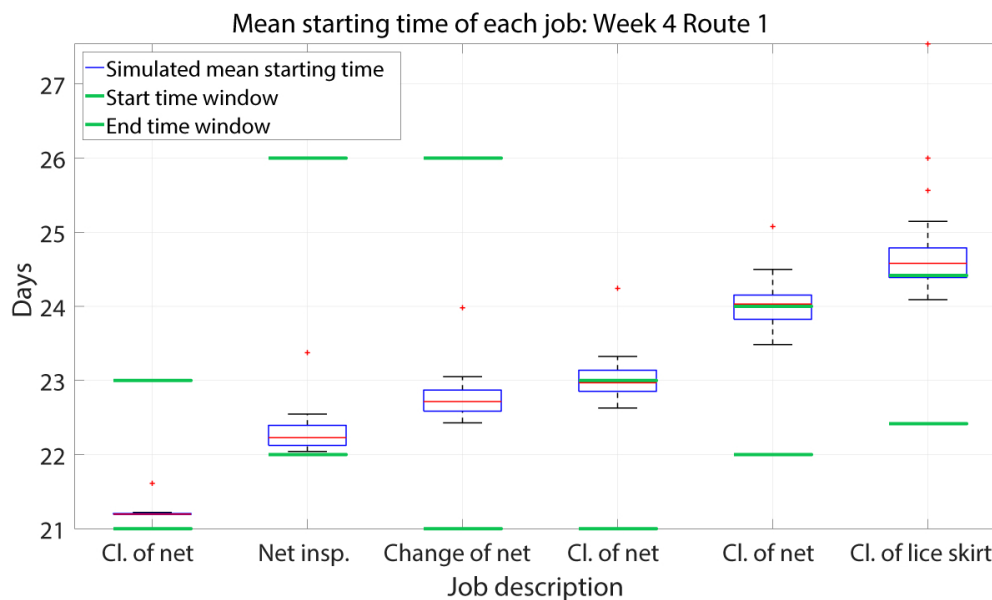
We first test the optimized routes assuming that we are in the late summer-early autumn season when the demand for maintenance operations is usually at its highest. The weather during this season is usually calm with small wave heights so we expect the routes to have few delays.

Table 23 shows how many jobs are performed within their respective time windows during each week and for all four weeks combined. As expected the results are quite good. However, week 4 stands out as considerably worse than the rest. Comparing this result with the results in figure 28 we can see that route 1 during week 4 is

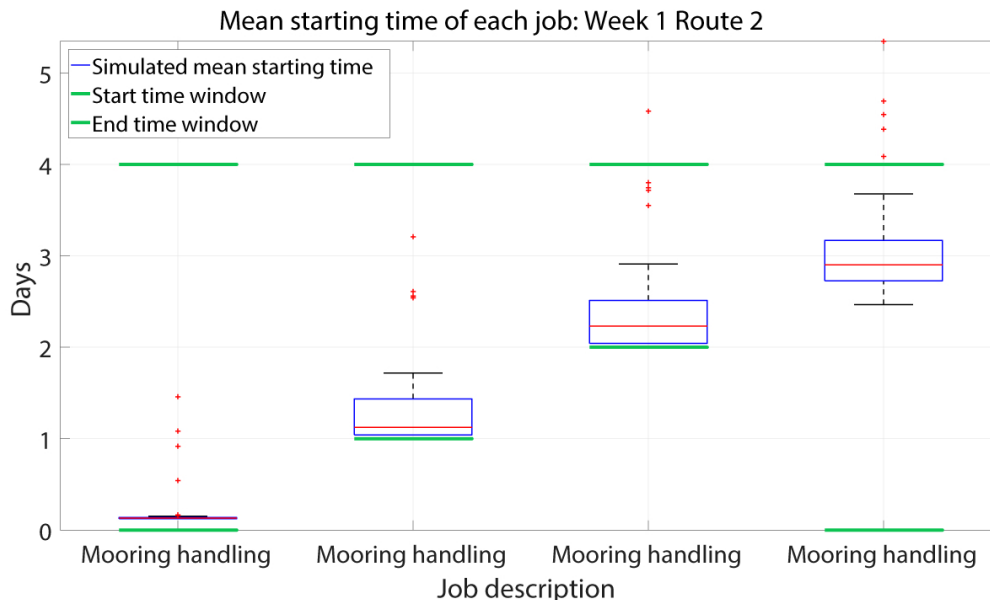
**Table 23:** Percentage of jobs performed within their respective time windows during each week in simulation model assuming calm weather.

Week	Robustness [%]
1	99.4
2	93.4
3	96.4
4	84.9
<b>Total</b>	<b>93.6</b>

challenging. This is a quite long route and we can see that the three last jobs are exposed to delays. One should therefore consider changing the routes during this week. One way of doing this could be to assign some of the jobs performed in route 1 to the 25 m catamaran which only performs one job on its route. Alternatively, one could change the order in which the jobs are performed. For example we can see that job nr 3 has a very big time window and can instead be done last on that route. This will lead to increased costs but reduces the risk of delays.



**Figure 28:** Week 4, Route 1: Mean starting time of each job. The starting times of each job are shown in a box-plot where the red line shows the median. Here, Cl.=Cleaning and insp=inspection. Median values for the last three jobs show that delays are likely.



**Figure 29:** Week 1, Route 2: Mean starting time of each job. The starting times of each job are shown in a box-plot where the red line shows the median. All median values are well within their time windows.

In figure 29 one can see an example of a route which performs quite good. All median values are well within their time windows. However, there are some extreme values outside the time windows, especially for the last job, which show that delays can happen.

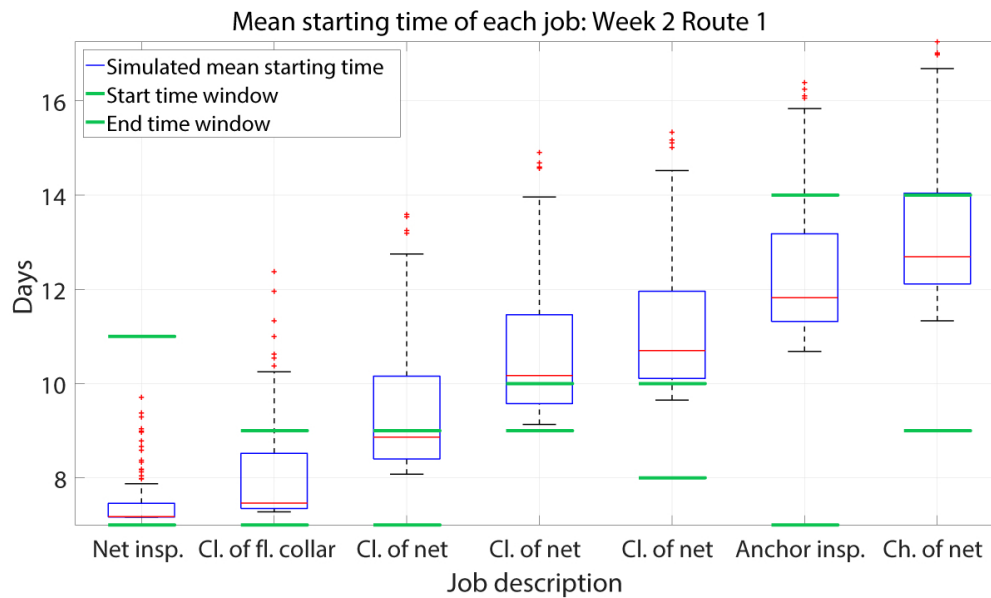
### 9.2.2 Simulation with rough weather

Now, we want to simulate the same routes, but instead of calm weather, the routes are exposed to rough weather with increased occurrences of large wave heights. Naturally, we expect this to give worse results than the previous simulation. In table 24 one can see that percentage of jobs done within their time windows is reduced drastically. Week 2 has the worst results, and

**Table 24:** Percentage of jobs performed within their respective time windows during each week in simulation model assuming rough weather.

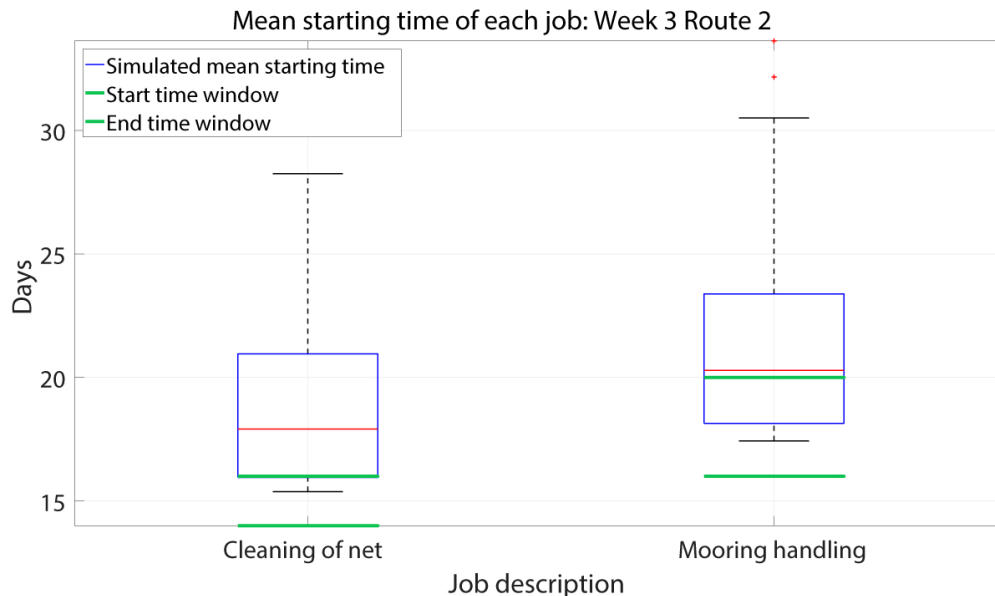
Week	Robustness [%]
1	83.0
2	70.9
3	72.1
4	76.0
<b>Total</b>	<b>75.7</b>

figure 30 shows that route 1 is experiencing difficulties. Especially the third, fourth and



**Figure 30:** Week 2, Route 1: Mean starting time of each job. The starting times of each job are shown in a box-plot where the red line shows the median. Here, insp=inspection, Cl.=Cleaning, Ch.=Change and fl.= floating. We can see that the median values for job 4 and 5 are outside their time windows.

fifth job are exposed to delays. Also route 1 during week 4 which was challenging in the previous simulation is naturally still problematic. Week 3 also has weak results. Figure 31 shows that route 2 is challenging. This is because the first job is located far away from port, causing delays already before the first job is started. Adding extra sailing time because of bad weather is included in the simulation model, but not in the optimization model. This causes the vessels to use a longer amount of time to the first job in the simulation model than in the optimization model.



**Figure 31:** Week 3, Route 2: Mean starting time of each job. The starting times of each job are shown in a box-plot where the red line shows the median. Both median values are outside their time windows and delays are likely to occur.

**Table 25:** Total robustness and total reduction in robustness for simulations with calm and rough weather. Reduction relative to 100%.

Scenario	Total robustness [%]	Reduction [%]
Calm weather	93.6	-
Rough weather	75.7	18.0

In table 25 we can see the total reduction in robustness from including rough weather in the simulation model. We can see that the operations are quite exposed to increased wave heights and many routes are delayed.

### 9.3 Optimal routes with rough weather included

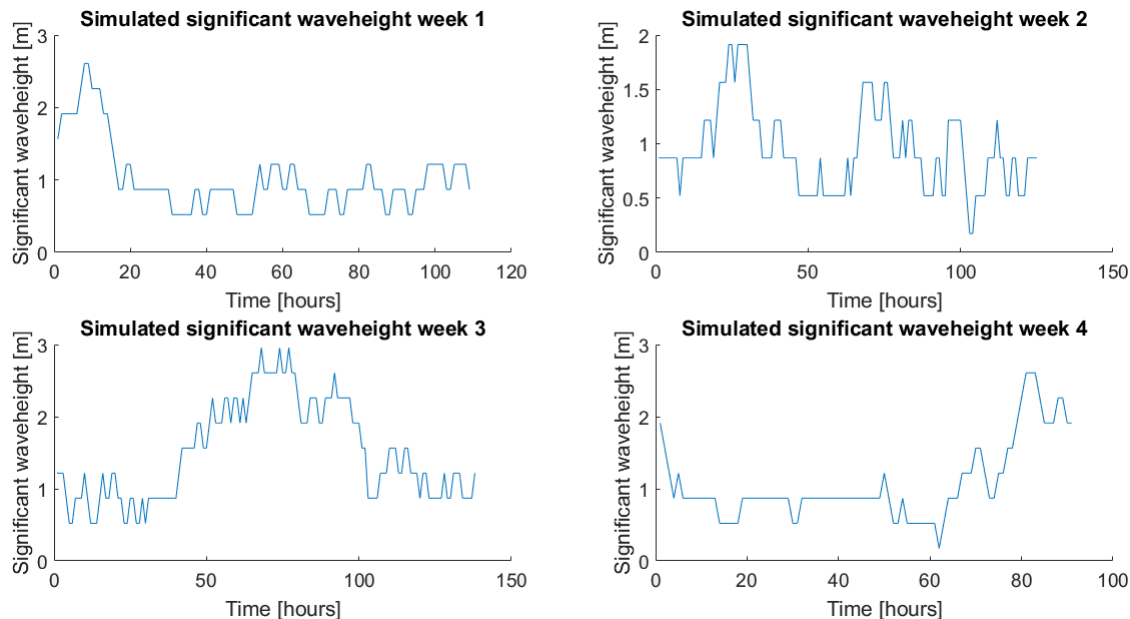
In this section we are going to test how the routes generated perform in the simulation model if weather constraints are also included in the optimization model. We run the optimization model, but include weather conditions which are based on the Markov chain simulation. Hopefully, this solution will perform better than the routes generated with the assumption of perfect weather. As discussed in 10.5.2 we will get a different solution for each weather

**Table 26:** Vessels used, route description and cost for optimal solution assuming rough weather. All costs in NOK.

	Vessels used	Jobs performed	Route cost	Weekly cost
<b>Week 1</b>				2 260 400
1	15 m catamaran	6, 2, 7	143 261	
2	25 m catamaran	9, 10, 11, 12	1 168 120	
3	40 m monohull	1, 4, 8, 3	409 227	
		Job nr 5 not performed	200 000	
<b>Week 2</b>				1 845 450
1	15 m catamaran	2, 3, 6, 5, 7	510 732	
2	15 m catamaran	8, 10	187 741	
3	25 m catamaran	1	291 438	
4	25 m catamaran with delouser	4, 11, 9	571 431	
<b>Week 3</b>				2 388 200
1	15 m catamaran	10, 4, 11	208 296	
2	25 m catamaran	9, 6	764 885	
3	40 m monohull	8, 2, 1, 7, 3	875 234	
		Job nr 5 not performed	200 000	
<b>Week 4</b>				2 300 340
1	15 m catamaran	5, 7, 10, 11, 9	444 872	
2	25 m catamaran	1, 8	629 884	
3	40 m monohull	4, 2, 3, 6	885 826	
<b>Sum weekly cost</b>				<b>8 794 390</b>

simulation which is run, and therefore simply choose one setting and stick with this when comparing solutions. The new solutions generated are shown in table 26.

The routes found were exposed to the significant wave heights seen in figure 32. As one can see, the waves during week 3 are quite high. As a consequence, the vessels were not able to perform one of the jobs during this week because the waves are too high during the entire time window of the job. Also during week 1, one of the jobs is not performed. This job involves crew transfer and has a very small time window. Therefore, this job is very exposed to rough weather. The cost for not doing this job is set unrealistically high, as the consequences of not doing this job is merely that workers may have to stay an additional day on board the production facility. The exact cost for not being able to perform a job is difficult to evaluate, so we have just made a very rough estimate and stated some values which can be found in appendix D.



**Figure 32:** Simulated significant wave height during four weeks.

We have run many simulations, but all solutions found had the same problem of not being able to perform some of the jobs due to bad weather. No matter how many vessels included in the fleet, the vessels are not able to do the job because of the operational limit. This problem will be treated further in section 9.3.1 and 9.3.2. Similar to the solution obtained with the assumption of perfect weather we get various fleet sizes across the weeks. Therefore, we perform the same test and adjust the fleet size and mix during week 2, which is the only one that differs from the rest, by replacing the 25 m catamaran with a delouser with the 40 m monohull. This gives a cost increase of 36 600 NOK, which is still much cheaper than the alternative cost, equal to 351 900 NOK, of having an extra 25 m catamaran with delouser not being used 3 weeks. Therefore, the solution is adjusted and replace the 25 m catamaran with a delouser, with the 40 m monohull. We also choose to not use the additional 15 m catamaran during week 2. In table 27 one can see that the fleet size and mix is equal to the solution found when assuming perfect weather, but the routes travelled are different.



**Table 27:** Vessels used, route description and cost for optimal solution assuming rough weather with adjusted fleet size and mix. All costs in NOK.

	Vessels used	Jobs performed	Route cost	Weekly cost
<b>Week 1</b>				2 260 400
1	15 m catamaran	6, 2, 7	143 261	
2	25 m catamaran	9, 10, 11, 12	1 168 120	
3	40 m monohull	1, 4, 8, 3	409 227	
		Job nr 5 not performed	200 000	
<b>Week 2</b>				1 962 290
1	15 m catamaran	8, 2, 10, 6, 5, 7	526 362	
2	25 m catamaran	1, 3	583 964	
3	40 m monohull	11, 4, 9	512 203	
<b>Week 3</b>				2 388 200
1	15 m catamaran	10, 4, 11	208 296	
2	25 m catamaran	9, 6	764 885	
3	40 m monohull	8, 2, 1, 7, 3	875 234	
		Job nr 5 not performed	200 000	
<b>Week 4</b>				2 300 340
1	15 m catamaran	5, 7, 10, 11, 9	444 872	
2	25 m catamaran	1, 8	629 884	
3	40 m monohull	4, 2, 3, 6	885 826	
<b>Sum total cost</b>				<b>8 911 230</b>

We can summarise the costs of different fleet compositions in table 28. The costs of vessels not being used all weeks are included. The most cost optimal solution is shown in bold.

**Table 28:** Total cost and cost differences of different fleet compositions assuming rough weather. All costs in NOK.

Fleet composition	Total cost	Cost reduction	Cost reduction [%]
1	9 381 554	-	-
2	9 241 536	140 018	1.5
3	8 951 626	429 928	4.6
4	9 201 150	180 404	1.9
<b>5</b>	<b>8 911 230</b>	<b>470 324</b>	<b>5.0</b>

1 = No fleet adjustments.

2 = Exclude 40 m monohull.

3 = Exclude 25 m with delouser.

4 = Max one 15 m catamaran, and exclude 40 m monohull.

5 = Max one 15 m catamaran, and exclude 25 m catamaran with delouser.

### 9.3.1 Increased operability

As shown in section 9.3, we were not able to find any solutions where all jobs were performed, when rough weather was included in the route generation algorithm. Because of this we want to test the route generation algorithm when the operability of the vessels is increased. All limits regarding significant wave height are increased by 0.2 m, and run the optimization model with ten different weather scenarios. The new solutions with increased operational limit are compared with old solutions with the same weather conditions. We can see that with the increased operational limit, many of the jobs that were not possible to perform before are now possible. Below in table 29 one can see the resulting difference in costs. For the new solutions that contain jobs that were previously not possible to perform, it is difficult to compare the costs since the cost of not doing a job is difficult to evaluate. Because of this we can see that some of the solutions with increased operability actually have a higher cost due to longer routes for the vessels.

**Table 29:** Difference in costs and number of jobs performed with increased operability. All costs in NOK.

Cost old solution	Jobs not performed	Cost new solution	Jobs not performed	Cost reduction
9 055 120	3	9 163 090	0	-107 970
8 503 090	1	8 417 450	1	85 640
8 317 850	1	8 483 240	0	-165 390
8 806 760	3	8 707 750	3	99 010
8 366 230	1	8 538 050	0	-171 820
8 849 810	1	8 590 300	0	259 510
8 594 460	2	8 267 810	1	326 650
8 799 800	4	8 739 350	2	60 450
8 794 390	2	9 093 140	1	-298 750
8 702 730	2	8 769 990	1	-67 260

### 9.3.2 Increased time windows

We also want to see if the vessels are able to perform more jobs if the time windows are increased. This could indicate that the predefined time windows set by us are too strict when the weather gets worse. We expect that this will have a bigger effect than increasing the operability of the vessels.

The time windows are increased depending on the type of job. As discussed in section 7.3.1.2, some of the jobs will have expanded time windows during winter while others will not. Therefore, we will not increase the time windows of the jobs that are most critical during winter which typically are operations related to moorings and anchor lines. Ten different weather scenarios are tested and the results can be seen in table 30

**Table 30:** Difference in costs and number of jobs performed with increased time windows. All costs in NOK.

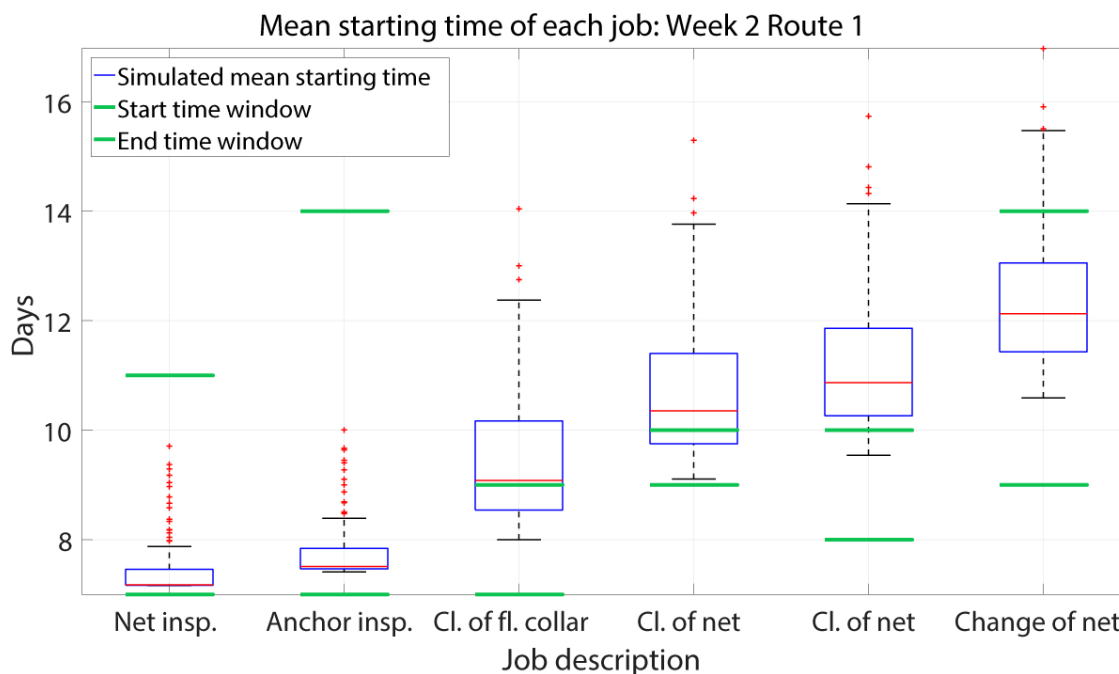
Cost old solution	Jobs not performed	Cost new solution	Jobs not performed	Cost reduction
9 055 120	3	8 615 010	1	440 110
8 503 090	1	8 293 970	1	209 120
8 317 850	1	8 162 460	1	155 390
8 806 760	3	8 693 880	1	112 880
8 366 230	1	8 239 380	1	126 850
8 849 810	1	8 658 630	1	191 180
8 594 460	2	8 291 010	2	303 450
8 799 800	4	8 335 330	1	464 470
8 794 390	2	8 437 470	0	356 920
8 702 730	2	8 467 720	2	235 010

We can see that the extended time windows have a positive impact on the cost which is not surprising. We can also see that still there are jobs that are not performed. What we have discovered is that it is usually always the same job which is not performed. This is because the job duration for this job is very long, making it very hard to perform because the weather has to be sufficiently good for a very long period of time. This is a flaw with the model which will be discussed in section 10.5.1.

### 9.3.3 Simulation of optimal routes created with rough weather included

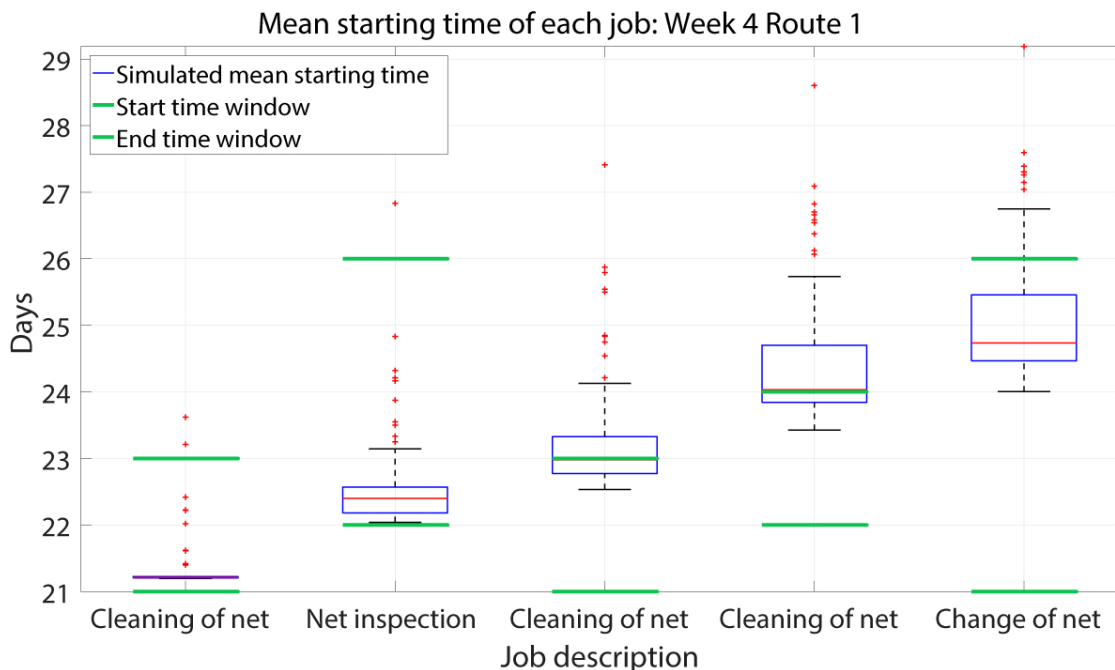
In this simulation we will see if the routes generated with rough weather included performs better on average than the routes generated assuming perfect weather.

Some of the results from the simulation can be seen in figure 33 and 34. Here, we can see how two selected routes perform.



**Figure 33:** Week 2, Route 1: Mean starting time of each job. The starting time of each job are shown in a box plot where the red line shows the median. Here: Cl.=Cleaning , insp=inspection and fl.=floating. Median values for job 3, 4 and 5 are outside their time windows and delays are likely.

If we look at figure 33 one can see that there are many delays and several jobs are not performed within their time windows. Especially job nr 3, 4 and 5 are the most challenging ones because of their small time windows. It should be mentioned that the time windows for these jobs may be unreasonably small since this simulation was performed with rough weather which occurs most during the winter season when the demand for cleaning is low as discussed in section 7.3.1.



**Figure 34:** Week 4, Route 1: Mean starting time of each job. The starting times of each job are shown in a box plot where the red line shows the median. Job 3 and 4 are exposed to delays.

In table 31 one can see the percentage of jobs done within their time windows. The results have improved surprisingly little compared to table 24. The total percentage has increased from 75.7% to 77.5%. Week 1 actually experiences a decrease from 83% to 79.8%. However, this seems to be rather coincidental since the routes travelled this week are all the same except route 1 which

performs one job less. One would expect this to lead to an increase in percentage and not a decrease. Week 2 gives the same poor result as before, because route 1 is still the same. Week 4 experiences a significant improvement from 75.7% to 85.2%. This is because route 1 seen in figure 34 is changed, and one of the jobs previously performed by this route is now transferred to route 2 travelled by the 25 m catamaran. This is the same alternative suggested earlier in section 9.2.1 and we can see the positive effects from this change.

**Table 31:** Percentage of jobs performed within their respective time windows during each week in simulation model.

Week	Robustness [%]
1	79.8
2	70.9
3	73.9
4	85.2
<b>Total</b>	<b>77.5</b>

**Table 32:** Cost difference and increase in robustness for new solution assuming rough weather. Increase in robustness relative to 100%. All costs in NOK.

<b>Solution</b>	<b>Total cost</b>	<b>Cost increase</b>	<b>Cost increase [%]</b>	<b>Increase in robustness [%]</b>
Original solution.	8 503 290	-	-	-
New solution with rough weather included.	8 911 230	407 940	4.8	1.9

The total impression from these results is that including rough weather in the optimization does not necessarily lead to increased robustness. The weather included in the optimization model is too specific and if this is to have a positive effect we would need to know the weather forecast upfront, increasing the probability of this weather actually being realised.

The total increase in cost compared to the solution in table 21 is 4.8%, but this includes the simplification concerning the cost of not doing a job, which makes the two solutions difficult to compare. The increase in robustness is quite small and only 1.9%.

## 9.4 Implementation of measures to increase robustness

This section looks into the possibility of increasing the robustness of the solutions by introducing different restricting constraints. We will look at different measures to increase the robustness as discussed in section 7.5 and evaluate them independently before seeing how they work combined.

### 9.4.1 Maximum number of jobs performed per route

As discussed in section 7.5.1, we believe that longer routes are more exposed to delays. In order to avoid long routes a constraint is implemented regarding maximum number of jobs performed for each route. The results from the simulations so far indicate that a maximum of four jobs per route seems to be a reasonable choice in order to try and avoid delays

**Table 33:** Vessels used, route description and cost for optimal solution, assuming perfect weather and maximum four jobs per route. All costs in NOK.

	Vessels used	Jobs performed	Route cost	Weekly cost
<b>Week 1</b>				2 050 890
1	15 m catamaran	5, 2, 6, 7	154 296	
2	25 m catamaran	9, 10, 11, 12	1 159 750	
3	40 m monohull	1, 4, 8, 3	397 081	
<b>Week 2</b>				1 812 740
1	15 m catamaran	2, 5, 6	330 285	
2	15 m catamaran	8, 10, 3, 7	335 474	
3	25 m catamaran	1	291 438	
4	25 m catamaran with delouser	4, 11, 9	571 431	
<b>Week 3</b>				2 472 530
1	15 m catamaran	9, 5	440 842	
2	15 m catamaran	10, 4, 11	208 296	
3	25 m catamaran	6	488 452	
4	25 m catamaran with delouser	2	105 754	
5	40 m monohull	1. 8, 3, 7	731 944	
<b>Week 4</b>				2 310 540
1	15 m catamaran	5, 7	196 284	
2	15 m catamaran	9, 10, 11, 8	269 677	
3	25 m catamaran	1	578 792	
4	40 m monohull	4, 2, 3, 6	885 826	
<b>Sum weekly cost</b>				<b>8 646 700</b>

and increase robustness. The optimization model is run assuming perfect weather. By implementing this constraint we get the result seen in table 33.

We can see that the number of routes travelled is now increased for week 2, 3 and 4. The total cost increase compared to the solution described in table 20 is 235 290 NOK or 2.8%. Similar to that solution we have a sub-optimal fleet size and mix across the different weeks. Therefore, a similar adjustment is performed as done in previous solutions and do not allow vessel type nr 3, 25 m catamaran with delouser, to be used since this is only used in week 2 and 3. Another observation made is that during week 3 there are five delousing jobs that need to be performed. Therefore, we allow for this week only to include five jobs in one route in order to to be able to use only one vessel to perform these jobs instead of two. With these new restrictions introduced, the solution can be seen in table 34.

**Table 34:** Vessels used, route description and cost for optimal solution assuming perfect weather, and maximum four jobs per route except during week 3. Adjusted fleet size and mix. All costs in NOK.

	Vessels used	Jobs performed	Total cost	Weekly cost
<b>Week 1</b>				2 050 890
1	15 m catamaran	5, 2, 6, 7	154 296	
2	25 m catamaran	9, 10, 11, 12	1 159 750	
3	40 m monohull	1, 4, 8, 3	397 081	
<b>Week 2</b>				1 849 360
1	15 m catamaran	2, 5, 6	330 825	
2	15 m catamaran	8, 10, 3, 7	335 474	
3	25 m catamaran	1	291 438	
4	40 m monohull	11, 4, 9	512 203	
<b>Week 3</b>				2 319 520
1	15 m catamaran	9, 5	440 842	
2	15 m catamaran	10, 4, 11	208 296	
3	25 m catamaran	6	488 452	
4	40 m monohull	1, 8, 2, 3, 7	801 962	
<b>Week 4</b>				2 310 540
1	15 m catamaran	5, 7	196 284	
2	15 m catamaran	9, 10, 11, 8	269 677	
3	25 m catamaran	1	578 792	
4	40 m monohull	4, 2, 3, 6	885 826	
<b>Sum weekly cost</b>				<b>8 530 310</b>

Relaxing the constraint of only 4 jobs per route during week 3 reduces the cost quite significantly. In addition to the cost reduction of having one vessel less during that week, we also have a cost reduction from having one vessel less during the other three weeks. We can summarise the costs of the different solutions with constraints regarding maximum jobs per route included in table 35. The costs of not using all vessels all weeks are included. The selected solution is shown in bold.



**Table 35:** Total cost of different fleet compositions assuming perfect weather, and maximum four jobs per route. All costs in NOK.

Fleet composition	Total cost	Cost reduction	Cost reduction [%]
1	9 134 576	-	-
2	9 347 184	-212 608	-2.3
3	9 431 300	-296 724	-3.3
4	8 867 572	267 004	2.9
<b>5</b>	<b>8 570 512</b>	<b>564 064</b>	<b>6.2</b>

1 = No fleet adjustments.

2 = Exclude 40 m monohull.

3 = Exclude 25 m with delouser.

4 = Allow 5 jobs per route during week 3 and exclude 40 m monohull.

5 = Allow 5 jobs per route during week 3 and exclude 25 m catamaran with delouser.

#### 9.4.2 Simulation of routes with maximum four jobs.

We now test the new routes created with the new constrains regarding maximum number of jobs per route included in the simulation model and see how they perform. Hopefully, the results will be better. The simulation is run with rough weather conditions. As one can see in table 36 the results are varying.

Week 3 stands out as the clearly worst week with poor performance. However, the total percentage of jobs done within their time windows increases from 75.7% to 82.9%.

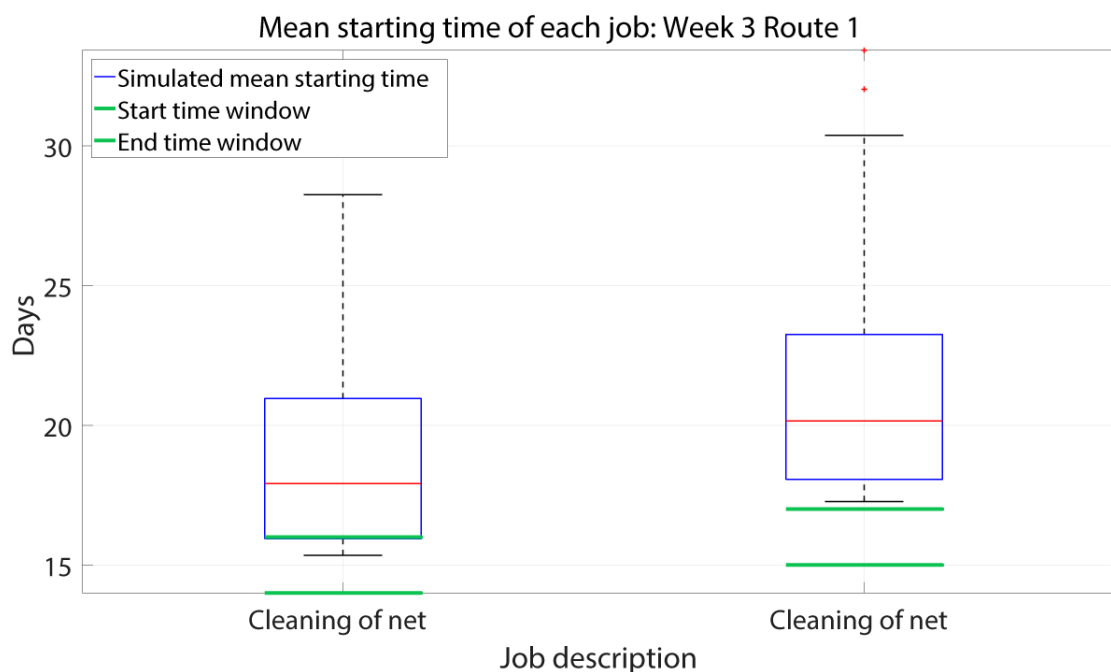
Similar to previous results one can see in figure 35 that route 1 travelled during week 3 is problematic. None of the simulations are able to perform the second job for this route within its time window. This is, as explained before, because of the long distance travelled before the first job.

**Table 36:** Percentage of jobs performed within their respective time windows during each week in simulation model with constraint regarding max jobs per route included.

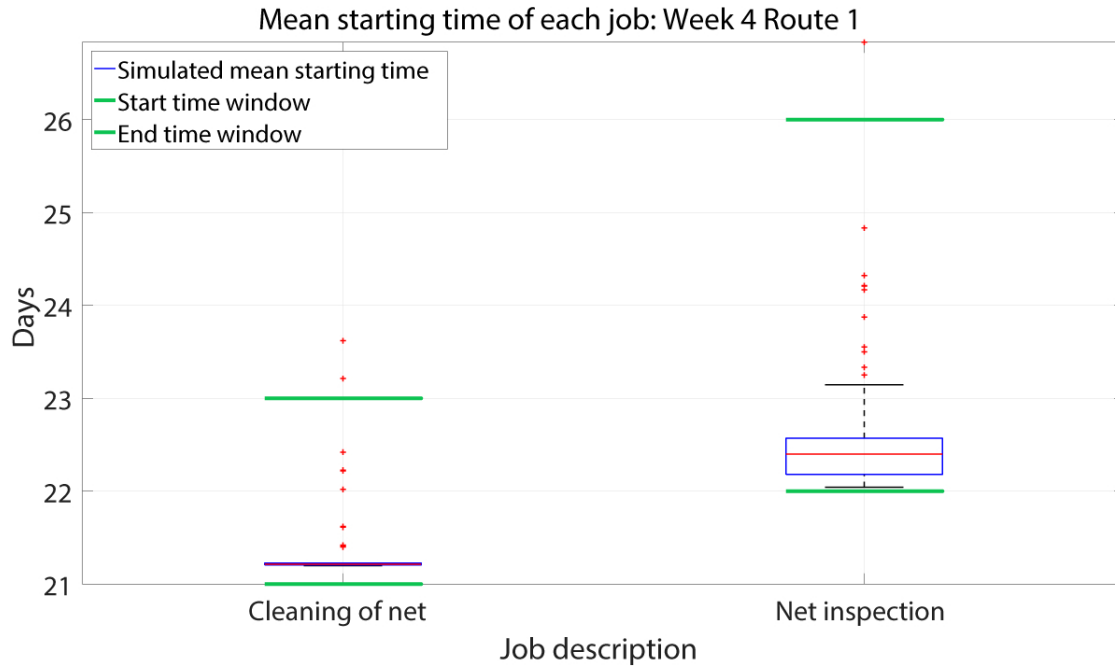
Week	Robustness [%]
1	80.8
2	85.1
3	70.4
4	95.6
<b>Total</b>	<b>82.9</b>

Both week 1 and week 3 actually have reduced performance regarding jobs done within their time windows compared to the results in table 24. For week 1 this is coincidental since the routes travelled are exactly the same. For week 3 however the routes are changed. It seems that especially the results for route 1 affect the total percentage for week 1 for the worse. The second job for this route is changed from job nr 6 to job nr 5, which has a tighter time window. This change causes the percentage of jobs performed within their time windows to decrease. Since none of the simulations are able to make the time window for this second job, it seems this route needs to be altered or we have to accept that delays are very likely to happen.

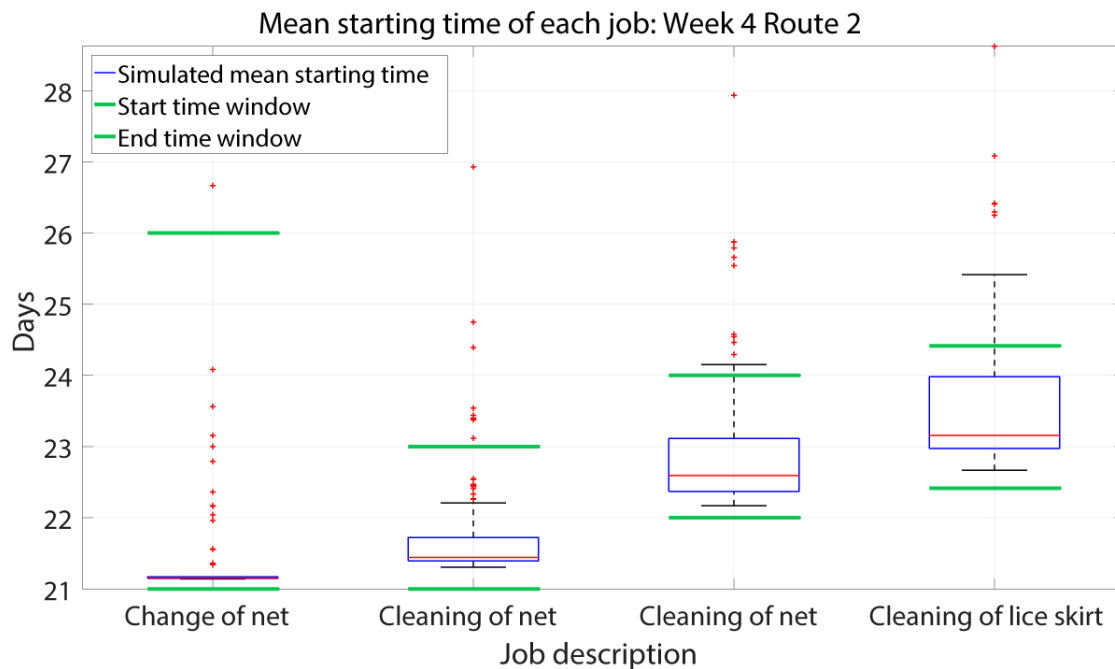
For week 2 and 4, on the other side, the new routes show significant improvements. Performance for week 2 increases from 70.9% to 85.1% and week 4 increases from 76% to 95.6%. These improvements come from splitting the long routes during these weeks up and using an extra vessel. This leads to only a small increase in cost of approximately 80 000 NOK or 2% for these two weeks and hence seems like a reasonable choice. In figure 36 and 37 one can see how the new routes for week 4 perform.



**Figure 35:** Simulation max 4 jobs, Week 3, Route 1: Mean starting time of each job. The starting times of each job are shown in a box plot where the red line shows the median. Median values show that delays are certain to happen.



**Figure 36:** Simulation max 4 jobs, Week 4, Route 1: Mean starting time of each job. The starting times of each job are shown in a box plot where the red line shows the median. Median values are well within their time windows.



**Figure 37:** Simulation max 4 jobs, Week 4, Route 2: Mean starting time of each job. The starting times of each job are shown in a box plot where the red line shows the median. Median values are significantly improved to previous results.

**Table 37:** Cost increase and increase in robustness with new constraints regarding max jobs per route introduced. Increase in robustness relative to 100%. All costs in NOK.

<b>Solution</b>	<b>Total cost</b>	<b>Cost increase</b>	<b>Cost increase [%]</b>	<b>Increase in robustness [%]</b>
Original solution	8 503 290	-	-	-
New solution with robustness included	8 570 512	67 222	0.8	7.2

If we compare the new solution with a constraint regarding maximum jobs per route included, with the original solution seen in table 21, the total cost will increase by 67 222 NOK or 0.8% as seen in table 37. The increase in robustness measured in total number of jobs performed within their time windows in the simulation model is equal to 7.2%. This indicates that this constraint is a quite effective measure with little increase in cost.

### 9.4.3 Slack

In this section slack is to be introduced the model. We introduce a restriction stating that each vessel must have at least a given number of hours of idle time between each job. We set the minimum number of idle hours equal to four and include this constraint in the route generation algorithm. We make sure that this constraint is not included if the next job is of the same job type and located at the same location as the previous job. This can occur for the bigger jobs which we have divided into smaller jobs in order to avoid the weather constraint being too strict as discussed in section 7.1.2. Including slack between these jobs cause unnecessary waiting. Slack before the first job is not included as this is equivalent to saying that all vessels have to wait 4 hours before they can leave port which seems unnecessary. However, this decision is controvertible since vessels may experience poor sailing conditions on the way to the first job, which can cause delays.

The first solution obtained has the same problem as before with different fleet compositions being used each week. Therefore, the first result obtained is adjusted and replace 25 m catamarans with delouser with 40 m monohulls. By doing this one is able to reduce the

**Table 38:** Vessels used, route description and cost for optimal solution assuming perfect weather, and minimum 4 hours idle time between each job. All costs in NOK.

	Vessels used	Jobs performed	Total cost	Weekly cost
<b>Week 1</b>				2 084 580
1	15 m catamaran	5, 2, 6, 7	157 082	
2	25 m catamaran	9, 10, 11, 12	1 168 110	
3	40 m monohull	4, 1, 8, 3	419 621	
<b>Week 2</b>				1 877 770
1	15 m catamaran	2, 5, 6	335 201	
2	15 m catamaran	8, 10, 3, 7	349 420	
3	25 m catamaran	1	295 019	
4	40 m monohull	11, 4, 9	518 169	
<b>Week 3</b>				2 353 750
1	15 m catamaran	9, 5	447 348	
2	15 m catamaran	10, 4, 11	218 522	
3	25 m catamaran	6	492 033	
4	40 m monohull	1, 8, 2, 3, 7	815 888	
<b>Week 4</b>				2 309 330
1	15 m catamaran	5, 8, 10, 11, 9, 7	487 440	
2	25 m catamaran	1	582 373	
3	40 m monohull	4, 2, 3, 6	899 752	
<b>Sum weekly cost</b>				<b>8 625 430</b>

cost by 430 000 NOK or 4.7%. We try altering the fleet further, by reducing the number of vessels used, but this increases the cost. The selected fleet size and mix with this new constraint included can be seen in table 38.

As one can see the routes during week 2 and 3 are exactly the same as the ones found in the previous section 9.4.1 which is quite coincidental, but shows that slack also has an effect on how many jobs a vessel is able to make per route within the time windows. However, the costs for these routes have increased since the vessels have to wait 4 additional hours between each job. This shows that including slack might cause unrealistically high costs for each route since the results from the constraints regarding maximum jobs per route indicate that the same routes should be possible to complete at a lower cost.

**Table 39:** Total cost of different fleet compositions assuming perfect weather and slack included. All costs in NOK

Fleet composition	Total cost	Cost reduction	Cost reduction [%]
1	9 138 007	-	-
2	8 994 884	143 123	1.6
<b>3</b>	<b>8 705 834</b>	<b>432 173</b>	<b>4.7</b>
4	9 029 470	108 537	1.2
5	8 740 430	397 577	4.4

1 = No fleet adjustments.

2 = Exclude 40 m monohull.

3 = Exclude 25 m with delouser.

4 = Max one 15 m catamaran and exclude 40 m monohull.

5 = Max one 15 m catamaran and exclude 25 m catamaran with delouser.

We can summarise the costs of the different solutions found with constraints regarding minimum idle hours between each job included in table 39. The cost of not using all vessels all weeks is included. The selected solution is shown in bold.

#### 9.4.4 Simulation of routes with slack included

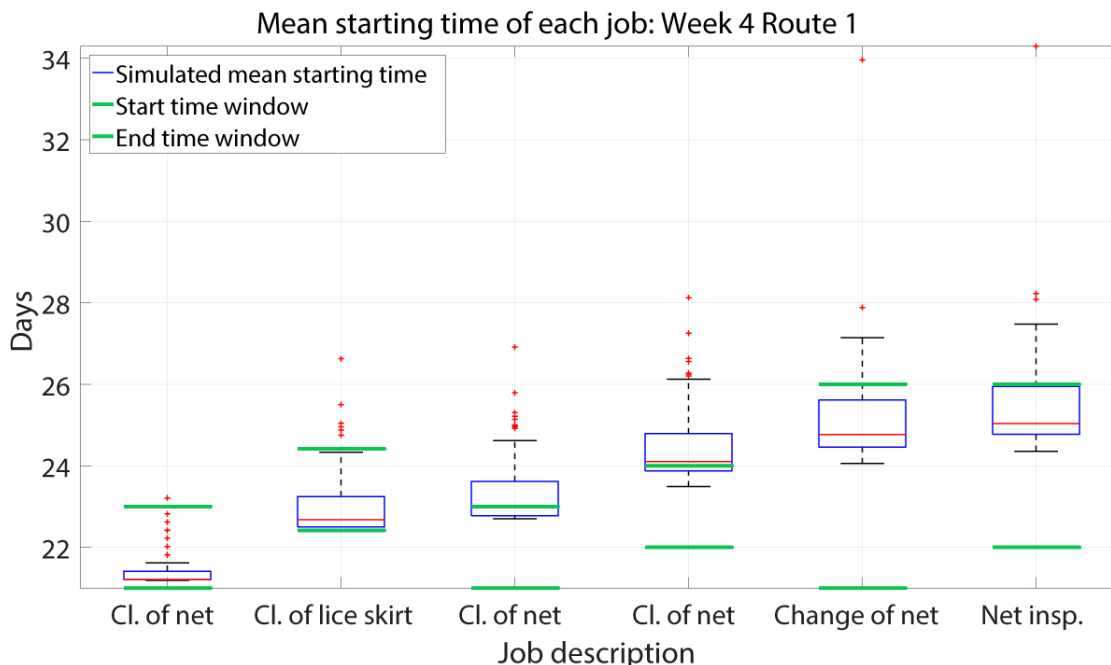
The results with slack included are tested in the simulation model. The percentage of jobs done within their time windows can be seen in table 40. As we can see from the table,

including slack as a constraint also increases the percentage of jobs performed within their time windows. The total percentage increases from 75.7% to 79.1%.

However the increase is not as good as for the previous case with maximum four jobs per route. Especially week 4 does not experience the same improvement which is due to the fact that we only use three vessels instead of four. Results for route 1 for this

**Table 40:** Percentage of jobs performed within their respective time windows during each week in simulation model with constraint regarding slack included.

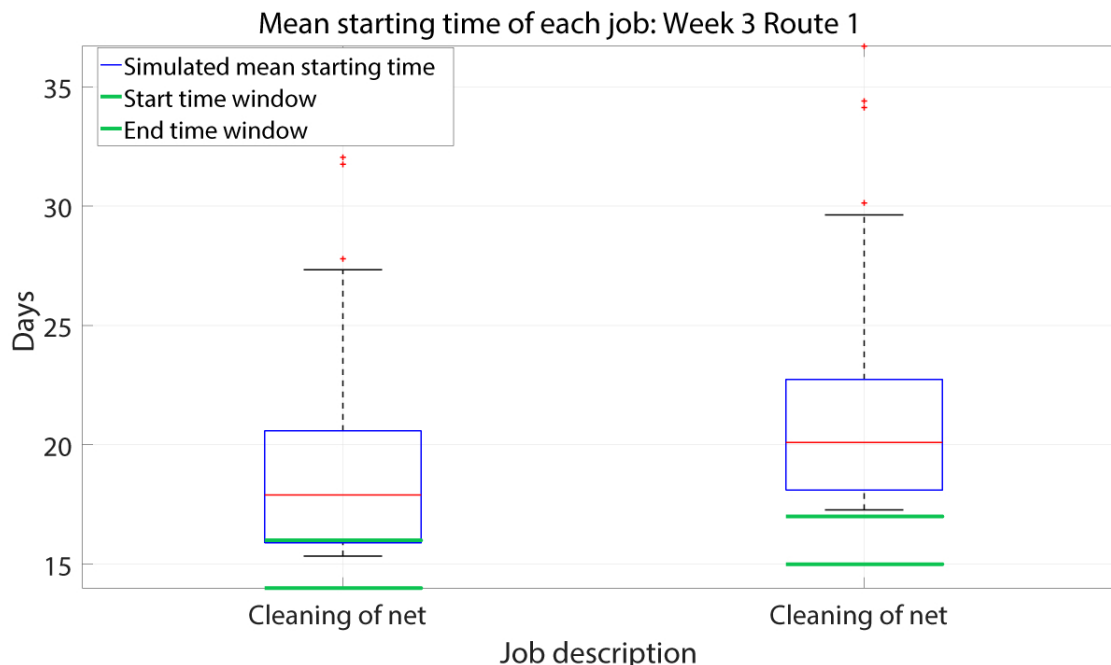
Week	Robustness [%]
1	81.1
2	83.0
3	67.5
4	84.8
<b>Total</b>	<b>79.1</b>



**Figure 38:** Simulation with slack, Week 4, Route 1: Mean starting time of each job. The starting times of each job are shown in a box plot where the red line shows the median. Here, Cl. = Cleaning, insp. = inspection. Median values show a decrease in robustness compared to figure 36 and 37.

week is showed in figure 38 where one can see that the this route is quite exposed to delays, especially for the third and fourth job performed.

Results for week 3 are reduced compared to the previous result, but again this has to be coincidental since the routes travelled are exactly the same. The results for route 1 during week 3 can be seen in figure 39 which still performs very poorly. However, we see the same effect as seen with the result in the previous section when compared with the original results seen in table 24. The new routes in week 3 using four vessels, perform worse than the original routes in table 21 where only three vessels are used. This is surprising and could be coincidental. Week 2 experiences a good improvement compared to the original results without any additional constraints which is not surprising since the routes are exactly the same as in the previous section with maximum four job per route.



**Figure 39:** Simulation with slack, Week 3, Route 1: Mean starting time of each job. The starting times of each job are shown in a box plot where the red line shows the median. Median values show that delays are certain to happen.

We can summarise all the different solutions found by implementing the different constraints regarding robustness in table 41. The cheapest constraint seems to be length of the routes. Implementing the constraint regarding maximum number of jobs per route only leads to a cost increase of 0.8%. In addition the increase in robustness regarding number of jobs performed within their time windows was the highest for this constraint in the simulation model.

**Table 41:** Summary of costs, cost increase and increase in number of jobs performed within their time windows from implementing different measures for robustness in the model. Costs in NOK.

Solution	Total cost	Cost increase	Cost increase [%]	Increase in robustness [%]
Original solution	8 503 290	-	-	
Rough weather	8 911 230	407 940	4.8	1.9
Max four jobs	8 570 512	67 222	0.8	7.2
Slack	8 705 834	202 544	2.4	3.5



### 9.4.5 Combining different measures for robustness

Now we want to test the different measures for robustness combined and see if the robustness can be further increased. The different measures to combine are:

- Include weather constraints in the route generation.
- Maximum jobs per route.
- Minimum idle hours between jobs.

#### 9.4.5.1 Combining max jobs per route and slack

First we test the combination of maximum jobs per route and minimum idle hours between jobs. Some adjustments to the fleet obtained have been made in order to reduce costs regarding vessels not used. By doing this we get the solution seen in table 42.

**Table 42:** Vessels used, route description and cost for optimal solution assuming perfect weather, and all robustness measures included. All costs in NOK.

	Vessels used	Jobs performed	Total cost	Weekly cost
<b>Week 1</b>				2 035 730
1	15 m catamaran	5, 2, 6, 7	157 082	
2	25 m catamaran	9, 10, 11, 12	1 168 110	
3	40 m monohull	4, 1, 8, 3	419 621	
<b>Week 2</b>				1 824 300
1	15 m catamaran	2, 5, 6	335 201	
2	15 m catamaran	8, 10, 3, 7	349 420	
3	25 m catamaran	1	295 019	
4	40 m monohull	11, 4, 9	518 169	
<b>Week 3</b>				2 353 750
1	15 m catamaran	9, 5	447 348	
2	15 m catamaran	10, 4, 11	218 522	
3	25 m catamaran	6	492 033	
4	40 m monohull	1, 8, 2, 3, 7	815 888	
<b>Week 4</b>				2 291 310
1	15 m catamaran	5, 7	202 790	
2	15 m catamaran	9, 10, 11, 8	279 903	
3	25 m catamaran	1	582 373	
4	40 m monohull	4, 2, 3, 6	899 752	
<b>Sum weekly cost</b>				<b>8 505 090</b>

One can see that the routes created are very similar to the ones seen in table 34, where we only included a constraint regarding maximum jobs per route. The only difference in fact is route 3 during week 1. Thus we can see that also including slack in the model has little effect in our case.

We can summarise the different solutions found with the two constraints included in table 43. The most cost optimal solution is shown in bold.

**Table 43:** Total cost of different fleet compositions assuming perfect weather, and both robustness measures included. All costs in NOK.

Fleet composition	Total cost	Cost reduction	Cost reduction [%]
1	8 985 471	-	-
2	9 464 294	-197 948	-2.1
3	9 567 850	-301 504	-3.3
4	8 990 142	276 204	3.0
<b>5</b>	<b>8 701 092</b>	<b>565 254</b>	<b>6.1</b>

1 = No fleet adjustments.

2 = Exclude 40 m monohull.

3 = Exclude 25 m with delouser.

4 = Allow 5 jobs per route during week 3 and exclude 40 m monohull.

5 = Allow 5 jobs per route during week 3 and exclude 25 m catamaran with delouser.

#### 9.4.5.2 Combining all three measures

In order to test the effects of all three constraints the same weather conditions as used in section 9.3 will be used. This is to be able to compare the results. We run the optimization with all constraints included and make appropriate fleet adjustments. This gives the solution shown in table 44.

**Table 44:** Vessels used, route description and cost for optimal solution assuming rough weather, and all robustness measures included. All costs in NOK.

	Vessels used	Jobs performed	Total cost	Weekly cost
<b>Week 1</b>				2 301 900
1	15 m catamaran	2, 6, 7	146 551	
2	25 m catamaran	9, 10, 11, 12	1 176 480	
3	40 m monohull	1, 4, 8, 3 Job nr 5 not performed	439 073 200 000	
<b>Week 2</b>				1 911 270
1	15 m catamaran	2, 3, 7, 5	447 225	
2	15 m catamaran	8, 10, 6	270 897	
3	25 m catamaran	1	295 019	
4	40 m monohull	11, 4, 9	518 169	
<b>Week 3</b>				2 431 800
1	15 m catamaran	10, 4, 11	218 522	
2	25 m catamaran	9, 6	768 466	
3	40 m monohull	8, 2, 1, 7, 3 Job nr 5 not performed	905 080 200 000	
<b>Week 4</b>				2 344 780
1	15 m catamaran	5, 7	202 790	
2	15 m catamaran	9, 10, 11, 8	279 903	
3	25 m catamaran	1	582 373	
4	40 m monohull	4, 2, 3, 6	899 752	
<b>Sum weekly cost</b>				<b>8 785 110</b>

An overview of the different solutions found can be seen in table 45. The most cost optimal solution is shown in bold.

**Table 45:** Total cost of different fleet compositions assuming rough weather, and all robustness measures included. All costs in NOK.

Fleet composition	Total cost	Cost reduction	Cost reduction [%]
1	9 621 928	-	-
2	9 795 566	-173 638	-1.8
3	9 923 332	-301 404	-3.1
4	9 316 044	305 884	3.2
<b>5</b>	<b>9 070 154</b>	<b>551 774</b>	<b>5.7</b>

1 = No fleet adjustments.

2 = Exclude 40 m monohull.

3 = Exclude 25 m with delouser.

4 = Allow 5 jobs per route during week 3 and exclude 40 m monohull.

5 = Allow 5 jobs per route during week 3 and exclude 25 m catamaran with delouser.

### 9.4.6 Simulation of combinations of measures for robustness

We now want to test the two different combinations of constraints in the simulation model. We start with the solution found assuming perfect weather and with both constraints regarding maximum number of jobs per route and slack included.

#### 9.4.6.1 Simulation of routes created with two measures included

Since the optimal routes found with the two constraints combined are almost the same as the ones found by only including the constraint regarding maximum jobs per route, we expect the results from the simulation to be very similar as well.

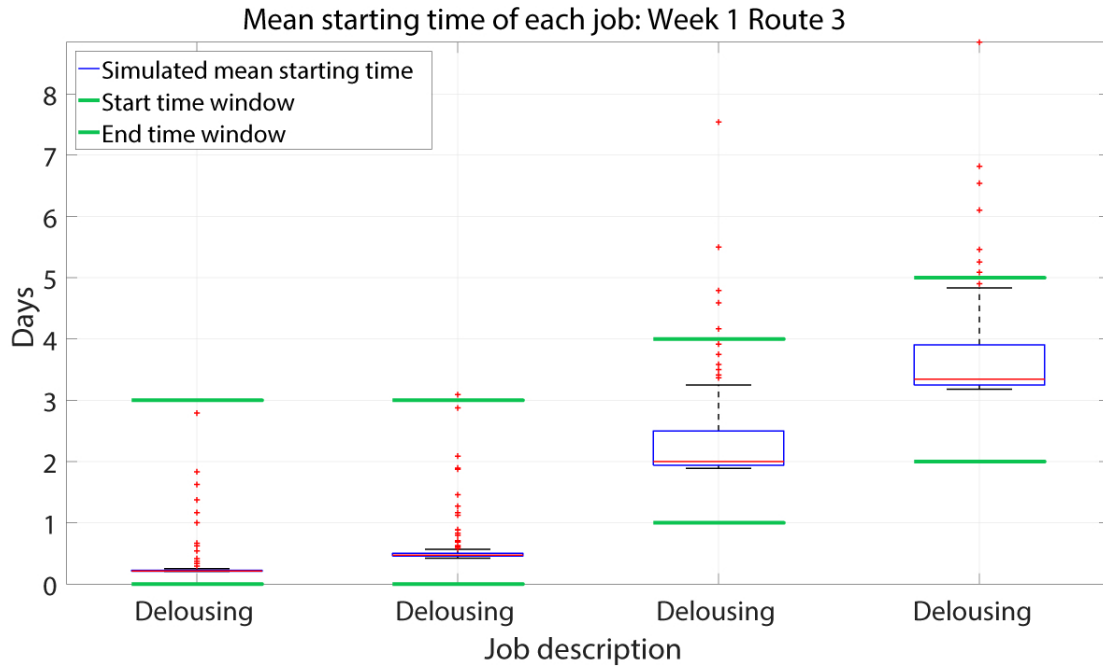
In table 46 one can see the results regarding percentage of jobs performed within their time windows. As expected these are similar to previous results. If we compare with the results obtained when only implementing the constraint regarding maximum jobs per route, we can see that the total percentage of jobs performed within their time windows has increased from 82.9% to 83.5% which is a small improve-

**Table 46:** Percentage of jobs performed within their respective time windows during each week in simulation model with both constraints regarding slack and max jobs per route included.

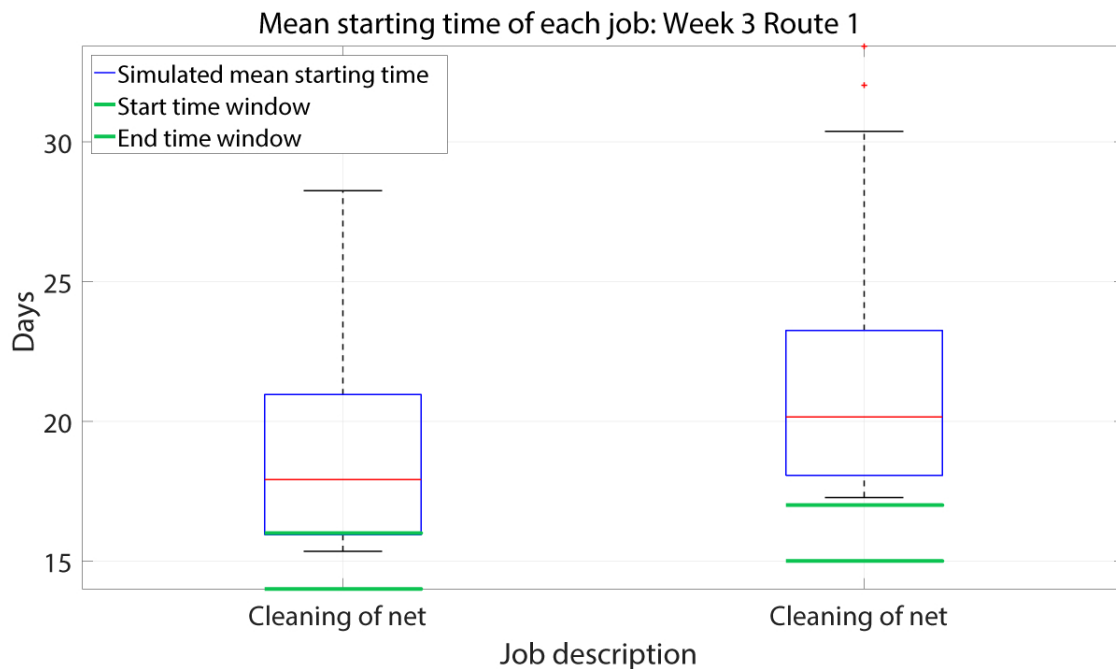
Week	Robustness [%]
1	82.9
2	85.3
3	70.4
4	95.6
<b>Total</b>	<b>83.5</b>

ment. However, we see that the percentage during week 1, which is the only week containing a different route than previous results, has increased from 80.8% to 82.9%. This indicates that combining slack with the constraint of maximum four jobs per route does have a positive effect. The results for the new route can be seen in figure 40. The results from the other weeks are very similar to previous results. We still experience problems regarding route 1 during week 3, which can be seen in figure 41, since the routes here are unchanged.

The cost increase of this combination compared to only including the constraint regarding maximum number of jobs per route is 130 580 NOK or 1.5%.



**Figure 40:** Robust simulation, Week 1, Route 3: Mean starting time of each job. The starting times of each job are shown in a box plot where the red line shows the median. Median values are well within their time windows and probability for delays is low.



**Figure 41:** Week 3, Route 1: Mean starting time of each job. The starting times of each job are shown in a box plot where the red line shows the median. Median values are still well outside their time windows and delays will happen.

### 9.4.6.2 Simulation of routes created with all three measures included

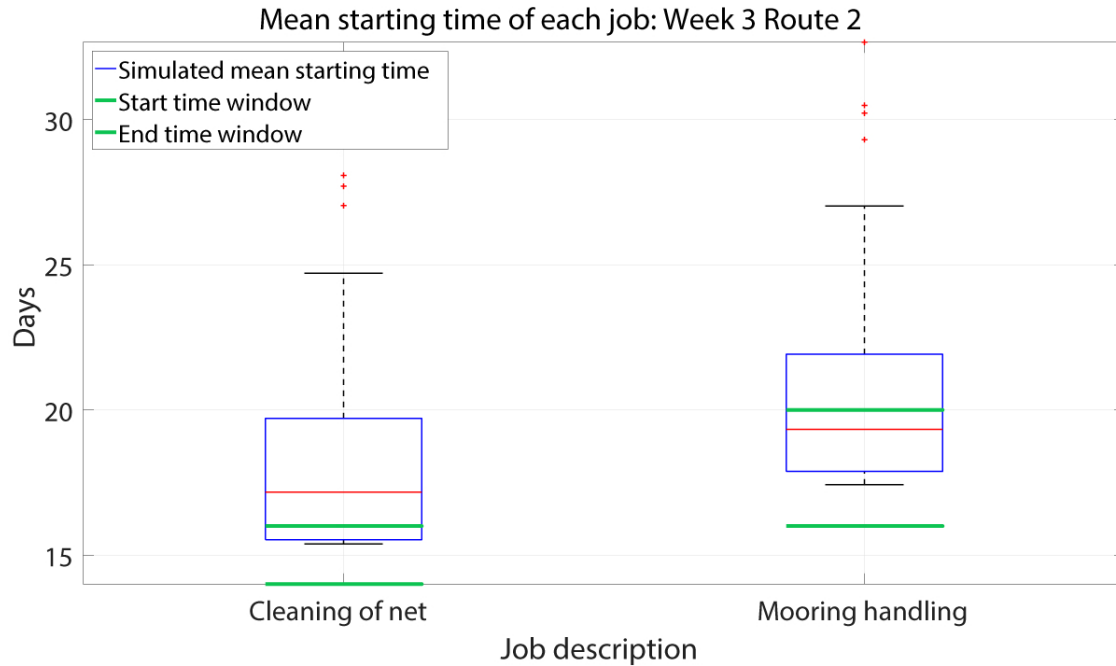
When we also include rough weather in the optimization model we see that especially week 3 is improved. This is because the route which has performed very poorly in the previous simulations is now changed as seen in figure 42. However week 1 and 2 seem to perform worse with rough weather included. This is strange and could simply be coincidental, since all the simulations are run with many stochastic parameters.

**Table 47:** Percentage of jobs performed within their respective time windows during each week in simulation model with all three constraints included.

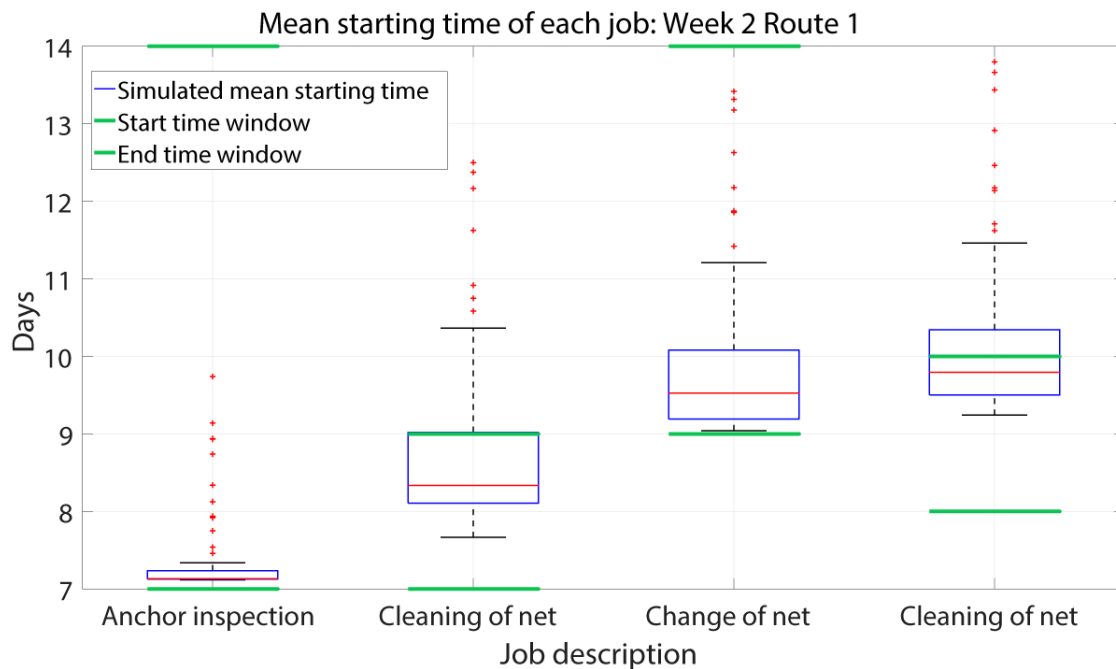
Week	Robustness [%]
1	78.0
2	82.0
3	73.4
4	95.2
<b>Total</b>	<b>82.4</b>

For week 1 the only difference is route 3, which is changed. Job nr 4 and 1 is done in the opposite order. It seems that this route is more exposed to delays than the one travelled in the previous solution with job nr 4 done before job nr 1, since the version with job nr 4 done before job nr 1 always seems to give better results. For week 2, route 1 and 2 are changed, and it seems the routes found with the rough weather included are more exposed to delays than the routes found assuming perfect weather. The results for route 1 during week 2 can be seen in figure 43.

Because of the reduction in performance during these two weeks, the overall result indicate that implementing rough weather in the optimization model does not have a positive effect. We can see that the total percentage of jobs done within their time windows decreases from 83.5% to 82.4%. This in combination with the fact that the overall cost of this solution increases make this a less desirable solution. One should however keep in mind that costs for waiting for bad weather is included in this solution, while this is not the case for the routes generated with perfect weather. Therefore the actual costs of the two different solutions might be different than what is seen in table 48.



**Figure 42:** Simulation, week 3, Route 2: Mean starting time of each job. The starting times of each job are shown in a box plot where the red line shows the median. Median values show improvements, but delays are still very likely.



**Figure 43:** Simulation, week 2, Route 1: Mean starting time of each job. The starting times of each job are shown in a box plot where the red line shows the median. Median values show last job is exposed to delays.

**Table 48:** Summary of costs, cost increase and increase in number of jobs performed within their time windows from combining different measures for robustness in the model. Costs in NOK.

<b>Solution</b>	<b>Total cost</b>	<b>Cost increase</b>	<b>Cost increase [%]</b>	<b>Increase in robustness [%]</b>
Perfect weather, max 4 jobs and min 4 hours slack	8 701 092	197 802	2.3	7.9
Rough weather, max 4 jobs and min 4 hours slack	9 070 154	566 864	6.7	6.7

We can summarise the two different combinations in table 48. We can see that including rough weather in the optimization increases the cost significantly, while it actually performs worse than the combination without the weather included regarding robustness.

## 9.5 Simulation with extended time windows

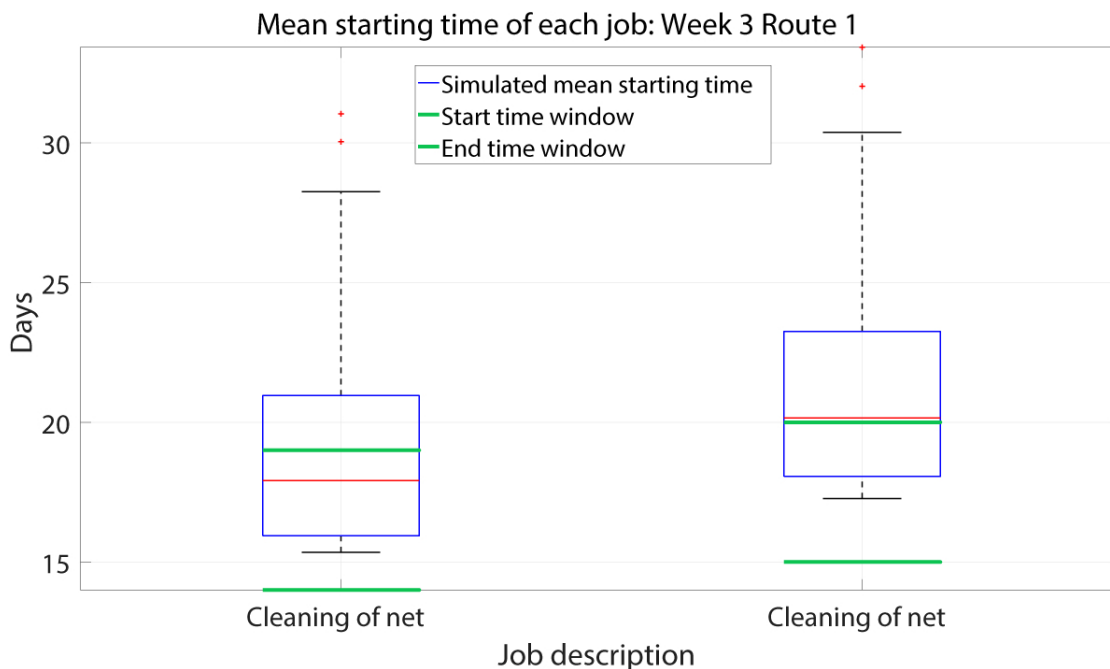
As one final test we wish to see how the results improve if we take the routes generated and test them in the simulation model with extended time windows. As discussed in section 7.3.1 the time windows are likely to vary with season. The time windows used in the routes generated so far, are set to the minimum level. However, most of the simulations are run with rough weather included which is most present during winter season. Therefore, we wish to investigate how the routes perform if we expand the time windows for the jobs which are most likely to have increased time windows during winter season. These are the same time windows used in section 9.3.2. When choosing which routes we want to test, we use the ones that have given the most satisfying result so far, which are the routes generated with the combination of maximum jobs per route and slack.



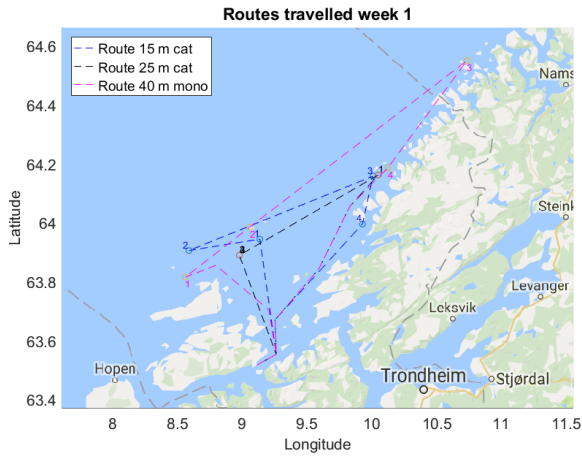
When increasing the time windows for the jobs with less demand during the winter season, one can see in table 49 that the total percentage of jobs performed within their time windows increase from 83.5% to 92.0%. Week 3 which has proved to contain the most challenging routes to perform without delays has improved from 70.4% to 84.7%. However, we can see in figure 44, that even with the extended time windows route 1 during week 3 is challenging. The median for second job is still outside the time window and it may be necessary to find alternative routes during this week. We will discuss this and the consequences of extended time windows more in chapter 10. All results from this simulation can be seen in appendix G.

**Table 49:** Percentage of jobs performed within their respective time windows during each week in simulation model with extended time windows.

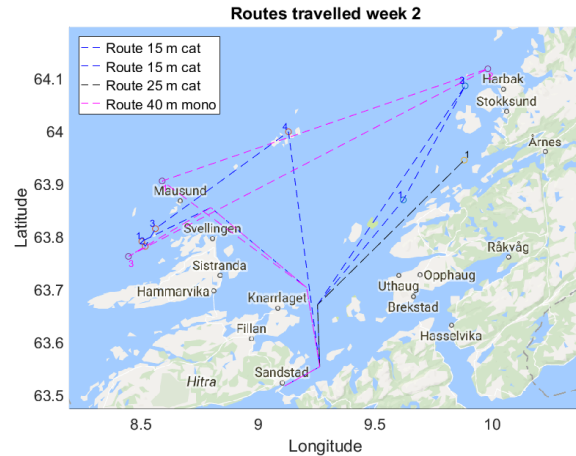
Week	Robustness [%]
1	88.2
2	96.1
3	84.7
4	99.2
<b>Total</b>	<b>92.0</b>



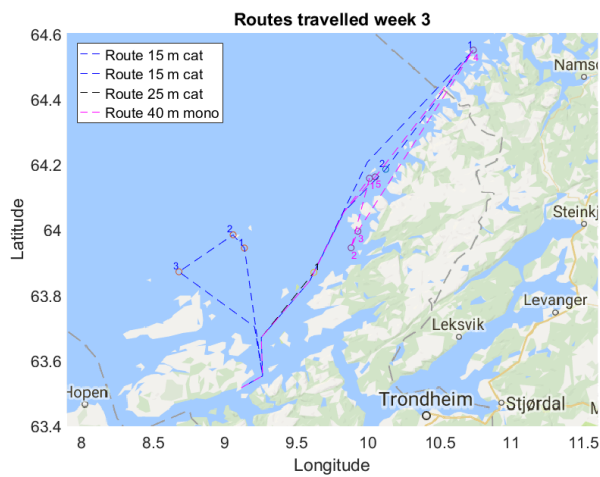
**Figure 44:** Extended time windows, week 3, Route 1: Mean starting time of each job. The starting times of each job are shown in a box plot where the red line shows the median. Median values show that last job is exposed to delays even with extended time windows.



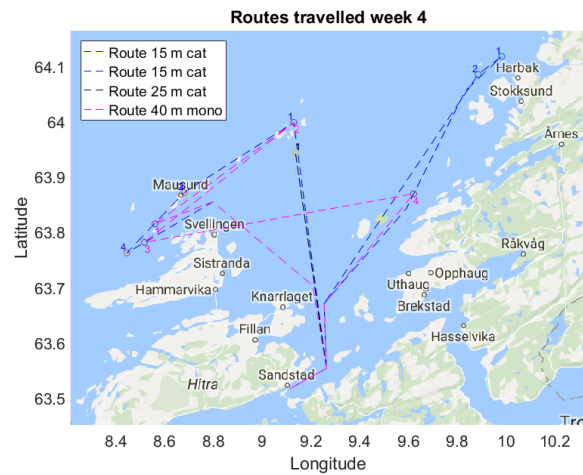
**Figure 45:** Optimal routes for week 1 with combination of constraints included and assuming perfect weather.



**Figure 46:** Optimal routes for week 2 with combination of constraints included and assuming perfect weather.



**Figure 47:** Optimal routes for week 3 with combination of constraints included and assuming perfect weather.



**Figure 48:** Optimal routes for week 4 with combination of constraints included and assuming perfect weather.

In figure 45, 46, 47 and 48 we can see the routes which gave the best results displayed on the map. These are the same routes as presented in table 42.

## 9.6 A summary of the results

Several different scenarios have been tested, and a summary of the most important results is therefore presented in table 50. The results obtained indicate that implementing extra constraints regarding robustness in the optimization model have a positive effect on reducing the risk of delays. The increase in cost from these additional constraints are small compared to the improvement in robustness. However, we also see that even with these extra constraints included, some of the routes proposed by the optimization model are quite exposed to delays due to bad weather. Therefore, additional evaluations of the routes proposed might be necessary in order to avoid delays.

**Table 50:** Summary of costs, cost increase and increase in number of jobs performed within their time windows from combining different measures for robustness in our model, compared to original solution with no extra constraints implemented. Costs in NOK.

<b>Solution</b>	<b>Total cost</b>	<b>Cost increase</b>	<b>Cost increase [%]</b>	<b>Increase in robustness [%]</b>
Original solution	8 503 290	-	-	
Rough weather	8 911 230	407 940	4.8	1.9
Max four jobs	8 570 512	67 222	0.8	7.2
Slack	8 705 834	202 544	2.4	3.5
Combination 1	8 701 092	197 802	2.3	7.9
Combination 2	9 070 154	566 864	6.7	6.7
Extended time windows	8 701 092	197 802	2.3	16.3

Combination 1 = Max 4 jobs per route and min 4 hours slack between jobs.

Combination 2 = Rough weather included in optimization model, max 4 jobs per route and min 4 hours slack between jobs.

## 10 Discussion

We will in the following chapter discuss the results obtained and their relevance towards to problem we have tried to solve. We will also discuss their credibility, the assumptions made when creating the models and potential weaknesses.

### 10.1 Hypothetical scenario

The first natural part of the model to discuss is the hypothetical scenario created which all the results are based on. We were not able to apprehend any real life scenarios for the demand of maintenance from the service companies, because they would not answer any of our requests. We therefore had to create our own scenario which naturally involves a lot of assumptions. These assumptions involve the amount of demand, especially considering the balance between the different kind of jobs, duration of jobs, time windows and costs. Even though the model contains many assumptions that may not be accurate, one should keep in mind that our main objective with this thesis is to illustrate how our methodology can be used in this industry. Input data to the model can easily be altered in order to represent a more realistic scenario.

#### 10.1.1 Demand for maintenance

When creating the hypothetical scenario for demand for maintenance, we have used the information retrieved from conversations with the service companies AQS and Frøygruppen. However, this information is mainly concerned with cleaning and delousing operations. Therefore, we have had to assume some demand for the other kinds of maintenance such as mooring handling and inspections. In addition, it was difficult to assess how often the different operations are performed compared to each other. We do not know if the scenario we have created involve some jobs being performed more often than what is realistic.

### 10.1.2 Costs

The costs involved in the models naturally contain many assumptions and simplifications. These involve investment costs, salaries, fuel costs, charter rates, and so on. In addition to the numerical values of the costs, it was difficult to evaluate how the costs should be included in the model. We have chosen to have a general view on costs and included costs for both the farmers and the service companies. This however, is problematic because some costs such as charter rates, are a profit for the service companies and a cost for the farmers. We have chosen to include the charter rates as a cost to make sure that operations are done in a cost efficient way. If one is use this model from only a service company's perspective it would be more logical to include this cost as a profit, or not include this cost at all because if all jobs need to be performed this cost would be a constant and not a variable.

Another cost involving a high level of uncertainty is the cost of starving the salmon before delousing operations. These costs are dependent on many factors. Firstly, they are dependent on the number of fish being deloused. Secondly they are dependent on the weight of the fish being deloused and the temperature in the water. This is because the growth rate for the salmon is dependent on both the temperature in the water and the size of the salmon. Small salmon in combination with warm water have a higher growth rate. This means that starving the salmon involves a higher cost in this case. Another assumption is how to evaluate this cost. We have assumed that starving the salmon leads to a direct cost in the form of reduced size of slaughtered salmon. This is a rather rough estimate since the farmer probably will not slaughter the salmon until it has reached the desired weight. The cost of this additional production time for the salmon will probably differ from our estimate.

## 10.2 Trends seen in results

The optimization and simulation model have been run with a variety of different settings and we have obtained many results. We want to summarise some of the findings in the following section. Our first observation is that all results indicate that the use of a multipurpose vessel in the form of a 25 m catamaran with the possibility of installing a delouser gives

suboptimal results. All the different results from the optimization model evaluates the use of a specialised delousing vessel as more cost efficient. This is however strongly related to the assumption that the delousing vessel has to go back to harbour and install and uninstall the delousing system whenever it is going to perform a different type of job. If one is able to build a vessel that does not require this process, this might be valued as a better alternative than the specialised delousing vessel. This is naturally very dependent on the cost of such a vessel. We have however not done more research into this possibility.

Our next observation is that the implementation of additional constraints to improve the robustness seem to have very positive effects regarding robustness compared to the increase in costs. However, even with these constraints included, many of the routes obtained with the optimization model are quite exposed to delays. This shows that when using such a model one has to perform an evaluation of the routes found and potentially make alterations to the most critical routes. How to spot the routes that are most critical can be difficult, but by the assistance of a simulation model this can be done with less effort. For example one could make a model that automatically testes all routes found by the optimization model in the simulation model and then implement a minimum limit regarding the percentage of jobs performed within their time windows. If the routes do not meet this limit, the optimization model is automatically run again and new routes are found. However if one is to make such an iterative model, one would have to design a more effective simulation model than we have been able to do, in order to have an acceptable running time for the model.

Another observation is that the routes that are most exposed to delays are usually the routes for the 15 m catamarans or the 25 m catamarans. The routes for the 40 m monohull always perform quite good. This indicates that the vessel might be able to perform more delousing jobs per week than what we have included in the model. In order to test test this we would have to include more delousing jobs in our scenario and see if the vessel is able to handle the increased demand.

### 10.3 Effects of optimization in fleet scheduling

If one is to argue for the use of optimization in fleet scheduling problems we have to be able to show potential cost reductions that can be achieved. We therefore ran a test showing how much a potentially poor solution to the problem would cost, by manipulating the set-partitioning model to find bad solutions. Our first test came up with a solution using all four ship types which cost approximately 13.68 mill NOK, equivalent to a cost increase of 60%. This was however an unrealistically poor solution and perhaps not a very good basis for comparison, so we did a new test where we used the same fleet size and mix as the optimal solution. This gave a cost of approximately 10.95 mill NOK or an increase of 29%. This increase is only a consequence of choosing different routes. All jobs are still performed. It should be mentioned that this includes the cost of starving the salmon, so the new manipulated model will try find routes where this waiting time is maximised. Naturally, this example illustrates a worst case scenario and is an extreme case of the potential savings, but still it showcases the potential benefits of efficient fleet scheduling. One might also avoid having an overcapacity in the fleet. In addition to these savings one can spare a lot of time and man hours compared to doing the fleet scheduling manually.

### 10.4 Robustness

We have tried implementing different constraints in the model in order to increase the robustness of the fleet and decrease the probability of delays. We will discuss the effects and consequences of the different constraints here.

#### 10.4.1 Maximum jobs per route

Including a constraint regarding the maximum number of jobs performed per route seems to be the constraint which is the most effective regarding both increased costs and robustness. The results obtained from the optimization model with this constraint included only had a small cost increase, while the results from the simulation model indicated a big improvement

regarding the number of jobs performed within their time windows. However, this constraint can be dangerous to implement without doing an evaluation of the results obtained. We saw for week 3, when this constraint was included, we first obtained a sub-optimal solution because this week had a demand of five delousing jobs. Because of the limit of max four jobs per route we had to use two vessels to perform these five jobs, while one vessel was perfectly capable of performing all five. This shows that we have to be careful when implementing such a constraint, because it may lead to an inefficient use of vessels.

#### **10.4.2 Consequences of slack**

The effects of the implemented slack can be seen in table 40. As one can see the slack has a positive effect on the robustness. In order to evaluate the value of this robustness, we need to discuss the consequences of including slack. By introducing slack we can avoid delays, but it can also create unnecessary waiting time. This will create increased costs regarding salary and also the vessels are not able to perform the same amount of jobs in the same time horizon. We can see from the results that the cost increase of implementing slack is equal to around 237 000 NOK or 3% for one month. This is a quite significant cost increase for a service company. The potential costs of not including slack in the fleet scheduling however, can be even greater. But these costs are likely to fall upon the farmer and not the service company in form of delayed jobs. Therefore, the service company might not be willing to pay for the extra cost incurred by implementing slack in the fleet scheduling.

#### **10.4.3 Extended time windows**

We have tested the simulation model with extended time windows. As discussed in section 9.5 this was because the time windows were perhaps set too tight during the winter season for the job types that have reduced demand during this season. This is especially applicable for cleaning and delousing jobs which are the most frequently required jobs in the hypothetical scenario we have created. We also saw in section 9.3.2 that increased time windows can lead to big cost reductions because of more effective routes. However, we must discuss the



consequences of extending the time windows. First of all, the possibility of extended time windows is an assumption. These extended time windows might not be accepted by the salmon farmers because it leads to increased costs for them. For example the delousing jobs are quite exposed to extended time windows because of the cost of starving the salmon before the operations. Extending the time windows for the cleaning jobs might lead to filthy nets which again can for example reduce the effect of cleaner fish and increase the number of lice in the cages. However, the results we have obtained show that a service company should investigate the possibilities for extended time windows together with the salmon farmers because the service companies can save a significant amount of money from extended time windows and possibly offer cheaper services to the farmers.

## **10.5 Weaknesses with the model**

The models we have created are designed to represent the real world as accurate as possible, but naturally we have to make some simplifications which cause weaknesses with our models.

### **10.5.1 Splitting up large jobs**

In our hypothetical scenario we have included jobs which last for several days. This is because larger operations in real life scenarios often last days and even weeks. One problem with this is the weather constraint implemented in the model. The weather constraint is stated in such a way that in order for a job to start, the significant wave height has to be below the predefined operational limit for the entire job duration. A long job duration makes it very hard to fulfil this requirement. A more realistic way of modelling this would be to check the wave height only the next, say 10 hours, and start the operation if the wave height is below the limit for only this period. However, with our modelling it is only possible to check the wave height before a job starts and not during. Once an operation has started it is not possible to stop the operation temporarily in order to wait for better weather. Thus we have to check the wave height for the entire job duration and can not check a subset of the time horizon.

As discussed in section 7.1.2 we have tried to handle this problem by dividing some of the jobs into smaller jobs. This however leads to another problem. We do not have a way of ensuring that that jobs are done in the correct order. When dividing the job, the model is allowed to treat these jobs as single jobs and we can have two vessels working on the same job simultaneously which is not feasible.

The best way to handle this problem would probably be to divide the job into smaller jobs as we have done, but implement some constraint making the sure the jobs are done in the correct order. For example if we are able to make sure that the same vessel performs the single jobs, the order in which they are done does not matter as long as they all represent the same job and all have the same job duration. We have however not been able to find a good way of doing this.

### **10.5.2 Weakness when using Markov chain in the optimization model**

For most of the solutions obtained in the optimization model, we have not included any constraints regarding weather and assumed that the weather is perfect. This is the easiest way of getting more general optimal solutions regardless of the wave heights. We have however tried to run the optimization model with weather constraints included as well using a Markov chain approach.

When using a Markov chain to simulate the wave heights we encounter one problem with the method, regarding the route generation method. When using the route generation method all input to the set-partitioning model is deterministic. This means that it is not possible to treat the weather as stochastic in the set-partitioning model. One problem with this is that for each Markov chain simulation, the route generation algorithm will produce different results, which again will affect the solutions generated by the set-partitioning model. In other words, when including weather constraints in the route generation algorithm, the routes generated will only be one realisation of the problem with that specific weather condition included. This means that when running the complete model with both route generation and optimization included, we will get different results each time. This makes it difficult to

evaluate the different solutions obtained, and to decide which solutions should be saved and tested in the simulation model.

We saw from the results obtained from the simulations of routes created with weather included in the optimization that these gave poor results regarding robustness. This shows that including weather in the optimization has little effect, because the solution obtained is only optimal for one specific weather scenario. One could argue that if one could use a realistic weather forecast for the next week as input to the Markov chain simulation, one might achieve good results from including weather constraints in the route generation algorithm. However, weather forecasts regarding wave heights are highly uncertain and using this data as input could also lead to very inefficient solutions if the forecast is wrong.

To avoid this problem we could instead of using a two step approach, use the original VRPTW formulation described in section 5.2 and include stochastic variables representing the weather. In order to do this we need to have a stochastic programming problem with both first stage and second stage variables. First and second stage variables represents decisions which need to be made before and after the uncertain parameters are known, respectively. This means our first stage variables in the problem will be the fleet size and mix. Our second stage variables will represent the routes travelled after the weather is known. When using this approach the optimization model will return a solution that evaluates many different weather scenarios and finds a fleet that best handles the uncertainty involved. This is perhaps a better way of solving the problem. However, this will make the number of variables and constraints in the model enormous which might lead to a very long solving time as discussed in section 5.3. Due to this fact and the increased difficulty of formulating such a model this method was not used in the thesis.

### **10.5.3 Limitation with number of sea states**

When creating a transition matrix by using a Markov chain simulation as discussed in section 5.4, we define a number of possible states which represents the significant wave heights. For example state 0, represents all significant wave heights from 0 to 0.3 m. In order to represent

the wave heights as precisely as possible, a high number of states is desired. However, the possible number of states is limited. When increasing the number of states we get a problem of absorbing states. By absorbing states we mean that some of the probabilities in the transition matrix reach a value of 1. This means that if we are in that particular state, it will always remain in the same state because the probability of staying in that state is 100%. Due to the limited number of states, it can be difficult to set the operational limit for the vessels. We know that the limits are 1.2 and 1.4 m significant wave height for the 15 catamaran and the 25 m catamaran, respectively. A wave height of 1.4 m may for example be within the wave state 5. However, the wave state 5 may represent all wave heights from 1.2 to 1.5 m because of the limited number of states. Therefore, if we set the limit for the 25 m catamaran to state 5, we allow wave heights up to 1.5 m, but if we set the limit to state 4 we only allow wave heights up to 1.2 m. In addition, we will get the same limit for both vessel types. This problem of accuracy is difficult to deal with, and we have had to make some simplifications when setting the operational limits for the vessels.

#### **10.5.4 Assumption regarding continuous operation of vessels**

As mentioned in section 7.3.2, we have assumed that the vessels are operated continuously during a route. This was done, because we were not able to implement resting time in the route generation algorithm in a good way. For the larger jobs lasting several days we have included rest in the job duration. However for the smaller jobs this is not included and a vessel can perform as many of these in a row as possible during each route without having to rest. In reality this is not possible since the vessels do not have enough crew members on board the ship to work in shift. A better way of solving this could have been to include some constraint stating that if rest is not included in the job duration, this is has to be accounted for. However it was difficult finding a general way of doing this in the route generation algorithm because all jobs have a different duration. Due to this simplification, some of the routes suggested by the algorithm might not be realistic to perform in real life. In order to avoid having to evaluate if the routes suggested by the optimization model are in fact viable, this problem needs to be solved.

## 11 Conclusion

The objective of this thesis was to investigate a fleet scheduling problem for service vessels used in the Norwegian aquaculture industry. An increasing growth of the Norwegian aquaculture industry has led to fish farms being placed at more exposed locations. This has led to service vessels designed for the aquaculture industry becoming larger and more specialised. Such vessels are more expensive to operate and leads to increased costs from unnecessary dead time, aborting operations and inefficient sailing time.

An optimization model has been created in order to demonstrate how mathematical models can be used to aid in solving this problem. A route generation algorithm combined with a set-partitioning model has been created and tested on a hypothetical scenario. The scenario consists of several production facilities placed off the coast of mid-Norway, requiring regular maintenance work during a time horizon of one month. The model includes four different types of service vessels which are a 15 m catamaran, a 25 m catamaran, a 25 m multipurpose catamaran and a 40 m monohull specialised for delousing operations.

The optimization model has been run with various settings. By using a simulation model we have tested the robustness of the routes suggested by the optimization model when exposed to rough weather conditions, and analysed the likelihood for delays to occur. The simulation model has been run 100 times with stochastic parameters regarding weather conditions and duration of operations. We have then seen how often jobs are performed within their predefined time windows, and hence been able to test the effects of introducing additional constraints in order to increase the robustness.

The vessels which have been evaluated as the most cost efficient by the model are the 15 m catamaran, the 25 m catamaran, and the 40 m monohull. The 25 m multipurpose catamaran has proved to be less cost efficient than the other vessels. This should however, be seen in the light of many assumptions regarding the cost and operational profile of such a vessel.

When testing the routes generated by the optimization model in the simulation model assuming calm weather, the results showed that around 94% of the jobs were performed within

their time windows. We then tested the same routes in the simulation model, assuming rough weather. Without including any measures to improve the robustness, the fleet was able to perform 76% of the jobs within their time windows, equal to a reduction of 18%.

The different approaches for increasing the robustness which have been tested are:

- Include weather constraints in the route generation.
- Setting a limit regarding how many jobs are allowed on each route.
- Including slack in the route generation algorithm.

The results from the simulation model showed that including weather constraints in the route generation has little effect, due to the weather being too specific. The two other approaches however, have shown considerable increase in robustness. By implementing the two constraints separately, we were able to increase the number of jobs performed within their time windows by 7% and 3%, respectively. The cost increase from implementing the constraints were 1% and 2%, respectively, hence we saw that the constraint regarding number of jobs performed per route was most effective. However, we had to make some adjustments to the solutions found using this approach because of ineffective routes. By combining the two constraints we were able to increase the number of jobs performed within their time windows by 8% with a cost increase of 2%.

As a final test we have run the simulation model with extended time windows to see how much better the fleet was able to perform with these new conditions. The extended time windows lead to an increase in number of jobs performed within their time windows of 16%.

The total impression from the results is that including additional measures for robustness has a positive effect compared to the additional costs. However, even with these constraints included, some routes are still exposed to delays. Therefore, additional evaluations should be performed in order to reduce the risk of delays. It should also be mentioned that the models created are quite restricted to problem sizes. Larger problem instances than the one investigated in this thesis will demand more effective algorithms in order to reduce the running time and be more attractive to the industry.

## 12 Further work

The results found during our work have many weaknesses. Further work could therefore be done regarding several of the topics included in the thesis. The most critical problems are related to the modelling, we will therefore present some of the topics which could be improved.

In order for the method used to be more attractive to use in the real life industry the models need to be more effective. The route generation algorithm we have created is appropriate for small problem instances such as our scenario, but with increasing problem sizes the algorithm is too time consuming. Adding additional constraints in order to cut of solutions that are obviously suboptimal could be done to reduce the running time.

The downside with the simulation model is that the lack of knowledge regarding SimEvent has made changes time consuming. Information regarding the use of SimEvent to solve problems related to our case is not very well documented. This has lead to a long simulation time. Further work should therefore be directed towards decreasing the running time of the models and expanding the scope.

The multipurpose vessel we have included in the model has shown poor results. However, this is due to assumptions regarding how it is operated. If one is able to design a vessel that can be more efficient than the vessel we have included in the model, it could be interesting to see at what investment cost such a vessel could be attractive.

Another case which we have not investigated is preparedness. We have only looked at planned operations, and have not done work regarding how the fleet can handle sudden, unforeseen events, such as accidents, holes in the nets or loose anchor lines. The likelihood for such events to occur, increases with rougher environment at more exposed locations. In such an event the vessels need to be able to respond in a short enough amount of time.

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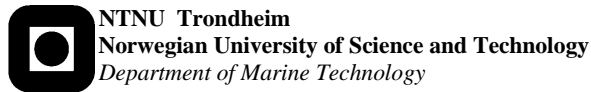
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# A Task description



## MASTER THESIS IN MARINE TECHNOLOGY

SPRING 2017

For stud.techn.

**Berge, Alexander Wallem. Ramm, Henrik**

### **Fleet Scheduling of Service Vessels used in a more exposed Norwegian Aquaculture Industry**

#### **Background**

Norway has for generations been among the best in world regarding ocean space. This is mostly because of our long coastline, competence, long-term thinking, courageous decisions and knowledge about ocean technology. The three big ocean space industries; marine, maritime and offshore are the most complete industries in Norway. The Norwegian ocean space industry has led to the growth of welfare in Norway for generations and has led to that the Norwegian industry today is a world leader within numerous ocean space industries.

Ocean farming is a relatively young industry that has had a significant change in technology the last 40 years. From the commercial breakthrough of the Norwegian aquaculture industry in the beginning of the 1970s, where each fish cage only consisted in volume of a few thousand cubic meters, to being the second largest exporter of seafood in the world in 2017. The Norwegian salmon farming industry has increased the production by 4000 tonnes since 1980. After a period of 20 years with very high production growth of salmon in Norway of about 10% each year, the production growth stagnated in 2013. The main reason was due to salmon lice and increasing strain on the Norwegian coastline

The Norwegian government's goal is to increase the production volume from one million tonnes in 2010 to 5 million tonnes by 2050. Sustainable solutions must therefore be developed to reach this target. However, the issues regarding salmon lice must be resolved in order to obtain this goal. New technology often comes from other related industries, like for example offshore and fishery. These industries have for many years been used to the rough working environment in the North sea. This knowledge and competence can be transferred to the ocean farming industry.

As any other nature based industry it is expected that the aquaculture industry should exercise and expand in an environmentally friendly and sustainable manner. Challenges for a sustainable operation varies over time and the main issues in the aquaculture industry in Norway in 2017 are summarised below.

#### Main challenges:

- Mortality and reduced fish welfare due to lice.
- Effects on wild salmon caused by salmon lice from fish farms.
- Escaping of fish from fish farms and genetic influence of wild salmon.
- Spread of diseases.
- Emissions of particular materials.
- Access to raw material for fish feed.



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A continuation of ocean farming towards 2050 will most likely involve a significant increase in production of salmon, but also a possible diversification of new species. This may involve several species of fish, seaweed and sea grass, shell and crustacean.

A realistic sustainable growth in ocean farming requires many states of indicators to cover the ecological influence the fish farms have. Increased knowledge and an assessment of ecological effects of ocean farming, together with development of new technological solutions are required to obtain a sustainable growth in the aquaculture industry.

Should the aquaculture industry succeed in achieving the goal of growth, there will be a need for new developments of fish farms to solve the environmental challenges ahead. This requires companies in the industry, that have the capital to invest in research, development and commercialisation of the new systems.

The need for increasing consolidation and professionalism in both the aquaculture industry and supply industry are therefore crucial. A collaboration between the different maritime industries is necessary in order to take advantage of solutions and knowledge other industries have. The offshore industry has great knowledge about offshore construction that the aquaculture industry should take advantage of in order to build fish farms at more exposed locations. With this transition from inland aquaculture to more exposed locations it is important that the design and capability of service vessels keep up with this development. The increased complexity of vessels and tougher working environment make fleet scheduling important in order to reduce delays and make sure the necessary maintenance operations are performed in an efficient way.

### **Objective**

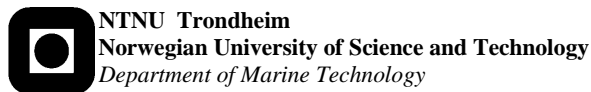
This thesis aims to study a maritime transportation problem for service vessels used in the aquaculture industry. Based on information gathered during the work with the project thesis written the fall of 2016, we will create an optimization model which will try to find the most efficient fleet and associated routes in order to meet a specific demand for maintenance. The optimization model will be tested on a hypothetical scenario, which will be based on a more exposed industry. The aim for the optimization model is to demonstrate how such a method can be utilised in order to increase fleet efficiency and how mathematical models can be used in order to improve the planning process.

In order to evaluate the fleet created with the optimization model we will create a simulation model where rough weather will be included. By doing this we wish to gain insight into how bad weather may create delays and how likely it is for delays to happen. We also wish to use the results from the simulation model to analyse how additional constraints can be added to the optimization model in order to reduce the probability for delays to occur.

### **Tasks**

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

- a. Review state of art within the topic. That means to document what others have done and published previously.
- b. Analyse the operability of service vessels used in today's aquaculture industry.
- c. Simulate stochastic weather scenarios in order to ensure a stochastic model
- d. Create an optimization model to treat the fleet scheduling problem.
- e. Create a simulation model to evaluate the results from the optimization model
- f. Analyse different approaches to increase the robustness of routes generated.



- g. State a set of recommended task for further work.

### **General**

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

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

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

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

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

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work.

The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

### **Deliverable**

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

**Deadline: 25.06.2017**



## B Growth rate for atlantic salmon

### MATFISK

#### Atlantisk laks

Tilvekst (% per dag) og biologisk förfaktor for Atlantisk laks (basert på resultater fra Skretting Rmax-databasen)

gram	Temperatur (°C)																				FF <sub>bio</sub>	Akk. FF <sub>bio</sub>
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20		
30	0,17	0,33	0,51	0,70	0,89	1,09	1,29	1,49	1,69	1,89	2,08	2,26	2,42	2,57	2,68	2,75	2,78	2,74	2,63	2,42	0,81	0,81
100	0,12	0,29	0,48	0,67	0,86	1,06	1,25	1,44	1,62	1,79	1,95	2,09	2,21	2,31	2,38	2,41	2,39	2,32	2,18	1,98	0,81	1,16
200	0,12	0,28	0,45	0,62	0,80	0,98	1,15	1,32	1,49	1,64	1,77	1,89	1,99	2,07	2,12	2,14	2,12	2,05	1,93	1,75	0,82	0,96
300	0,11	0,25	0,41	0,57	0,73	0,90	1,06	1,21	1,36	1,49	1,61	1,72	1,81	1,88	1,92	1,94	1,91	1,85	1,74	1,57	0,83	0,91
400	0,10	0,23	0,37	0,52	0,67	0,83	0,97	1,12	1,25	1,37	1,48	1,58	1,66	1,72	1,76	1,77	1,75	1,69	1,59	1,44	0,84	0,89
500	0,09	0,21	0,34	0,48	0,62	0,77	0,90	1,04	1,16	1,27	1,37	1,46	1,54	1,59	1,63	1,63	1,61	1,56	1,47	1,32	0,84	0,88
600	0,08	0,19	0,32	0,45	0,58	0,71	0,84	0,97	1,08	1,19	1,28	1,36	1,43	1,48	1,51	1,52	1,50	1,45	1,36	1,23	0,85	0,88
700	0,07	0,18	0,29	0,42	0,54	0,67	0,79	0,91	1,02	1,12	1,20	1,28	1,34	1,39	1,42	1,42	1,41	1,36	1,27	1,15	0,86	0,87
800	0,06	0,16	0,27	0,39	0,51	0,63	0,75	0,86	0,96	1,05	1,14	1,21	1,27	1,31	1,34	1,34	1,32	1,28	1,20	1,08	0,87	0,87
900	0,05	0,15	0,26	0,37	0,48	0,60	0,71	0,81	0,91	1,00	1,08	1,14	1,20	1,24	1,26	1,27	1,25	1,21	1,13	1,02	0,88	0,87
1000	0,05	0,14	0,24	0,35	0,46	0,57	0,67	0,77	0,87	0,95	1,03	1,09	1,14	1,18	1,20	1,20	1,19	1,15	1,07	0,97	0,88	0,87
1100	0,04	0,13	0,23	0,33	0,44	0,54	0,64	0,74	0,83	0,91	0,98	1,04	1,09	1,12	1,14	1,15	1,13	1,09	1,02	0,92	0,89	0,88
1200	0,04	0,12	0,22	0,32	0,42	0,52	0,62	0,71	0,79	0,87	0,94	1,00	1,04	1,07	1,09	1,10	1,08	1,04	0,98	0,88	0,90	0,88
1300	0,04	0,12	0,21	0,30	0,40	0,50	0,59	0,68	0,76	0,84	0,90	0,96	1,00	1,03	1,05	1,05	1,03	1,00	0,93	0,84	0,91	0,88
1400	0,03	0,11	0,20	0,29	0,38	0,48	0,57	0,65	0,73	0,80	0,87	0,92	0,96	0,99	1,01	1,01	0,99	0,96	0,90	0,80	0,91	0,88
1500	0,03	0,11	0,19	0,28	0,37	0,46	0,55	0,63	0,71	0,78	0,84	0,89	0,93	0,95	0,97	0,97	0,96	0,92	0,86	0,77	0,92	0,89
1600	0,03	0,10	0,18	0,27	0,36	0,45	0,53	0,61	0,68	0,75	0,81	0,86	0,89	0,92	0,94	0,94	0,92	0,89	0,83	0,74	0,93	0,89
1700	0,03	0,10	0,18	0,26	0,35	0,43	0,51	0,59	0,66	0,73	0,78	0,83	0,86	0,89	0,90	0,91	0,89	0,86	0,80	0,72	0,94	0,89
1800	0,03	0,09	0,17	0,25	0,33	0,42	0,50	0,57	0,64	0,71	0,76	0,80	0,84	0,86	0,88	0,88	0,86	0,83	0,77	0,69	0,95	0,89
1900	0,03	0,09	0,16	0,24	0,33	0,41	0,49	0,56	0,63	0,69	0,74	0,78	0,81	0,84	0,85	0,85	0,83	0,80	0,75	0,67	0,95	0,90
2000	0,03	0,09	0,16	0,24	0,32	0,40	0,47	0,54	0,61	0,67	0,72	0,76	0,79	0,81	0,82	0,82	0,81	0,78	0,73	0,65	0,96	0,90
2250	0,02	0,08	0,15	0,22	0,30	0,37	0,44	0,51	0,57	0,63	0,67	0,71	0,74	0,76	0,77	0,77	0,75	0,72	0,68	0,60	0,98	0,91
2500	0,02	0,08	0,14	0,21	0,28	0,35	0,42	0,48	0,54	0,59	0,64	0,67	0,70	0,72	0,72	0,72	0,71	0,68	0,63	0,56	1,00	0,92
2750	0,02	0,07	0,13	0,20	0,27	0,33	0,40	0,46	0,52	0,56	0,60	0,64	0,66	0,68	0,68	0,68	0,67	0,64	0,60	0,53	1,02	0,93
3000	0,02	0,07	0,13	0,19	0,26	0,32	0,38	0,44	0,49	0,54	0,58	0,61	0,63	0,64	0,65	0,65	0,63	0,61	0,56	0,50	1,04	0,94
3250	0,02	0,07	0,12	0,18	0,25	0,31	0,37	0,42	0,47	0,52	0,55	0,58	0,60	0,62	0,62	0,62	0,60	0,58	0,54	0,48	1,06	0,95
3500	0,02	0,07	0,12	0,18	0,24	0,30	0,36	0,41	0,46	0,50	0,53	0,56	0,58	0,59	0,60	0,59	0,58	0,55	0,51	0,46	1,08	0,96
3750	0,03	0,06	0,11	0,17	0,23	0,29	0,34	0,40	0,44	0,48	0,51	0,54	0,56	0,57	0,57	0,57	0,56	0,53	0,49	0,44	1,10	0,97
4000	0,03	0,06	0,11	0,17	0,22	0,28	0,33	0,38	0,43	0,47	0,50	0,52	0,54	0,55	0,55	0,55	0,54	0,51	0,47	0,42	1,12	0,98
4250	0,03	0,06	0,11	0,16	0,22	0,27	0,33	0,37	0,42	0,45	0,48	0,51	0,52	0,53	0,54	0,53	0,52	0,49	0,46	0,41	1,14	0,99
4500	0,03	0,06	0,11	0,16	0,21	0,27	0,32	0,37	0,41	0,44	0,47	0,49	0,51	0,52	0,52	0,51	0,50	0,48	0,44	0,39	1,16	1,00
4750	0,03	0,06	0,10	0,15	0,21	0,26	0,31	0,36	0,40	0,43	0,46	0,48	0,50	0,50	0,51	0,50	0,49	0,46	0,43	0,38	1,18	1,01
5000	0,03	0,06	0,10	0,15	0,20	0,26	0,31	0,35	0,39	0,42	0,45	0,47	0,48	0,49	0,49	0,49	0,47	0,45	0,42	0,37	1,20	1,02
5250	0,03	0,06	0,10	0,15	0,20	0,25	0,30	0,34	0,38	0,42	0,44	0,46	0,47	0,48	0,48	0,48	0,46	0,44	0,41	0,36	1,22	1,03

# C Project thesis: Logistics of service vessels in aquaculture industry.

## 1 Introduction

The Norwegian fish farming industry has grown remarkably the last decade. The need for increased food production has caused Norwegian salmon to become a major export industry, delivering around 14 million meals of salmon everyday[19]. The technological evolution in the industry in combination with growth in average size of the fish cages, have created a market for service vessels designed specifically for maintenance of the fish farming cages along the Norwegian coastline.

Service companies involved in this industry have experienced a massive growth in demand for maintenance. A look into the key figures from selected companies show a large increase in revenue. Two of the biggest service companies in Norway, AQS AS and Frøy Akvaservice AS, have had an increase in operational revenue of 300% [35] and 260% [36] respectively from 2013 to 2015.

The need for better production environment and increased space have caused fish farmers to move their facilities towards more exposed areas[47]. In addition to better live environment caused by increased flow of water, this reduces unwanted environmental impacts on the Norwegian coastline. Examples are increased stock of salmon lice and spread of diseases. However, the farming companies who have placed production facilities at more exposed locations, report of increased difficulties maintaining a regular production. The exposed locations have stronger currents and winds, and larger waves, increasing the structural loads on the facilities and complicating regular operations.

A series of incidents the last years indicate that there is a need for improvement in the service vessel segment. Decisions regarding when it is safe to perform an operation on the farming facilities is today based on experience and puts a lot of pressure on the workers to make the right call. A decision support tool is therefore something that is very sought after in this business both to reduce the risk of injury, and avoid unnecessary costs of having to abort an operation.

Large operations like delousing require the vessels to move close to the fish cage. This operation can increase the danger of damage on equipment, people and escaping of fish. Bigger vessels as a consequence of more exposed fish farms will increase this danger even further. To be able to perform these operations, the maintenance crew are dependent on calm sea states. The time limit is narrowed even more for more exposed locations. New solutions on vessel design and moorings are therefore needed when moving fish farms offshore.

The increase in complexity of vessels and number of service vessels, cause an increasing demand for efficient routing to avoid dead time and unnecessary costs. The trend of placing facilities further away from land also increases the demand for efficient routing as the sailing time increases.

### State of art

Very little research has been conducted regarding logistics of service vessels in the aquaculture industry. The sailing distances are in general relatively small as the facilities lie very close to shore, making the potential cost reductions from efficient routing quite small. However, with the increasing number of fish farms placed further offshore leading to larger distances and more complex vessels,

the demand for better routing increases.

The existing research today regarding service vessels in the aquaculture industry mainly consists of vessel designs and risk analysis. A research project has been carried out by SINTEF to develop better vessel designs and concepts for safe and cost efficient fish farming maintenance. The project is based on an identification of all critical operations involving service vessels. This information has been used to create a design for a service vessel with all necessary equipment to handle the operations[16].

Hatlem and Kvamme (2016)[15] perform a risk analysis of operations involving service vessels close to floating cage collars and evaluate if the collars and vessels are fitted to each other to create optimal working conditions. Risk, safety and efficiency is evaluated by the use of recognized methodologies and risk is found to be unacceptable. Efficiency is also found to be low due to poor planning procedures leading to aborted operations and suboptimal equipment with poor design.

Pedersen and Roppestad (2016)[34] develop a decision support tool for predictive maintenance of aquaculture structures. Their prototype of a decision support system is able to support an operator regarding decisions to be made when previously experienced situations occur. Their system also provides early notification of possible structural damage. The system collects data about the current situation, compares it with a data storage of previous situations and tells the user what to do.

None of the above mentioned papers have looked into the logistics of service vessel. The problem remains to be solved to evaluate fleet performance and create a decision support tool for better planning of operations involving service vessels.

### **Objectives**

This project thesis aims to study the Norwegian aquaculture industry and the development of the service vessels used for maintenance. The main goal is to develop a significant amount of knowledge regarding the whole industry and the recent developments with a special focus towards the operational aspect of the service vessels involved. This knowledge will be used to create a simulation model which will analyse the capacity of a fleet, given a specific demand. The goal is to use this knowledge for further work in the master thesis which will be delivered the summer of 2017. The following problem definition has been developed:

- Investigate the operational limits for service vessels and assess their availability and performance given a specific fleet size and demand for maintenance.

### **Structure**

This thesis is structured as follows. Chapter 2 will cover the background history of the Norwegian aquaculture industry, and its development. The chapter will describe the industry in general before focusing on service vessels. In chapter 3 a system description will be performed explaining the system which this thesis will analyze. A case study performed by SINTEF on the operability of four service vessels will be presented, showcasing the limits of existing service vessels and comparing monohulls and catamarans of different sizes. The problem description in chapter 4, will go through

challenges related to both existing fish farming technologies and discuss possible challenges in the future, considering more exposed aquaculture. Chapter 5 will present our methodology for creating a possible way of treating these problems and exploring different ways of meeting the challenges. Previous research regarding similar problems will also be introduced. After introducing our methodology, we will in chapter 6 present our simulation model and discuss input data and model structure. In chapter 7 we will discuss results, before making a conclusion in chapter 8. The final chapter 9 will discuss further work.

**Discrepancies from task description**

The thesis title has been modified from the previous handed in task description earlier this fall. This was to better fit the scope of the thesis. The title has been changed from "Maintenance of floating fish farming cages" to "Logistics of service vessels in the Norwegian aquaculture industry". The task description can be found in appendix A

## 2 Background

### 2.1 Aquaculture

From the beginning of the 21st century the world's food reserves have been reduced. The food production can not keep up with the growth in population, and have led to an increase of the food price. In addition, the world does not have enough fresh water and unoccupied land to increase the food production on land. Norway has a long coastline with many fjords with strong currents, skerries and straits which offer extremely good conditions for salmon farming. This gives Norway a great opportunity to produce food and biomass in the ocean[23].

Norway is the second largest exporter of seafood in the World after China. 95% of all seafood produced is exported which gave a total revenue of 69 billion NOK in 2014[27]. Norway has had an increase in export of approximately 6% a year from 2000 to 2010. Experts believe that the growth will continue in the future and SINTEF has estimated that the marine value generation can reach as high as 500 billion NOK in 2050 if the correct measures are taken[23].

The production of salmon and brown trout has had an increase from 0.5 million tons to 1 million tons from 2000 to 2010, which gave an annual average growth of 8 %.

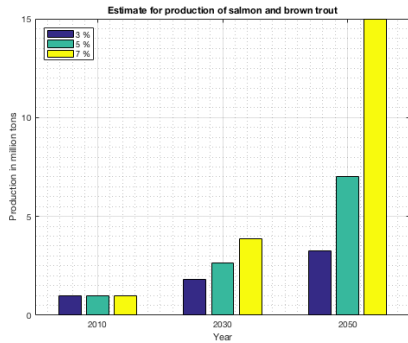


Figure 1: Estimated production growth of salmon and brown trout in 2030 and 2050 for three annual increase rates.

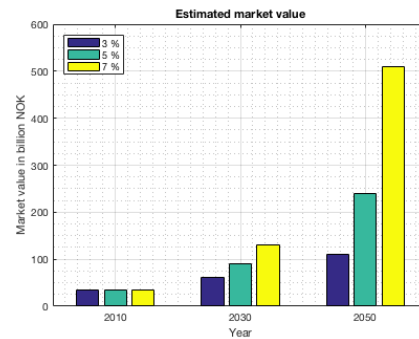


Figure 2: Expected market value from salmon and brown trout in 2030 and 2050 for three annual increase rates.

From figure 1 one can see a graph of the expected increase of total production of salmon and brown trout in 2030 and 2050. Three different annual increase rates are shown to display possible future scenarios. For an annual rate of 3 % increase until 2050, the total production of salmon and brown trout will be 3.2 million tons, for 5 % approximately 7 million. The Norwegian aquaculture industry believe that it is possible to produce 5 million tons of salmon and brown trout in 2050, given that the these conditions still remain: Still shortage of food and a desire to eat healthy; increased purchasing power among middle class; increased value of residual raw materials; increased processing into

fillets and semi-manufactured products; and more knowledge embedded in products[46]. The most probable annual increase rate will then be approximately 4 %.

Figure 2 shows the expected growth of market value in 2030 and 2050. In 2010 the market value was at 34 billion NOK. The 5 % increase is the most realistic expectation and is for when the production of salmon is 5 million a year in 2050. The other increase rates show how the market value varies depending on the expected production and if the conditions for the increase are still valid.

### **Transfer of technology**

Ever since the oil price started to decrease in 2014, several of the biggest oil supply companies have started to think of other ways to generate income.

As mentioned, the Norwegian government has said that Norway shall be the world's leading seafood nation in the future, with the ambition to increase production by three times within 2030 and by five times within 2050.

This has led to a bigger interest in the fish farming industry. Kongsberg Maritime and Aker Solutions and several other actors from the oil- and offshore industry have started to look at the possibilities to be a part of this growth. The two mentioned companies are now contributing in two different projects to help the fish farming companies with knowledge and technology to better help them move the fish farms further offshore.

Kongsberg says that their main expertise lies within sensor- and echo sounder systems. The goal is to analyze and control the operation of the fish cage in a better way than the existing systems which will improve the fish health, and decrease sickness and escaping of fish. It will also increase the income and decrease the environmental footprints the fish production creates.

Aker Solutions on the other hand will contribute on the construction of offshore fish farms. They have designed the construction Salmar's ocean farm so that it can be operable in up to 15 meters significant wave height. Existing fish farms can only work in up to 4.5 meters significant wave heights. The fish farm is dimensioned for the rough weather in the North sea[21]. Salmar's ocean fish farm will be discussed later in the problem description in chapter4.

## **2.2 Fish cage development**

In the last 50 years, the fish cages used for aquaculture have continued to increase in size, both in terms of circumference and depth. The first floating fish cages were placed in shallow and sheltered waters with small waves and little current. They had a circumference of around 40 m and a volume of around 640 m<sup>3</sup>[13]. These were easy to maintain, but had a very limited production capacity due to poor flow of water and supply of oxygen. In addition there was a lot of accumulation of feces since it was not washed away. Since then, the cages have continued to grow, but with an increase in size there was a need for increased currents through the net to maintain sufficient water quality. The fjords also have limited space and there was a need to move to the cages further

offshore. This process has led to fish farms being placed more exposed with stronger currents and bigger waves.

Today the biggest cages have a circumference of around 200 m and a volume of up to 160 000 m<sup>3</sup>. The basic concept with a net attached to a floating collar has stayed more or less unchanged the last 30 years. However, with production capacities of up to 200 000 fish or 60 mill NOK per cage with today's export price of 60 NOK/kg [8], there is a significant need for maintenance as production stops are very costly. It is also very important to maintain a high water quality and keep diseases to a minimum to achieve a low death rate. With the cages being placed further offshore, maintenance has become more difficult increasing the need for service vessels with good seakeeping abilities. In addition the increase in size of the fish cages has created a need for vessels with powerful cranes with increased lifting capacities. Stronger cranes lead to larger moments which require bigger vessels.

### **2.3 Service vessels**

The development of service vessels has not been at the same pace as the rest of the aquaculture industry. The vessels have mostly become wider, but not longer than 15 meter. The fundamental cause has been the lack of restrictions and rules for cargo ships under 15 meters in Norway before 1.January 2015. The requirements before 2015 were only valid for cargo vessels over 15 meter, and had rules for expertise and certification. However, the rules were not easy to adapt to the aquaculture industry.

As a consequence many old service vessel had a length of 14.99 meters to avoid the requirements for cargo vessels. In addition, international rules stated that if there are no formal construction requirements for a vessel, qualification requirements for the driver of the vessel do not apply. This means that the captain does not need any specific qualifications to steer the boat. However, Norwegian legislation[22] states that, those who are doing a job on board, need the qualifications and prospective certifications that is required for a certain task. Since there were not any tangible requirements, the international rules did not apply to them either.

#### **2.3.1 New requirements**

There have been many accidents due to heavy lifts on service vessels during the last years. From capsizing to heavy objects falling and causing injuries and damage on the vessel. Between 1982 and 2013, 33 people died in the aquaculture industry. The fish farm industry is considered to be the second most dangerous workplace in Norway [37]. It was concluded that the size of the service vessel had a connection with the many accidents, and that the vessels were not big enough to handle such heavy lifts in a safe and efficient manner.

The industry had for a long time requested new and improved requirements for cargo vessels between 10 and 24 meters. They were under the impression that the rules were poorly adaptive to the the

ocean fish farm industry’s special needs. A good set of rules was a condition for safe, considerate and efficient operations.

The industry also meant that there was a mismatch between the capacities of the cranes and winches and the size of the vessels. As long as the fish cages were increasing in size, the vessels length had to increase to be able to have stronger cranes and perform safe operation.

The Norwegian government and the aquaculture industry formed a new set of requirements for cargo vessels between 8 and 24 meters, which came into operation on 01.01.2015. The new set of rules included requirements for construction, stability documentation, stability criteria, freeboard, machinery and electrical installation, fire protection etc. The new set of rules were also stricter when it came to inspections of the service vessels. [32]

Over the past 20 years, the design of service vessels have changed from consisting of only monohull vessels to consist of more catamaran vessels. The catamaran vessel had more deck space and stability under heavy lifts when the vessels still had to be under 15 meter. Recently there has been constructed catamarans up to 25 m. The service companies who have ordered these vessels say that the increase in deck space and crane capacity make these vessels preferable[43]. A sample of service vessels that are under operation or construction are shown in figure 3 and 4 to show how the change of vessel dimensions have changed in recent years. Unfortunately, we were not able to find that many vessels built earlier than 2010 and not every vessel built after, so the figures can only give an indication of change.

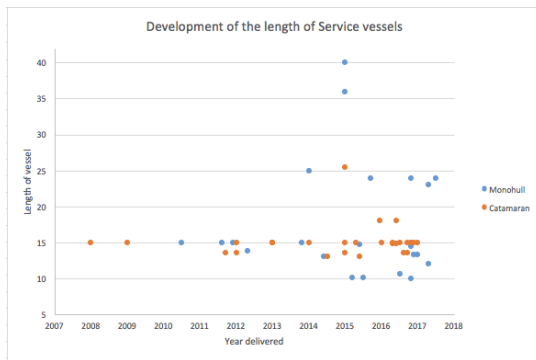


Figure 3: A tendency of development of the length of service vessels from a sample of service vessel vessels

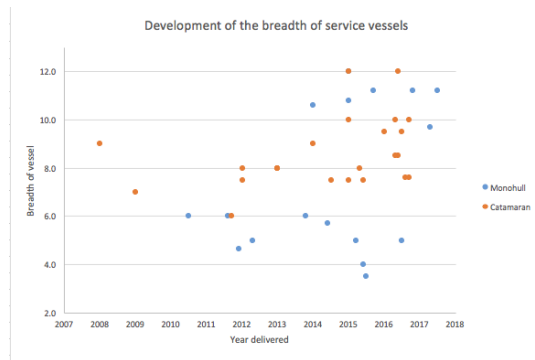


Figure 4: A tendency of development of the breadth of service vessels from a sample of service vessel vessels

Figure 3 shows the development of change in length the last ten years. One can see that the there are quite a few service vessels with length over 15 meter built after 2014. However, most vessels built are still under 15 meter. The main reason is that most operations do not require the stability and extra deck space. It is mainly during the most critical operations or operations that require a lot of deck space that bigger vessels are needed. The distribution of monohulls and catamarans may be misleading since we have not included every existing service vessel. After conversations with service



companies and research on the Internet it is more common these days to have smaller catamarans for normal maintenance operations and a bigger monohull vessel for the critical operations. Many fish farms have in addition a smaller speed boat to be able to do inspections at short notice. Figure 4 shows the development of breadth during the last 10 years. The plot can indicate an increase of breadth from 2014. This may very likely be a result of the new requirements that came in the beginning of 2015. The sample of service vessels can be seen in appendix E.

### **2.3.2 Two concepts for safe and efficient maintenance**

A research project, Servicefartøy 2010, was a collaboration project between many aquaculture companies, "Forskningsrådet" (The Norwegian research council), and SINTEF that lasted from 2008 to 2012. The project was a reaction to the many accidents on existing service vessels, in which short and partly wide vessel capsized during heavy lifts when doing maintenance on the fish farms. Their goal was then to develop a service vessel, with all the necessary functions, procedures and methods for a safe, considerate, and cost-effective handling of offshore fish farm constructions [53]. They identified existing service vessels and service operations in the future, and the risk of doing the maintenance with service vessels. Many indications pointed to a demand for bigger vessels, because the demand for carrying capacity of transport capacity for the heaviest operations were increasing, the distances between port and the fish farm increased, exposed ocean farms demanded a better operability in rougher weather, and a bigger vessel could give a better HSE and thereby attract a qualified crew.

As a result two concepts were introduced. One 40 meter long monohull vessel, and a 24 meter long catamaran. In recent years the designs developed from the project have been constructed and put into operation. Two examples of the designs are shown below.

#### **Catamaran - AQS Loke**

AQS Loke is a specialized mooring vessel and is at the moment the biggest service catamaran vessel ever built. The vessel has two big cranes to handle the mooring operations safely and efficiently. AQS Loke have room for five containers that can carry up to 120 tons of hydrogen peroxide for delousing. This catamaran will also take part in normal maintenance operations whenever needed. [28] The vessel dimensions and figure are shown below.



Figure 5: AQS Loke, a service catamaran in operation, aqs.no

Table 1: AQS Loke vessel details.

Dimensions	Values
Length [m]	25.5
Breadth [m]	12
Container capacity	5
Delivered	02.10.2015
Price [NOK]	43 mill

### Monohull - Frøy Fighter

Frøy Fighter is a 40 meter long monohull vessel that is specialized for delousing. The vessel has the world's biggest delousing system on board[42], called Thermolicer. Thermolicer will be discussed in section 3.1.3. Below is a picture of the vessel and its main dimensions.



Figure 6: Frøy Fighter, a monohull, in operation [18]

Table 2: Frøy Fighter vessel details.

Dimensions	Values
Length [m]	40
LPP [m]	37.87
Breadth [m]	12
Depth [m]	4.50
Cargo capacity [m <sup>3</sup> ]	320
Container capacity	12
Delivered	17.12.2015
Price [NOK]	60 mill

Both vessels are designed to have enough deck space to carry enough equipment that is needed to perform the delousing and/or mooring operation. They have strong winches and cranes with great arm sweep to perform their task with great precision and in a safe and efficient way. AQS Loke and Frøy Fighter have been designed to offer a great working environment, in order to attract a good crew[2][40].

## 2.4 Challenges

### 2.4.1 Salmon lice

One of the biggest challenges the aquaculture industry faces today is salmon lice. Salmon lice exist naturally in all waters and are a problem because they can infect wild salmon living in waters close to the fish farms. The growing aquaculture industry have caused the lice to be present in fjords and shallow waters during seasons which they normally are not [38], which can harm wild salmon and smolt. Lice is not a big problem for the salmon quality as they are easy to wash off, but wild smolt are very vulnerable to lice as they have not yet developed resistance against the lice and can easily be killed from the contamination. Salmon in the fish cages can also be harmed if they are host for too many lice as it can cause many wounds and makes the salmon more susceptible to diseases[38].

A report written by Nofima in collaboration with Analyse AS estimated that the total cost of delousing activities in 2014 was 3.2 billion kroner. These costs involve counting of lice, pharmaceutical treatments, lice eating fish (wrasse), and cleaning of nets. The treatments are the biggest cost which contributes to about 47% of the total cost. Nofima estimates that the cost of salmon lice was approximately 5 billion kroner in 2015[17]. The most common methods for removing lice today involve lice eating fish in combination with medical treatments. These treatments often involve the use of service vessels.

### 2.4.2 Fouling

The fish farming cages lie under water all year round which means that they are very exposed to fouling. Fouling is a problem due to several reasons[6]:

- Reduces the flow of water through the net, which reduces the water quality.
- Increases the weight of the fish cage, causing extra strain on moorings and the floating collar.
- Reduces the efficiency of wrasse, because they feed off the fouling instead of lice.
- Increases the spread of diseases.

One of the main reasons for fouling are organisms called hydroids which feed off of plankton. In order to reduce fouling, the fish nets are impregnated with copper, but the effect of the copper wears off after a while, usually around 6 months[7]. In addition to copper, the nets are cleaned using high-pressure hoses, but this will also damage the impregnation increasing the growth rate of fouling[6]. Cleaning of the nets gives good temporary results, but the fouling quickly returns. Nets can also be taken out of the water, cleaned, dried and re-impregnated.

The use of copper has decreased due to the negative environmental impact it has on the surrounding marine life near the fish cages, instead the nets are cleaned more often[3]. However, frequent cleaning

of the nets can tear the net increasing the risk of holes. In addition, the cleaning process will spread organic material over the sea bottom.

### 2.4.3 Escape of fish



Figure 7: Graph showing number of escaped salmon the last ten years.

Although the number of escaped fish has been reduced the last ten years, this is still an issue with over 100000 escaped salmon in 2016. Escape of salmon is an issue because they can interfere with wild salmon and spread diseases. Farmed salmon do not have the same genetics as the wild salmon, and crossing the two kinds will create salmon with serious shortcomings[? ]. In addition to negative effects on wild salmon, the cost of escape is also severe. 100000 escaped salmon corresponds to around 30 mill NOK in lost export income.

The most common reason for escape is structural failure due to problems with mooring lines, collapsed floating collars or holes torn in the netting of the sea cage. Bad weather is also a contributing factor[14]. Other service operations that require service vessels to lie beside the cage for a longer period of time can also damage the net. To avoid escape of salmon the fish cages need to be inspected regularly.

## 2.5 The future of offshore fish farms

As already mentioned, Norway has had an annual growth of approximately 6 % of exported fish from 2000 to 2010. To be able to continue this growth of Salmon export in the future, some challenges have to be overcome. Lice on salmon costs several billion kroner every year in Norway, and the use of pharmaceutical products to get rid of the lice contribute to harm the environment around the fish farm. The escaping of fish is also a major issue that can affect the environment in the ocean.

These issues have led to several new designs for fish production. Two solutions will be discussed.

### Nordlaks ocean farm

Nordlaks fish farm is designed by NSK ship Design for offshore fish farm production of salmon. The vessel dimensions can be seen in table 3. By moving the production offshore they believe the problems with lice and fouling will be reduced.



Figure 8: Nordlaks ocean farm vessel for offshore production of salmon

Table 3: Nordlaks vessel dimensions.

Dimensions	Values
Length [m]	431
Breadth [m]	54
Depth [m]	10
Depth of fish cage [m]	60
Number of fish cages	6
Production capacity[tons]	10.000
Significant wave height[m]	10

The Nordlaks fish farm vessel shall swing at anchor based on technological solutions from the offshore industry. This is to better spread the waste over a much bigger area. The vessel can move within a circle with diameter of almost one kilometer, which is 27 times bigger than for existing fish farms. The facility shown in figure 8 is designed for manual removal of lice. The fish nets are 10 meters deep to reduce and almost remove the growth conditions. An ROV will be placed on board the vessel for continuous inspection and maintenance. There will also be service wagons and a multipurpose machine that will almost replace the need for service vessels on Nordlaks fish farm vessel [30] .

#### 2.5.1 Salmar ocean farm

Salmar ocean farm is based on both Norwegian fish farming technology and offshore oil-platform technology to best design a construction that can withstand the rough weather offshore. The construction is built on the same fundamental characteristics as semisubmersible installations offshore. The design of the fish farm can be seen below from figure 9.

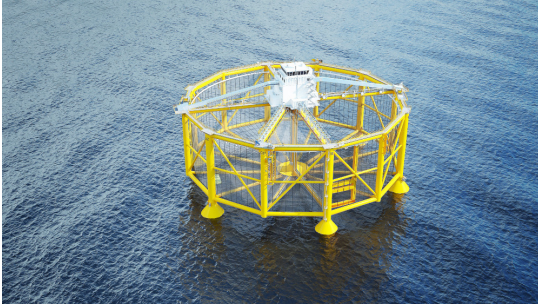


Figure 9: Salmar fish farm, an offshore construction for production of salmon.

Table 4: Salmar fish farm dimensions.

<b>Dimensions</b>	<b>Values</b>
Diameter [m]	110
Depth [m]	42
Total height [m]	67
Depth of fish cage [m]	60
Production capacity[tons]	10.000
Significant wave height[m]	10

The facility will have a moving bulkhead and two fixed bulkheads to divide the fish cage into three zones for different operations. There will also be installed jet nozzles on the bulkheads for daily cleaning if necessary. Heavy manual operations are automated to increase the safety and efficiency for the crew and fish farm. There will also be two to four crew members working on the facility on a daily basis for monitoring of operations. However, it is possible to monitor and control the operations from land if necessary.

Both designs will try to reduce the problem that lice has become. Reducing this problem will affect the environment but also reduce the high maintenance costs since the delousing of the fish is very expensive.

### 3 System description

The system which we intend to analyze consists of a fleet of service vessels, and a variable number of fish farming facilities placed in mid-Norway which need regular maintenance. There are several different kinds of maintenance that needs to be performed, but in our thesis we will focus on cleaning of nets, inspection of net and moorings, and delousing. In addition the service vessels perform installation of new facilities, change of nets, towing, anchor handling and some other minor jobs, but these operations will not be covered in our model as these are more irregular.

#### 3.1 Maintenance

##### 3.1.1 Cleaning of nets

One of the most common operations is cleaning of nets. The nets are cleaned using a remotely operated net cleaner (RONC). This machine uses high pressure washers to remove the fouling. At most the nets are cleaned about every 10th day. The demand for cleaning varies depending on water temperature and weather conditions, like strength of currents. The demand is usually at its highest during late summer. Each cleaning operation varies in duration depending on weather condition and amount of fouling, but average duration is around three hours[10]. When cleaning operations are performed, the service company usually cleans the whole facility before moving to another job.

##### 3.1.2 Inspection of moorings and net

To make sure the cage is kept in place and to minimize forces on the cage, the moorings need to be inspected regularly. Inspections are performed with the help of divers and ROV. On average, inspections are performed every six weeks, depending on weather conditions[10], often in combination with inspection of holes in the net. The duration of the inspections vary, but 2-3 hours per cage is common[10]. Inspection of a complete facility can take from 10 hours up to two days depending on the size of facility and the location[33].

##### 3.1.3 Delousing

Delousing is one of the more advanced operations and requires several vessels to cooperate, depending on the method used. There are many different techniques for delousing the salmon, but in this thesis we focus on the method using hydrogen peroxide in combination with a tarpaulin. This method is used by AQS, and is recognized as cost efficient and environmentally friendly. One main vessel delivers the peroxide and the tarpaulin while the other vessels help bring the tarpaulin around the net. The duration of the operation varies depending on weather conditions and size of the cage,

but average duration is around three hours per cage. The vessel is able to service a number from 1-5 cages per day given a 24-hour work day[10].



Figure 10: Delousing process using tarpaulin. Photo: AQS.

Another method of delousing is using a machine called Thermolicer which is used by the company Frøygruppen. This takes advantage of the lice's vulnerability towards hot water. The fish is pumped through a system and exposed to tempered water for around 30 seconds which kills most of the lice. The machine can treat around 80 tonnes of salmon per hour[49], which corresponds to 12.5 hours for one cage with 200 000 fish which is the max limit in Norway. Frøygruppen's main vessel for delousing, Frøy Fighter, has three Thermolicers installed[43] which can treat around 200 tonnes per hour[42].

Delousing can also be done mechanically. The company Skamik delivers a system which pumps the lice onboard the ship and brushes the lice off of the salmon[48]. This system is used by the service company Lerow AS and is installed on their main ship Lerow star which is a rebuilt vessel from the oil industry. The vessel is the biggest delousing vessel in Norway and can treat around 80-120 tonnes salmon per hour[20].

The demand for delousing varies a lot seasonally due to the fact that the amount of lice increases as the salmon grows. New stocks of salmon are usually deployed into the cage two times a year[5]. This results in the amount of lice being highest two times a year, usually late autumn, and early spring. During these periods, delousing is performed on average every 14th day[10]. Whenever delousing operations are planned, the salmon need to be starved for a couple of days. This is costly for the salmon breeders as it slows down the growth of the salmon. Therefore it is important that delousing operations are performed on schedule.



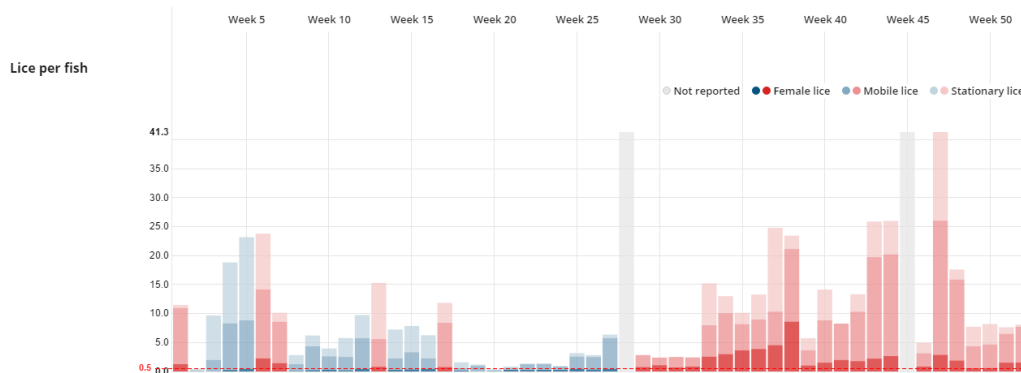


Figure 11: Typical annual distribution of lice amount. Figure: Barentswatch.com.

### 3.1.4 Installation of new facilities

Before installing new facilities, thorough analysis of the site in question needs to be performed. This is done by surveying the bottom and making sure that it fulfills the necessary requirements. When a decision has been made whether installation should be continued, the complete operation varies around 2-3 weeks depending on the size of the facility and the location. The operation is done with just one vessel as this requires less documentation[33].

## 3.2 Operational profiles

The operational profiles of the vessels vary depending on the vessel type. In this thesis we focus mainly on three types; 15 m catamarans, 25 m catamarans and large monohulls around 35-40 m used for delousing. These vessels are the dominating kind and as described in chapter 2, the newbuildings mainly consist of these kinds of vessels.

### 3.2.1 Catamarans

The catamarans in general have a 12 hour work day[10]. Although the distance back to harbour is usually quite small, often not more than half an hour, the catamarans often stay out by the fish farming facility over night. This is preferred by the service companies as it saves time and fuel. The small 15 m catamarans however, have quite small fuel capacities and need to refill once a week on average. The larger catamarans can run without having to refill for around one month on average, but are usually in harbour at least once a week to refill necessary equipment or food and water.

### 3.2.2 Monohulls

The large monohulls have a more continuous operation profile than the catamarans with longer work days. Both Frøygruppen and AQS have 24 hour operation of their delousing vessels, and delousing operations are performed both day and night[10]. The vessels can run between 1-2 months before refilling fuel, but are usually in port more often depending on what kind of equipment they need for delousing. AQS use hydrogen peroxide which needs to be refilled after around 3 delousing operations depending on the size of the fish cages and the container capacity of the vessel. For that reason, their main vessel AQS Odin needs to go back to harbour around every second day. Refilling of containers is usually done at night and takes around 4-5 hours[33]. Frøygruppen on the other hand uses a machine called Thermolicer for delousing. This does not need any refilling and their vessel Frøy Fighter can operate continuously for several weeks before harbouring to refill supplies and fuel[43].

### 3.3 Operability of four service vessels

*This section is not included due to a confidentiality agreement. Include page 18 to 20.*

## 4 Problem description

The entire system of operations described in chapter 3 involves many challenges. This thesis will focus on the operation profiles of the service vessels and the logistical problems regarding fleet size and mix. We will present problems both related to traditional aquaculture and more exposed aquaculture which has become more common recent years.

### 4.1 Routing of service vessels

The aquaculture maintenance industry is a highly stochastic industry with a very short planning horizon. There are no long term contracts of regular maintenance operations which makes a routing planning problem quite difficult to solve. After conversation with AQS we have learned that all jobs are more or less contracted from a "spot market" where the aquaculture companies call the service companies whenever they need a ship to perform an operation on their facilities. This means that the planning horizon is very short as the service companies do not know where their ships will be needed the next day or the next week. Therefore our simulation model will not focus on efficient routing of ships, but rather how many ships are needed in order to meet a given stochastic amount of demand for maintenance. This is also a more interesting view as the distances covered by the vessels are quite small and a limited amount of potential reductions regarding sailing time is possible.

### 4.2 Exposed aquaculture

#### 4.2.1 Delousing with tarpaulin

This operation is considered to be particularly challenging since delousing with a complete tarpaulin is a relatively new operation that was introduced in 2011. Fish cages which are situated in a more exposed area have to deal with rough weather, strong currents and big waves. Many companies have to retrieve extra manpower for this major operation, which can result in difficult situations because manpower acquired may not be used to cooperate in this manner, and the allocation of responsibility may be a bit vague[41].

#### 4.2.2 Crane- and cleaning operations

The cattlemen working on the fish farm are often saying that the tasks involving crane operation is a task they respect deeply. Like lifting the bottom ring or floating collar while doing the cleaning. The people doing the operation are not comfortable that the crane and vessel are strong enough to lift the heavy equipment in a safe way[41].

On exposed locations with big waves, work above sea level is the biggest challenge, especially crane operation. When the vessel and bottom ring are offset from each other the work is done at high

risk. Lifting objects high up in the air while swaying is one of the main challenges.

At locations with strong currents the biggest challenges are operations situated under water. During delousing with tarpaulin, the tarpaulin has to be completely compact and stretched out. The consequence of not being compact is that the water stream on the outside can break in the tarpaulin so that water flowing in could misshape the tarpaulin. The strong current may also increase the water inside the tarpaulin which can result in an increase of the weight and it will be heavier to lift. As a consequence some fish farms have set a maximum limit to the current per second. The limit is set by experience.

#### **4.2.3 Autonomous operation**

As the fish farms are placed further offshore it is important to include the increased risk of doing maintenance on the fish farms. The safety of personnel is essential when new solutions are introduced. A newly started research project as a collaboration between the Institute of Marine Technology at NTNU, and SINTEF will for the next three years, look at methods on how to reduce the risk in aquaculture and improve the operational efficiency, safety and sustainability[50]. Their goal is to develop new concepts for autonomous operations and technology. In particular the project will address daily operations for exposed locations.

Offshore fish farms are more exposed to rough weather, wind and waves and the risk of damage on the fish cages increase and can lead to escaping of fish but also injuries on personnel. Many operations include risks that the crew has to be aware of every day. The crew members are working on a slippery surface with heavy moving objects swaying near them. Delousing involves the use of big cranes on the vessels that are not always dimensioned for the task. Senior researcher at SINTEF, Ingunn Marie Holmen, says that it is desirable to be able to automate the delousing process in the future, but at this point it is a demanding operation that requires manual operation. She does not believe that it is possible to automate the delousing with today's technology. However, Holmen does not rule out that the demand for delousing decreases at more exposed locations. For other manual operations on the ocean farm she believes they are easier to automate and may be controlled from land or at best be fully automated in the future.

Daily inspections at the fish farms are required. When the weather is rough, the safety of personnel is at risk. It is therefore not always easy to do maintenance as required, and the weather may decrease the operational window for regular operations. It is natural to evaluate if other industries have found solutions to similar problems. The offshore petroleum industry has dealt with the same problems for many years and it is therefore relevant to see if it is possible to use the knowledge and technology they have and find ways to transfer the knowledge to the aquaculture industry.

ROVs and divers are mainly used for subsea operations, like inspections and repair of fish nets. A goal for the project is to find out if these operations can be done by a more autonomous ROV or a AUV (Autonomous Underwater vehicle) instead, which will be a great improvement, especially for

the safety, but also the operating efficiency. The ROVs are controlled by humans on service vessels, and when the facilities are moved further offshore it will involve a more challenging environment for the operators. To introduce an autonomous functionality in the underwater vehicles would decrease the manual working load, as well as increase the safety of personnel at the fish farm. However, electrical systems and autonomous systems require manning and maintenance, and have to be able to withstand corrosion from the seawater.

A possible consequence of more autonomous systems is a reduction in the need for service vessels. The project will be completed by 2019 and it is interesting to see what the future will bring the aquaculture industry.

For our project this will may involve less manual maintenance and less need for service vessels in exposed areas and in general in the future.

# D Data for hypothetical scenario

Week	Job nr	Location	Location nr	Job type	Job type nr	Time window1	Time window2	Duration job for		vessel type1	vessel type2	vessel type3	vessel type4	Duration job for	Number of cages to be maintained	Number of fish to be deloused	Penalty for not doing job [NOK]
								vessel type1	vessel type2								
Week1	1	Sørpfløssa	1	Delousing	1	0	72	6	6	6	6	6	2.5	1	200000	300000	
	2	Salatstjåera	5	Net inspection	3	24	96	5	5	5	5	5	5	1	0	300000	
	3	Farmannssya	17	Delousing	1	48	120	12	12	12	12	12	5	2	400000	300000	
	4	Ruggstein	9	Delousing	1	0	72	6	6	6	6	6	2.5	1	200000	300000	
	5	Håbränden	18	Crew transfer	10	0	8	2	2	2	2	2	2	2	0	200000	0
	6	Buholmen	15	Change of net	4	24	144	5	5	5	5	5	5	5	1	0	200000
	7	Jektholmen	12	Cleaning of fl. Collar	6	48	96	8	8	8	8	8	8	8	2	0	200000
	8	Makrellskjæret	7	Delousing	1	24	96	6	6	6	6	6	6	2.5	1	200000	300000
	9	Masterholman	16	Mooring handling	2	0	96	36	36	36	36	36	36	6	6	0	300000
	10	Ukjent	19	Mooring handling	2	0	96	24	24	24	24	24	24	24	1	0	500000
	11	Ukjent	19	Mooring handling	2	24	96	24	24	24	24	24	24	24	1	0	500000
	12	Ukjent	19	Mooring handling	2	48	96	12	12	12	12	12	12	12	1	0	500000
Week2	1	Krabholmen	4	Mooring handling	2	168	264	24	24	24	24	24	24	4	4	0	500000
	2	Tristeinen	3	Inspection of anchor	11	168	336	18	18	18	18	18	18	8	8	0	400000
	3	Ruggstein	9	Cleaning of net	5	168	216	24	24	24	24	24	24	4	4	0	200000
	4	Gjæsingen	14	Delousing	1	168	240	6	6	6	6	6	6	2.5	1	200000	300000
	5	Hosenøyen	13	Cleaning of net	5	192	240	24	24	24	24	24	24	24	6	0	200000
	6	Hosenøyen	13	Cleaning of net	5	216	240	12	12	12	12	12	12	6	6	0	300000
	7	Hallarey	2	Change of net	4	216	336	4	4	4	4	4	4	4	1	0	200000
	8	Olausskjæret	3	Net inspection	3	168	264	3	3	3	3	3	3	3	1	0	300000
	9	Ørnøya	8	Delousing	1	240	312	12	12	12	12	12	12	5	2	400000	300000
	10	Rataren	6	Cleaning of fl. Collar	6	168	216	24	24	24	24	24	24	24	4	0	200000
	11	Salatstjåera	5	Delousing	1	168	240	12	12	12	12	12	12	6	2	400000	300000
	Week3	1	Buholmen	15	Delousing	1	336	408	24	24	24	24	24	10	3	600000	300000
2		Jektholmen	12	Delousing	1	336	408	6	6	6	6	6	2.5	1	200000	300000	
3		Makrellskjæret	7	Delousing	1	384	456	12	12	12	12	12	5	2	400000	300000	
4		Sørpfløssa	1	Cleaning of net	5	336	384	24	24	24	24	24	24	24	4	0	200000
5		Farmannssya	17	Cleaning of net	5	360	408	48	48	48	48	48	48	8	8	0	200000
6		Tristeinen	3	Mooring handling	2	384	480	36	36	36	36	36	36	8	0	500000	
7		Masterholman	16	Delousing	1	384	456	12	12	12	12	12	12	2	2	400000	300000
8		Krabholmen	4	Delousing	1	336	408	6	6	6	6	6	6	2.5	1	200000	300000
9		Makrellskjæret	7	Cleaning of net	5	336	384	24	24	24	24	24	24	24	4	0	200000
10		Håbränden	18	Crew transfer	10	336	344	2	2	2	2	2	2	2	2	0	200000
11		Kattholmen	6	Net inspection	3	336	408	8	8	8	8	8	8	8	2	0	300000
Week4		1	Håbränden	18	Mooring handling	2	504	600	48	48	48	48	48	48	1	1	0
	2	Hallarey	2	Delousing	1	504	576	6	6	6	6	6	2.5	1	200000	300000	
	3	Rataren	10	Delousing	1	552	624	24	24	24	24	24	10	3	600000	300000	
	4	Ruggstein	9	Delousing	1	504	576	24	24	24	24	24	10	3	600000	300000	
	5	Gjæsingen	14	Cleaning of net	5	504	576	24	24	24	24	24	24	24	4	0	200000
	6	Tristeinen	3	Delousing	1	552	624	12	12	12	12	12	12	5	2	400000	300000
	7	Hosenøyen	13	Net inspection	3	528	624	8	8	8	8	8	8	2	2	0	300000
	8	Ørnøya	8	Cleaning liceskirt	5	538	586	4	4	4	4	4	4	4	1	0	300000
	9	Hallarey	2	Change of net	4	504	624	4	4	4	4	4	4	4	1	0	200000
	10	Kattholmen	6	Cleaning of net	5	504	552	24	24	24	24	24	24	24	6	0	200000
	11	Kattholmen	6	Cleaning of net	5	528	576	12	12	12	12	12	12	12	6	0	200000

Figure 49: All data for our hypothetical scenario used as input to our models

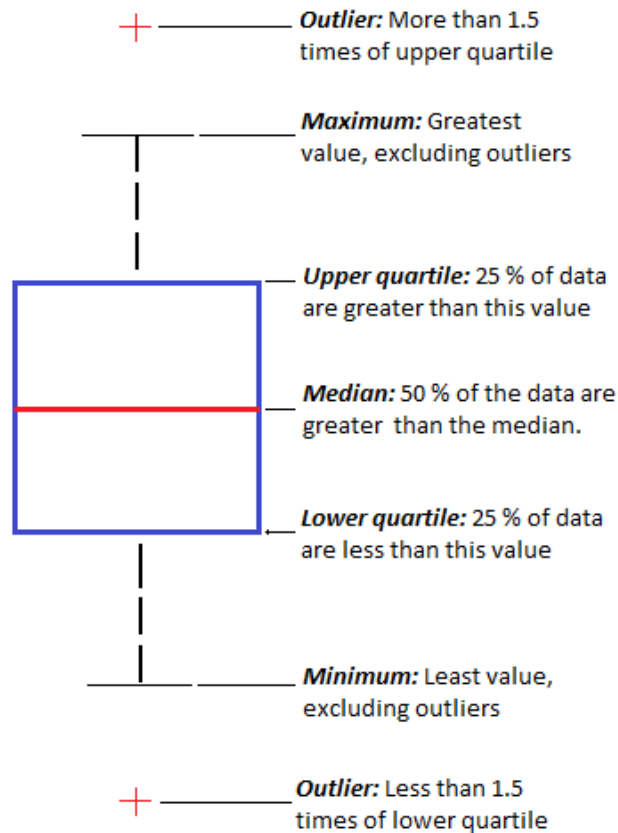
## E Reduction factors

**Table 51:** Reduction factors for wave heights for all locations.

<b>Location</b>	<b>Reduction factor</b>
Sørøyflesa	0.7
Hallarøy	0.5
Tristeinen	0.6
Krabbholmen	0.5
Salatskjæra	1
Kattholmen	0.6
Makrellskjæret	1
Ørnøya	0.8
Ruggstein	0.8
Rataren	0.8
Olausskjæret	0.8
Jektholmen	0.5
Hosenøyan	0.7
Gjæsingen	0.7
Buholmen	0.7
Masterholman	0.7
Farmannsøya	0.6
Håbranden	1
New location	1

## F Description of box plot

Using box plot is an easy way to represent statistical data and display patterns of the quantitative data. Figure 50 underneath gives a description of how the box plot works and how to evaluate the data.

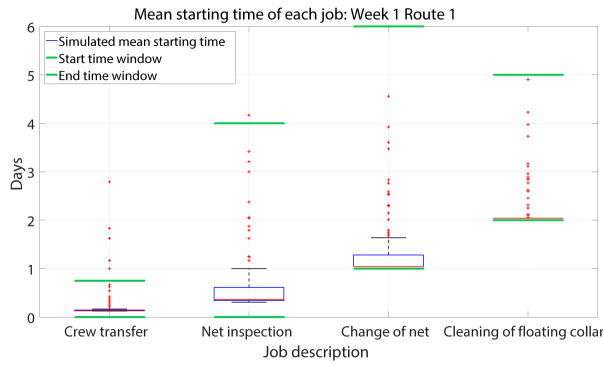


**Figure 50:** Describing how a box plot works.

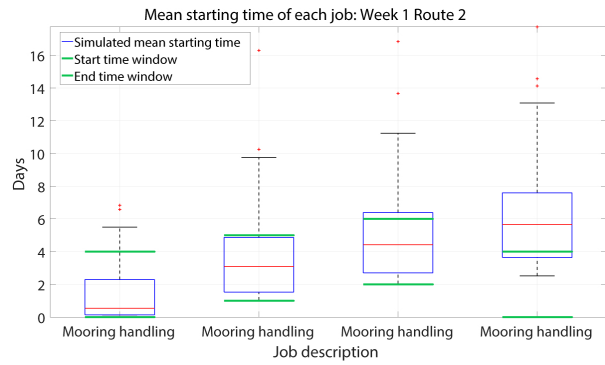
If the median is closer to the upper or lower quartile, the box plot shows a sample skewness. This means that the sample has more data points in the upper or lower area of the box.



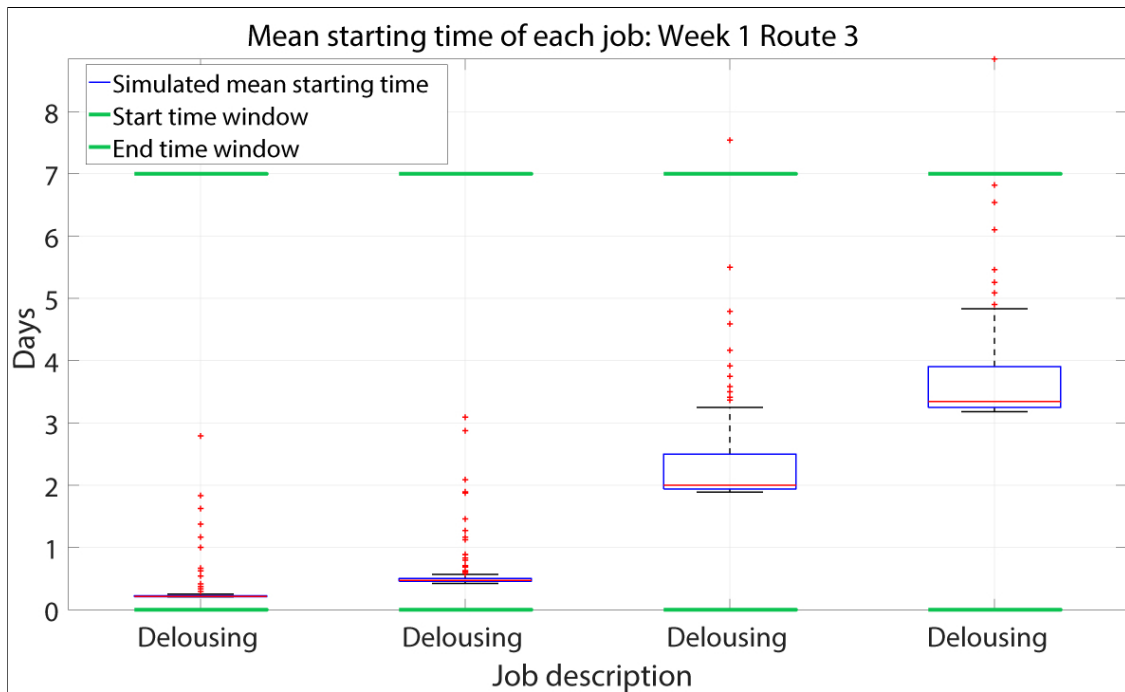
## G Figures from the simulation with extended time windows



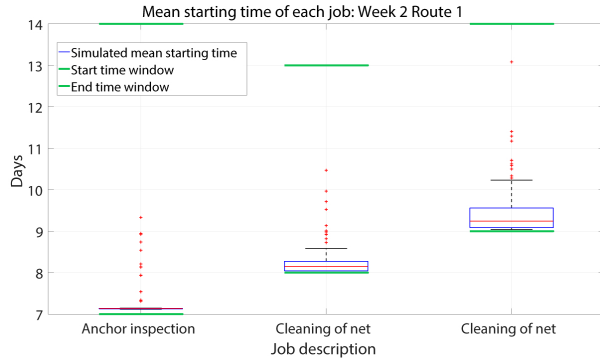
**Figure 51:** Simulation with extended time windows. Week 1, Route 1: Mean starting time of each job.



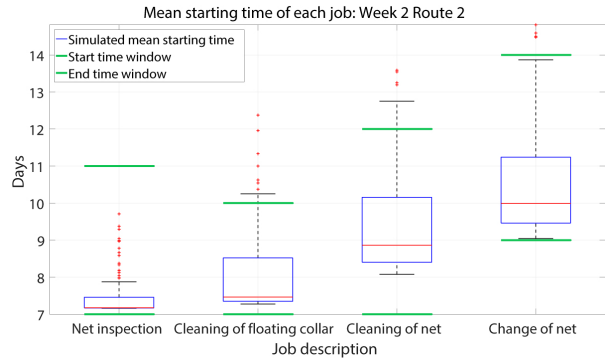
**Figure 52:** Week 1, Route 2: Mean starting time of each job.



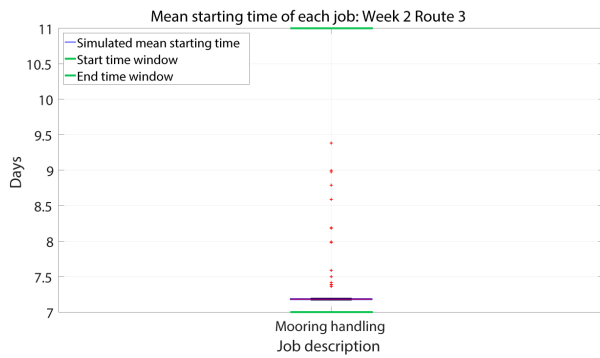
**Figure 53:** Simulation with extended time windows. Week 1, Route 3: Mean starting time of each job.



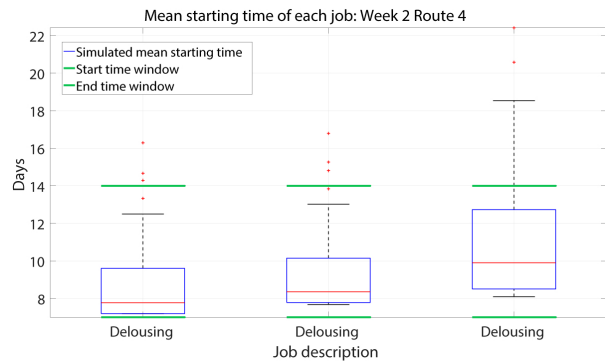
**Figure 54:** Simulation with extended time windows. Week 2, Route 1: Mean starting time of each job.



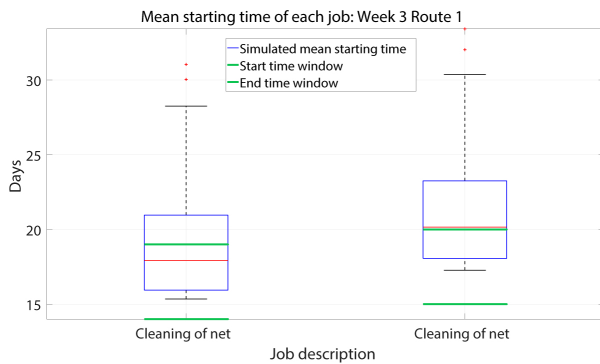
**Figure 55:** Simulation with extended time windows. Week 2, Route 2: Mean starting time of each job.



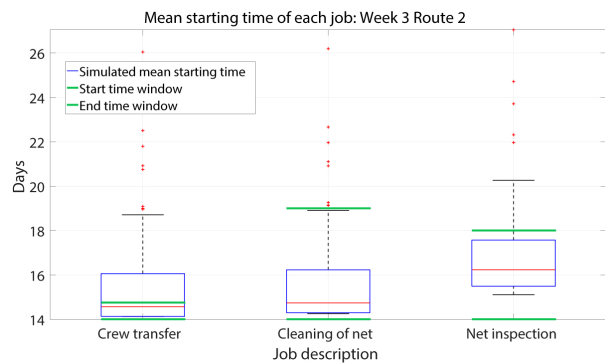
**Figure 56:** Simulation with extended time windows. Week 2, Route 3: Mean starting time of each job.



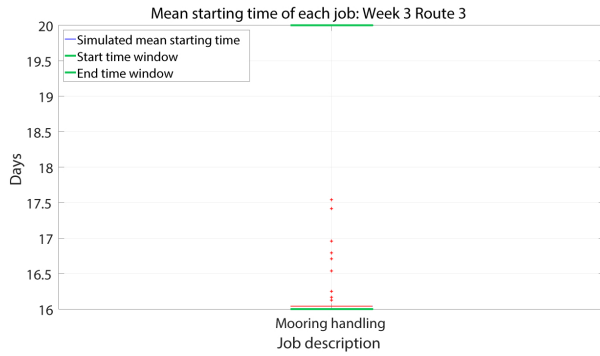
**Figure 57:** Simulation with extended time windows. Week 2, Route 4: Mean starting time of each job.



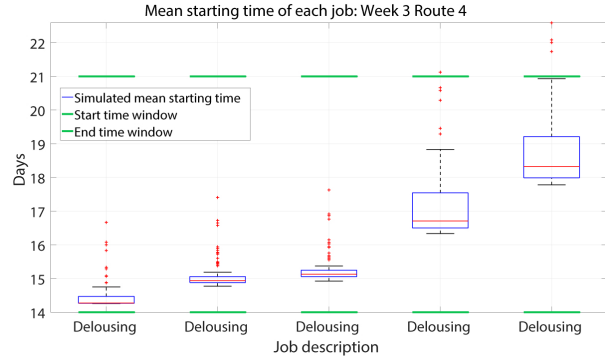
**Figure 58:** Simulation with extended time windows. Week 3, Route 1: Mean starting time of each job.



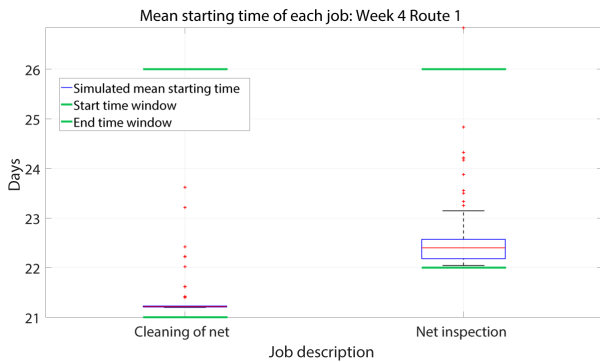
**Figure 59:** Simulation with extended time windows. Week 3, Route 2: Mean starting time of each job.



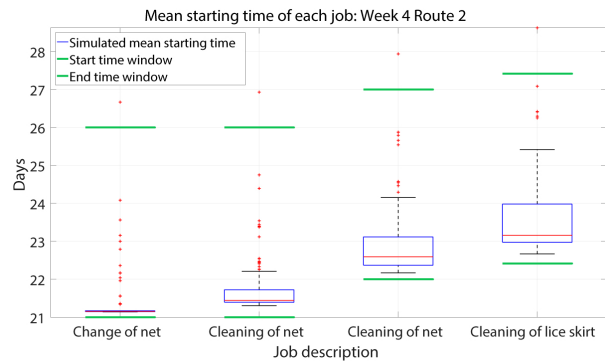
**Figure 60:** Simulation with extended time windows. Week 3, Route 3: Mean starting time of each job.



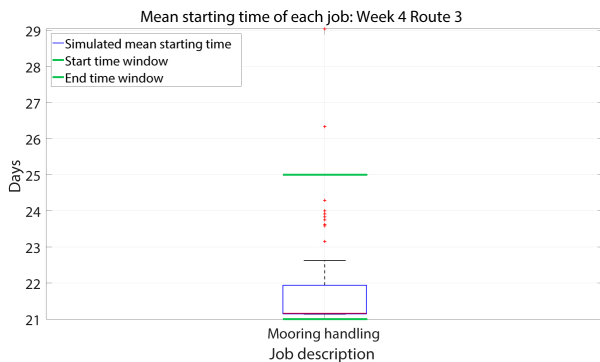
**Figure 61:** Simulation with extended time windows. Week 3, Route 4: Mean starting time of each job.



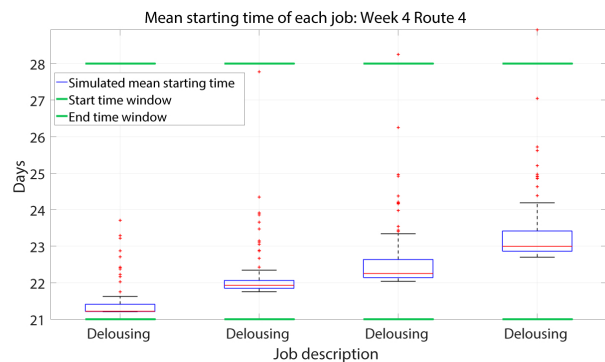
**Figure 62:** Simulation with extended time windows. Week 4, Route 1: Mean starting time of each job.



**Figure 63:** Simulation with extended time windows. Week 4, Route 2: Mean starting time of each job.



**Figure 64:** Simulation with extended time windows. Week 4, Route 3: Mean starting time of each job.



**Figure 65:** Simulation with extended time windows. Week 4, Route 4: Mean starting time of each job.

## H Matlab script for route generation

```
1 %%%Script for creating feasible routes%%%
2
3 clc
4 clear all
5 tic
6 %Read in feasible timewindows
7 TimeWindow = xlsread('Lokasjoner Salmar.xlsx','Ark1','H26:I37');
8 %Read in feasible extended timewindows
9 %TimeWindow = xlsread('Lokasjoner Salmar.xlsx','Ark2','D4:E15');
10 %Read in duration of each job
11 JobDuration = xlsread('Lokasjoner Salmar.xlsx','Ark1','J26:M37');
12 %Read in the distance from the depot to each job
13 DistanceFromDepot = xlsread('Routegeneration.xlsx','Ark1','D4:D22');
14 %Read in binary matrix for jobtype-shiptype compatibility
15 JobShipCompatibility = xlsread('Routegeneration.xlsx','Ark2','D4:N7');
16 %Read in job type for each job
17 JobType = xlsread('Lokasjoner Salmar.xlsx','Ark1','G26:G37');
18 %Read in location for the jobs.
19 Location = xlsread('Lokasjoner Salmar.xlsx','Ark1','E26:E37');
20 %Read in Hsfactor to multiply with the HsData set to compensate for more
21 %inshore locations
22 Hsfactor = xlsread('Lokasjoner Salmar.xlsx','Ark1','I4:I22');
23 %Read in the cost of starving salmon before delousing
24 NumberSalmon = xlsread('Lokasjoner Salmar.xlsx','Ark1','P26:P37');
25 %Read in penalty for not performing a job.
26 Penalty = xlsread('Lokasjoner Salmar.xlsx','Ark1','Q26:Q37');
27 %Read in operational waveheight limit for each Job and shiptype
28 MaxHs = xlsread('Routegeneration.xlsx','Ark2','D20:N23');
29 %Read in lateral coordinates for port.
30 %Portx = xlsread('PortxPorty.xlsx','Ark1','E5:I23');
31 %Read in longitudinal coordinates for port.
32 %Porty = xlsread('PortxPorty.xlsx','Ark1','K5:O23');
33 %Set penalty value to very large number to make sure all jobs are
```

```
34 %performed if possible.
35 Penalty = Penalty * 100;
36 GrowthRate = (0.49/100)/24; %Growth rate salmon per hour (11 degree celcius)
37 rng('shuffle') %Shuffle the random number generator to make sure rand
38         %functions give different results
39
40 Distancegen; %Create distance matrix based on coordinates for locations.
41 mcHs; %Create weather scenario
42 %Set starting number for where in weather matrix the weather should be
43 %retrieved
44 HsStart = randi(length(simValues1));
45 Hs = zeros(1,2000); %Create zeros vector to put weather states in.
46 %Make sure that we do not try to retrieve weather states from outside of
47 %vector length.
48 if HsStart >2000
49     HsStart = HsStart-2000;
50 end
51 for i = 1:2000
52     %Put the simulated weather states into the zeros vector created before.
53     Hs(i) = simValues1(HsStart+i);
54 end
55
56 %Create zeros matrix for to put sailing times in.
57 TravelTime = zeros(length(DistanceFromDepot),length(DistanceFromDepot),3);
58 %Put calculated sailing times in matrix for each vessel type
59 TravelTime(:, :, 1) = TimeMatrix1;
60 TravelTime(:, :, 2) = TimeMatrix2;
61 TravelTime(:, :, 3) = TimeMatrix3;
62 TravelTime(:, :, 4) = TimeMatrix4;
63
64 %Create zeros matrix for sailing times from port to each location.
65 TimeFromDepot = zeros(length(DistanceFromDepot),3);
66 %Put calculated sailing time from port in vector for each vessel type
67 TimeFromDepot(:, 1) = DistanceFromDepot/10;
68 TimeFromDepot(:, 2) = DistanceFromDepot/9;
69 TimeFromDepot(:, 3) = DistanceFromDepot/9;
```

```
70 TimeFromDepot(:,4) = DistanceFromDepot/8;
71
72 %Create zeros matrix for cost for sailing from port.
73 CostFromDepot = zeros(length(DistanceFromDepot),3);
74 %Put calculated sailing costs from port in vector for each vessel type
75 CostFromDepot(:,1) = TimeFromDepot(:,1)*44.44*10;
76 CostFromDepot(:,2) = TimeFromDepot(:,2)*44.44*10;
77 CostFromDepot(:,3) = TimeFromDepot(:,2)*44.44*10;
78 CostFromDepot(:,4) = TimeFromDepot(:,3)*39.11*10;
79 %Create zeros matrix forFor sailing costs between locations
80 TravelCost = zeros(length(DistanceFromDepot),length(DistanceFromDepot),3);
81 %Put calculated sailing costs between locations into matrix for each vessel
82 %type
83 TravelCost(:,:,1) = CostMatrix1;
84 TravelCost(:,:,2) = CostMatrix2;
85 TravelCost(:,:,3) = CostMatrix3;
86 TravelCost(:,:,4) = CostMatrix4;
87
88
89 A1 = []; %Create binary feasible routes matrix for ship type 1
90 A2 = []; %Create binary feasible routes matrix for ship type 2
91 A3 = []; %Create binary feasible routes matrix for ship type 3
92 A4 = []; %Create binary feasible routes matrix for ship type 4
93 %A4 = [];
94
95 %Set initial number of feasible routes for each vessel type
96 numRoutes1 = 0;
97 numRoutes2 = 0;
98 numRoutes3 = 0;
99 numRoutes4 = 0;
100 %Set inital cost vector for routes travelled for each vessel type.
101 Cost1 = [];
102 Cost2 = [];
103 Cost3 = [];
104 Cost4 = [];
105
```

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```

106 %Set initial time matrix fro routes travelled for each vessel type.
107 Time1 = [];
108 Time2 = [];
109 Time3 = [];
110 Time4 = [];
111
112 %Cost of leasing vessel for the farmers
113 LeasingCostVessel= [6000 12000 17000 30000];
114 %Salary for crew per hour. Use this for waiting hours.(Overtime)
115 SalaryCrew = [930 1195 1195 1990];
116 %Fuel cost for doiung anchor handling operations
117 FuelCostAH = 0.5.*[100*10 100*10 100*10 80*10];
118 %Multiply wave limit with 100 if we assume perfect weather
119 MaxHs = 100*MaxHs;
120 %Increase wave limit by 0.2 to test increased operability for vessels
121 %MaxHs = MaxHs + 0.2;
122
123 for a = 1:4 %For each vesselk type
124     A = zeros(length(JobType),200000); %Create binary matrix
125     Time = zeros(length(JobType),200000); %Create time matrix
126     numRoutes = 0; %Set initial number of feasible routes
127     Cost = zeros(1,200000); %Create cost vector
128     for i = 1:length(JobType) % For each job needed to be performed
129         k = 0; %Set a counter to 0
130         t = 0; %Set inital number of waited hours because of bad weather to 0.
131         %Check if vessel can reach job before timewindow closes, if vessel is
132         %compatible with job type, and if wave height is above set limit for
133         %vessel type during operation
134         if TimeFromDepot(Location(i),a) < TimeWindow(i,2) && ...
135             JobShipCompatibility(a,JobType(i)) == 1 && max(Hs(max(ceil...
136                 (TimeFromDepot(Location(i),a),TimeWindow(i,1)):ceil(max(...
137                     TimeFromDepot(Location(i),a),TimeWindow(i,1))+JobDuration(i,a))))...
138                     *Hsfactor(Location(i))>=MaxHs(a,JobType(i))
139                 numRoutes = numRoutes +1; %Increase number of routes travelled by 1
140                 t = 1; %Set number of hours waited due to bad weather to 1.
141                 A(i,numRoutes) =1; %Include new route in binary matrix

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142     %Include cost from depot in cost vector
143     Cost(numRoutes) = CostFromDepot(Location(i),a);
144     %While wave height is above operational limit during operation,
145     %increase hours waited by 1.
146     while max(Hs(max(ceil(TimeFromDepot(Location(i),a),...
147         TimeWindow(i,1))+t:ceil(max(TimeFromDepot(Location(i),a),...
148         TimeWindow(i,1))+JobDuration(i,a))+t))*Hsfactor(Location...
149         (i))>=MaxHs(a,JobType(i))
150         %Increase number of hours waited because of bad weather by 1
151         %hour.
152         t = t+1;
153     end
154     %Update time matrix
155     Time(i,numRoutes) = max(TimeFromDepot(Location(i),a),TimeWindow...
156         (i,1))+t;
157     %Update cost vector
158     Cost(numRoutes) = Cost(numRoutes) + t*SalaryCrew(a);
159 end
160     %Check if sailing time from depot plus eventual hours waited for bad
161     %weather is within time window, if vessel is compatible with job
162     %type, and if wave height is below operational limit during job
163     %duration
164     if TimeFromDepot(Location(i),a)+t < TimeWindow(i,2) && ...
165         JobShipCompatibility(a,JobType(i)) == 1 && max(Hs(max(ceil(...
166         TimeFromDepot(Location(i),a),TimeWindow(i,1))+ceil(max(...
167         TimeFromDepot(Location(i),a),TimeWindow(i,1))+JobDuration(i,a))+t...
168         ))*Hsfactor(Location(i))<MaxHs(a,JobType(i))
169         %Check if number of hours waited because of bad weather is greater
170         %than 0
171         if t >0
172             %Check if current time is greater than start of time window
173             if Time(i,numRoutes) >=TimeWindow(i,1)
174                 %Update time matrix
175                 Time(i,numRoutes) = Time(i,numRoutes) + JobDuration(i,a);
176                 %Check if job is in another production zone
177                 if Location(i) == 7

```

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```

178         %Add extra time for cleaning vessel if it crosses
179         %production zone
180         Time(i,numRoutes) = Time(i,numRoutes) + 24;
181     end
182 else %If time window for job has not opened yet.
183     %Add cost for waiting for time window to open.
184     Cost(numRoutes) = Cost(numRoutes) + (TimeWindow(i,1)-...
185         Time(i,numRoutes))*SalaryCrew(a);
186     %Update time matrix
187     Time(i,numRoutes) = TimeWindow(i,1) + JobDuration(i,a);
188     %Check if job is in another production zone
189     if Location(i) == 7
190         %Add extra time for cleaning vessel if it crosses
191         %production zone
192         Time(i,numRoutes) = Time(i,numRoutes) + 24;
193     end
194 end
195
196 else %If number of hours waited because of bad weather is 0
197     numRoutes = numRoutes + 1; %Update number of feasible routes
198     A(i,numRoutes) = 1; %Add job to new row
199     %Update cost vector
200     Cost(numRoutes) = CostFromDepot(Location(i),a);
201     %Check if current time is greater than time window for job
202     if TimeFromDepot(Location(i),a) >= TimeWindow(i,1)
203         %Update time matrix
204         Time(i,numRoutes) = TimeFromDepot(Location(i),a) + ...
205             JobDuration(i,a);
206         %Check if job is in another production zone
207         if Location(i) == 7
208             %Add extra time for cleaning vessel if it crosses ...
209             %production zone
210             Time(i,numRoutes) = Time(i,numRoutes) + 24;
211         end
212     else %If time window for job has not opened yet.
213         %Add cost for waiting for time window to open.

```

```
214         Cost(numRoutes) = Cost(numRoutes) + (TimeWindow(i,1)...
215             -TimeFromDepot(Location(i),a))*SalaryCrew(a);
216         %Update time matrix
217         Time(i,numRoutes) = TimeWindow(i,1) + JobDuration(i,a);
218         %Check if job is in another production zone
219         if Location(i) == 7
220             %Add extra time for cleaning vessel if it crosses
221             %production zone
222             Time(i,numRoutes) = Time(i,numRoutes) + 24;
223         end
224     end
225 end
226
227
228 n = 1; %Set counter
229 %Create store matrix 1 to keep track of jobs already visited
230 Store1 = [];
231 %Create store matrix 2 to add new jobs in storage.
232 Store2 = [];
233 %Check new routes as long as more jobs can be added
234 while n<length(JobType)
235     %Check if we are in first step such that store matrix is empty
236     if n == 1
237         %For remaining possible jobs to add to route
238         for j = 1:length(JobType)
239             %Set number of hours waited because of bad weather to 0
240             t = 0;
241             z=0; %Set counter to zero
242             x = 0; %Set binary variable to zero
243             if a == 3 %If vessel type is 25 catamaran with delouser
244                 %If vessel does not cross production zone
245                 if Location(i) ~=7 && Location(j) ~= 7
246                     %Check if jobtype finished is delousing and if
247                     %next potential job is not delousing
248                     if JobType(i) == 1 && JobType(j) ~= 1
249                         x = 1; %If yes, set binary variable to 1
```

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```

250         %Check if jobtype finished is not delousing and
251         %if next potential job is delousing
252         elseif JobType(i) ~= 1 && JobType(j) == 1
253             x = 1; %If yes, set binary matrix to 1
254         end
255         %If vessel does not cross production zone
256         elseif Location(i) == 7 && Location(j) == 7
257             %Check if jobtype finished is delousing and if
258             %next potential job is not delousing
259             if JobType(i) == 1 && JobType(j) ~= 1
260                 x = 1; %If yes, set binary variable to 1
261                 %Check if jobtype finished is not delousing and
262                 %if next potential job is delousing
263                 elseif JobType(i) ~= 1 && JobType(j) == 1
264                     x = 1; %If yes, set binary variable to 1
265                 end
266             end
267         end
268         %Check if vessel can reach new job before time window
269         %closes, if vessel is compatible with next job type and
270         %if wave height is above operational limit during job
271         %duration
272         if (Time(i,numRoutes) + (1-x)*TravelTime(Location(i)...
273             ,Location(j),a)+x*(TimeFromDepot(Location(i),a)...
274             +8+TimeFromDepot(Location(j),a)) < TimeWindow(j,...
275             2)&& A(j,numRoutes)==0 && JobShipCompatibility...
276             (a,JobType(j)) == 1 && max(Hs(max(ceil(Time(i,...
277             numRoutes)+(1-x)*TravelTime(Location(i),Location...
278             (j),a)+x*(TimeFromDepot(Location(i),a)+8+...
279             TimeFromDepot(Location(j),a))),TimeWindow(j,1)):...
280             ceil(max(Time(i,numRoutes)+(1-x)*TravelTime(...
281             Location(i),Location(j),a)+x*(TimeFromDepot(...
282             Location(i),a)+8+TimeFromDepot(Location(j),a)),...
283             TimeWindow(j,1)+JobDuration(j,a))) *Hsfactor(...
284             Location(j)) >=MaxHs(a,JobType(j))
285         %Update number of feasible routes

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```

286         numRoutes = numRoutes+1;
287         k = k+1; %Update counter
288         Store1 = [Store1;j]; %Update store vector
289         %Update binary matrix
290         A(:, numRoutes) = A(:, numRoutes-k);
291         %Update time matrix
292         Time(:, numRoutes) = Time(:, numRoutes-k);
293         A(j, numRoutes) = 1; %Add new job to row
294         %Update cost vector with sailing cost to new job
295         Cost(numRoutes) = Cost(numRoutes-k)+(1-x)*TravelCost...
296             (Location(i), Location(j), a)+x*(CostFromDepot(...
297             Location(i), a)+10000+CostFromDepot(Location(j), a));
298         %Set number of hours waited because of bad weather to 1.
299         t = 1;
300         z=1; %Set counter to 1
301         %While wave height is above operational limit during
302         %operation, increase hours waited by 1.
303         while max(Hs(max(ceil(Time(i, numRoutes-1)+(1-x)*...
304             TravelTime(Location(i), Location(j), a)+x*(...
305             TimeFromDepot(Location(i), a)+8+TimeFromDepot...
306             (Location(j), a)), TimeWindow(j, 1))+t:ceil(...
307             max(Time(i, numRoutes-1)+(1-x)*TravelTime(...
308             Location(i), Location(j), a)+x*(TimeFromDepot...
309             (Location(i), a)+8+TimeFromDepot(Location(j), a...
310             )), TimeWindow(j, 1))+JobDuration(j, a))+t))*...
311             Hsfactor(Location(j)) >= MaxHs(a, JobType(j))
312         %Increase number of hours waited because of bad weather
313         %by 1 hour.
314         t = t+1;
315         end
316         %Update time matrix
317         Time(j, numRoutes) = max(Time(i, numRoutes-k) + (1-x)...
318             *TravelTime(Location(i), Location(j), a)+x*(...
319             TimeFromDepot(Location(i), a)+8+TimeFromDepot...
320             (Location(j), a)), TimeWindow(j, 1))+t;
321         %Update cost vector

```

---

```

322     Cost(numRoutes) = Cost(numRoutes)+SalaryCrew(a)*t;
323     end
324     %Check if vessel can reach new job before time window
325     %closes, if vessel is compatible with next job type and
326     %if wave height is below operational limit during job
327     %duration
328     if (Time(i,numRoutes-z) + (1-x)*TravelTime(Location...
329         (i),Location(j),a)+x*(TimeFromDepot(Location(i),...
330         a)+8+TimeFromDepot(Location(j),a))+t) < TimeWindow...
331         (j,2) && A(j,numRoutes-z)==0 && ...
332         JobShipCompatibility(a,JobType(j)) == 1 && max...
333         (Hs(max(ceil(Time(i,numRoutes-z)+(1-x)*TravelTime...
334         (Location(i),Location(j),a)+x*(TimeFromDepot...
335         (Location(i),a)+8+TimeFromDepot(Location(j),a))),...
336         TimeWindow(j,1))+t:ceil(max(Time(i,numRoutes-z)...
337         +(1-x)*TravelTime(Location(i),Location(j),a)+...
338         x*(TimeFromDepot(Location(i),a)+8+TimeFromDepot(...
339         Location(j),a)),TimeWindow(j,1))+JobDuration(j,a...
340         ))+t))*Hsfactor(Location(j))<MaxHs(a,JobType(j))
341         %Check if number of hours waited because of bad
342         %weather is greater than 0
343         if t>0
344             %Check if current time is greater than start of
345             %time window
346             if Time(j,numRoutes) >=TimeWindow(j,1)
347                 %Update time in time matrix
348                 Time(j,numRoutes) = Time(j,numRoutes) +...
349                 JobDuration(j,a);
350                 %Check if new job is in anoter production
351                 %zone
352                 if Location(i) ~= 7 && Location(j) == 7
353                     %Add extra time for cleaning vessel if
354                     %it crosses production zone
355                     Time(j,numRoutes) = Time(j,numRoutes...
356                     ) + 24;
357                 end

```

---

```
358         %Check if new job is in anoter production
359         %zone
360         if Location(i) == 7 && Location(j) ~= 7
361             %Add extra time for cleaning vessel if
362             %it crosses production zone
363             Time(j,numRoutes) = Time(j,numRoutes...
364                 ) + 24;
365         end
366     else %If time window for job has not opened
367         %Add cost for waiting for time window to open
368         Cost(numRoutes) = Cost(numRoutes) + (...
369             TimeWindow(j,1)-Time(j,numRoutes))...
370             *SalaryCrew(a);
371         %Update time matrix
372         Time(j,numRoutes) = TimeWindow(j,1) + ...
373             JobDuration(j,a);
374         %Check if new job is in anoter production
375         %zone
376         if Location(i) ~= 7 && Location(j) == 7
377             %Add extra time for cleaning vessel
378             %if it crosses production zone
379             Time(j,numRoutes) = Time(j,numRoutes...
380                 ) + 24;
381         end
382         %Check if new job is in anoter production
383         %zone
384         if Location(i) == 7 && Location(j) ~= 7
385             %Add extra time for cleaning vessel if
386             %it crosses production zone
387             Time(j,numRoutes) = Time(j,numRoutes...
388                 ) + 24;
389         end
390     end
391 end
392 %Check if number of hours waited because of bad
393 %weather is 0
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```

394         if t == 0
395             numRoutes = numRoutes +1; %Add new route
396             k = k+1; %Update counter
397             Store1 = [Store1;j]; %Add new job to store.
398             %Add new column to A
399             A(:,numRoutes) = A(:,numRoutes-k);
400             %Add new column to Time
401             Time(:,numRoutes) = Time(:,numRoutes-k);
402             %Add new column to cost vector
403             Cost(numRoutes) = Cost(numRoutes-k);
404             A(j,numRoutes) = 1; %Add new job to to new column
405             %Update cost vector with sailing cost to new job
406             Cost(numRoutes) = Cost(numRoutes)+(1-x)*...
407                 TravelCost(Location(i),Location(j),a)+x*...
408                 (CostFromDepot(Location(i),a)+10000+...
409                 CostFromDepot(Location(j),a));
410             %Check if time window has opened
411             if (Time(i,numRoutes-1) + (1-x)*TravelTime(...
412                 Location(i),Location(j),a)+x*(TimeFromDepot...
413                 (Location(i),a)+8+TimeFromDepot(Location(j),a)...
414                 ))>=TimeWindow(j,1)
415                 %Update time in time matrix
416                 Time(j,numRoutes) = Time(i,numRoutes-k) + ...
417                     (1-x)*TravelTime(Location(i),Location(j)...
418                     ,a)+x*(TimeFromDepot(Location(i),a)...
419                     +8+TimeFromDepot(Location(j),a))+...
420                 JobDuration(j,a);
421             %Check if new job is in anoter production zone
422             if Location(i) ~= 7 && Location(j) == 7
423                 %Add extra time for cleaning vessel if it
424                 %crosses production zone
425                 Time(j,numRoutes) = Time(j,numRoutes) + 24;
426             end
427             %Check if new job is in anoter production zone
428             if Location(i) == 7 && Location(j) ~= 7
429                 %Add extra time for cleaning vessel if it

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```

430         %crosses production zone
431         Time(j,numRoutes) = Time(j,numRoutes) + 24;
432     end
433 else %If time window for job has not opened
434     %Add cost for waiting for time window to open
435     Cost(numRoutes) = Cost(numRoutes) + (TimeWindow...
436         (j,1)-(Time(i,numRoutes-1)+(1-x)*...
437         TravelTime(Location(i),Location(j),a)+x*(...
438         TimeFromDepot(Location(i),a)+8+TimeFromDepot...
439         (Location(j),a))) *SalaryCrew(a);
440     %Update time matrix
441     Time(j,numRoutes) = TimeWindow(j,1) +...
442         JobDuration(j,a);
443     %Check if new job is in anoter production zone
444     if Location(i) ~= 7 && Location(j) == 7
445         %Add extra time for cleaning vessel if it
446         %crosses production zone
447         Time(j,numRoutes) = Time(j,numRoutes) + 24;
448     end
449     %Check if new job is in anoter production zone
450     if Location(i) == 7 && Location(j) ~= 7
451         %Add extra time for cleaning vessel if it
452         %crosses production zone
453         Time(j,numRoutes) = Time(j,numRoutes) + 24;
454     end
455 end
456 end
457 %Check if current time is greater than time window
458 %for new job because of hours waited for bad
459 %weather
460 elseif (Time(i,numRoutes-z) + (1-x)*TravelTime(...
461     Location(i),Location(j),a)+x*(TimeFromDepot...
462     (Location(i),a)+8+TimeFromDepot(Location(j)...
463     ,a))+t)>= TimeWindow(j,2) && A(j,numRoutes-...
464     z)==0 && JobShipCompatibility(a,JobType(j))...
465     == 1 && t>0

```

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```

466         %If yes
467         k = k-1; %Reduce counter
468         Store1(length(Store1)) = []; %Remove job added
469         A(:,numRoutes) = []; %Remove column from A matrix
470         %Remove column from time matrix
471         Time(:,numRoutes) = [];
472         %Remove column from cost vector
473         Cost(:,numRoutes) = [];
474         %Reduce number of feasible routes by 1.
475         numRoutes=numRoutes-1;
476     end
477 end
478 else %If we are not in first step
479     %For all new jobs added jobs added we need to check next
480     %possible job to add.
481     for c = 1:length(Store1)
482         %For remaining possible jobs to add
483         for j = 1:length(JobType)
484             %Set number of hours waited because of bad weather
485             %to 0
486             t = 0;
487             z=0; %Set counter to zero
488             x=0; %Set binary variable to zero
489             %If vessel type is 25 m catamaran with delouser
490             if a == 3
491                 %If vessel does not cross production zone
492                 if Location(Store1(c)) ~=7 && Location(j) ~= 7
493                     %Check if jobtype finished is delousing
494                     %and if next potential job is not delousing
495                     if JobType(Store1(c)) == 1 && JobType(j)...
496                         ~= 1
497                         x = 1; %Set binary variable to 1
498                         %Check if jobtype finished is not delousing
499                         %and if next potential job is delousing
500                         elseif JobType(Store1(c)) ~= 1 && ...
501                             JobType(j) == 1

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---

```

502         x = 1; %Set binary variable to 1
503     end
504     %If vessel does not cross production zone
505     elseif Location(Store1(c)) == 7 && Location...
506         (j) == 7
507         %Check if jobtype finished is delousing and
508         %if next potential job is not delousing
509         if JobType(Store1(c)) == 1 && JobType(j)...
510             ~= 1
511             x = 1; %Set binary variable to 1
512             %Check if jobtype finished is not delousing
513             %and if next potential job is delousing
514             elseif JobType(Store1(c)) ~= 1 && ...
515                 JobType(j) == 1
516                 x = 1; %Set binary variable to 1
517             end
518         end
519     end
520     %Check if vessel can reach new job before time
521     %window closes, if vessel is compatible with next
522     %job type and if wave height is above operational
523     %limit during job duration
524     if (Time(Store1(c), numRoutes-length(Store1)+c-...
525         length(Store2)) + (1-x)*TravelTime(Location(...
526         Store1(c), Location(j), a) + x*(TimeFromDepot(...
527         Location(Store1(c), a) + 8 + TimeFromDepot(...
528         Location(j), a)) < TimeWindow(j, 2) && A(j, ...
529         numRoutes-length(Store1)+c-length(Store2))...
530         == 0 && JobShipCompatibility(a, JobType(j))...
531         == 1 && max(Hs(max(ceil(Time(Store1(c), ...
532         numRoutes-length(Store1)+c-length(Store2))...
533         +(1-x)*TravelTime(Location(Store1(c)), ...
534         Location(j), a) + x*(TimeFromDepot(Location...
535         (Store1(c), a) + 8 + TimeFromDepot(Location(j), ...
536         a))), TimeWindow(j, 1)) : ceil(max(Time(Store1...
537         (c), numRoutes-length(Store1)+c-length(Store2)...

```

---

```

538         )+(1-x)*TravelTime(Location(Store1(c)),...
539         Location(j),a)+x*(TimeFromDepot(Location...
540         (Store1(c),a)+8+TimeFromDepot(Location(j),a...
541         )),TimeWindow(j,1))+JobDuration(j,a)))...
542         *Hsfactor(Location(j))>=MaxHs(a,JobType(j))
543 numRoutes = numRoutes + 1; %Add new route
544 %Add new column to A
545 A(:,numRoutes) = A(:,numRoutes-length(Store1)-...
546         length(Store2)-1+c);
547 %Add new column to Time
548 Time(:,numRoutes) = Time(:,numRoutes-length...
549         (Store1)-length(Store2)-1+c);
550 %Add new column to Cost
551 Cost(numRoutes) = Cost(:,numRoutes-length(...
552         Store1)-length(Store2)-1+c);
553 A(j,numRoutes) = 1; %Add new job to column
554 %Update cost vector with sailing cost to new job
555 Cost(numRoutes) = Cost(numRoutes)+(1-x)*...
556         TravelCost(Location(Store1(c)),Location(j),...
557         a)+x*(CostFromDepot(Location(Store1(c)),a)+...
558         10000+CostFromDepot(Location(j),a));
559 %Set number of hours waited because of bad weather
560 %to 1
561 t = 1;
562 z=1; %Set counter to 1
563 %While wave height is above operational limit
564 %during operation, increase hours waited by 1.
565 while max(Hs(max(ceil(Time(Store1(c),numRoutes-...
566         1-length(Store1)+c-length(Store2)))+(1-x)*...
567         TravelTime(Location(Store1(c)),Location(j),...
568         a)+x*(TimeFromDepot(Location(Store1(c)),a)...
569         +8+TimeFromDepot(Location(j),a))),TimeWindow...
570         (j,1))+t:ceil(max(Time(Store1(c),numRoutes...
571         -1-length(Store1)+c-length(Store2)))+(1-x)*...
572         TravelTime(Location(Store1(c)),Location(j),...
573         a)+x*(TimeFromDepot(Location(Store1(c)),a)+...

```

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```

574         8+TimeFromDepot(Location(j),a),TimeWindow...
575         (j,1))+JobDuration(j,a)+t))*Hsfactor(...
576         Location(j))>=MaxHs(a,JobType(j))
577 t = t+1; %increase hours waited by 1 hour.
578 end
579 %Update time matrix
580 Time(j,numRoutes) = max(Time(Store1(c),...
581         numRoutes-length(Store1)-length(Store2)-1+c)...
582         +(1-x)*TravelTime(Location(Store1(c)),...
583         Location(j),a)+x*(TimeFromDepot(Location(...
584         Store1(c),a)+8+TimeFromDepot(Location(j),...
585         a),TimeWindow(j,1))+t);
586 %Update cost vector with cost for waiting for bad
587 %weather
588 Cost(numRoutes) = Cost(numRoutes) + ...
589         SalaryCrew(a)*t;
590 end
591 %Check if vessel can reach new job before time
592 %window closes, if vessel is compatible with next
593 %job type and if wave height is below operational
594 %limit during job duration
595 if (Time(Store1(c),numRoutes-z-length(Store1)+c-...
596         length(Store2))+(1-x)*TravelTime(Location(...
597         Store1(c),Location(j),a)+x*(TimeFromDepot(...
598         Location(Store1(c),a)+8+TimeFromDepot(...
599         Location(j),a))+t)<TimeWindow(j,2) && A(j,...
600         numRoutes-z-length(Store1)+c-length(Store2))...
601         == 0 && JobShipCompatibility(a,JobType(j))...
602         == 1 && max(Hs(max(ceil(Time(Store1(c),...
603         numRoutes-z-length(Store1)+c-length(Store2))...
604         +(1-x)*TravelTime(Location(Store1(c)),...
605         Location(j),a)+x*(TimeFromDepot(Location...
606         (Store1(c),a)+8+TimeFromDepot(Location(j),a...
607         )),TimeWindow(j,1))+t:ceil(max(Time(Store1...
608         (c),numRoutes-z-length(Store1)+c-length(...
609         Store2))+(1-x)*TravelTime(Location(Store1(c)...

```

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```

610         ), Location(j), a) + x * (TimeFromDepot(Location...
611         (Store1(c), a) + 8 + TimeFromDepot(Location(j), ...
612         a), TimeWindow(j, 1) + JobDuration(j, a) + t) ...
613         * Hsfactor(Location(j)) < MaxHs(a, JobType(j))
614 %Check if number of hours waited because of bad
615 %weather is greater than 0
616 if t > 0
617     %Check if current time is greater than time
618     %window for new job
619     if Time(j, numRoutes) >= TimeWindow(j, 1)
620         %Update time in time matrix
621         Time(j, numRoutes) = Time(j, numRoutes) + ...
622             JobDuration(j, a);
623         %If next job is in another production zone
624         if Location(Store1(c)) ~= 7 && Location(j) == 7
625             %Add extra time for cleaning vessel if it
626             %crosses production zone
627             Time(j, numRoutes) = Time(j, numRoutes) + 24;
628         end
629         %If next job is in another production zone
630         if Location(Store1(c)) == 7 && Location(j) ~= 7
631             %Add extra time for cleaning vessel if it
632             %crosses production zone
633             Time(j, numRoutes) = Time(j, numRoutes) + 24;
634         end
635     else %If time window for new job has not opened
636         %yet
637         %Add cost for waiting for time window to open
638         Cost(numRoutes) = Cost(numRoutes) + ...
639             (TimeWindow(j, 1) - Time(j, numRoutes)) ...
640             * SalaryCrew(a);
641         %Update time matrix
642         Time(j, numRoutes) = TimeWindow(j, 1) + ...
643             JobDuration(j, a);
644         %If next job is in another production zone
645         if Location(Store1(c)) ~= 7 && Location(j) == 7

```

---

```

646         %Add extra time for cleaning vessel if it
647         %crosses production zone
648         Time(j,numRoutes) = Time(j,numRoutes) + 24;
649     end
650     %If next job is in another production zone
651     if Location(Store1(c)) == 7 && Location(j) ~= 7
652         %Add extra time for cleaning vessel if it
653         %crosses production zone
654         Time(j,numRoutes) = Time(j,numRoutes) + 24;
655     end
656 end
657 end
658 %If number of hours waited for bad weather is zero
659 if t == 0
660     numRoutes = numRoutes + 1; %Add new route
661     %Add new column to A
662     A(:,numRoutes) = A(:,numRoutes-length(Store1)-...
663         length(Store2)-1+c);
664     %Add new column to Time
665     Time(:,numRoutes) = Time(:,numRoutes-length...
666         (Store1)-length(Store2)-1+c);
667     %Add new column to Cost
668     Cost(numRoutes) = Cost(:,numRoutes-length(...
669         Store1)-length(Store2)-1+c);
670     A(j,numRoutes) = 1; %Add new job to column
671     %Update cost vector with sailing cost to new job
672     Cost(numRoutes) = Cost(numRoutes)+(1-x)*...
673         TravelCost(Location(Store1(c)),Location(j)...
674         ,a)+x*(CostFromDepot(Location(Store1(c)),a)...
675         +10000+CostFromDepot(Location(j),a));
676     %Check if current time is greater than time window
677     %for new job
678     if (Time(Store1(c),numRoutes-1-length(Store1)...
679         +c-length(Store2))+ (1-x)*TravelTime(Location...
680         (Store1(c)),Location(j),a)+x*(TimeFromDepot...
681         (Location(Store1(c)),a)+8+TimeFromDepot...

```

```

682         (Location(j), a)) >= TimeWindow(j, 1)
683     %Update time matrix
684     Time(j, numRoutes) = Time(Store1(c), numRoutes - ...
685         length(Store1) - length(Store2) - 1 + c) + (1 - x) * ...
686         TravelTime(Location(Store1(c)), Location(j) ...
687         , a) + x * (TimeFromDepot(Location(Store1(c)), a) ...
688         + 8 + TimeFromDepot(Location(j), a)) + ...
689         JobDuration(j, a);
690     %If next job is in another production zone
691     if Location(Store1(c)) ~= 7 && Location(j) == 7
692         %Add extra time for cleaning vessel if it
693         %crosses production zone
694         Time(j, numRoutes) = Time(j, numRoutes) + 24;
695     end
696     %If next job is in another production zone
697     if Location(Store1(c)) == 7 && Location(j) ~= 7
698         %Add extra time for cleaning vessel if it
699         %crosses production zone
700         Time(j, numRoutes) = Time(j, numRoutes) + 24;
701     end
702     else %If timw window has not opened yet
703         %add cost for waiting for time window to open
704         Cost(numRoutes) = Cost(numRoutes) + ...
705             (TimeWindow(j, 1) - (Time(Store1(c), ...
706             numRoutes - 1 - length(Store1) + c - length(...
707             Store2)) + (1 - x) * TravelTime(Location(...
708             Store1(c), Location(j), a) + x * (...
709             TimeFromDepot(Location(Store1(c)), a) + ...
710             8 + TimeFromDepot(Location(j), a)))) * ...
711             SalaryCrew(a);
712         %Update time matrix
713         Time(j, numRoutes) = TimeWindow(j, 1) + ...
714             JobDuration(j, a);
715     %If next job is in another production zone
716     if Location(Store1(c)) ~= 7 && Location(j) == 7
717         %Add extra time for cleaning vessel if it

```

```

718         %crosses production zone
719         Time(j,numRoutes) = Time(j,numRoutes) + 24;
720     end
721     %If next job is in another production zone
722     if Location(Store1(c)) == 7 && Location(j) ~= 7
723         %Add extra time for cleaning vessel if it
724         %crosses production zone
725         Time(j,numRoutes) = Time(j,numRoutes) + 24;
726     end
727 end
728
729 end
730 Store2 = [Store2;j]; %Add new job to store.
731 %Check if current time is greater than time window
732 %for new job because of hours waited for bad
733 %weather
734 elseif (Time(Store1(c),numRoutes-z-length(Store1...
735         )+c-length(Store2))+(1-x)*TravelTime(...
736         Location(Store1(c)),Location(j),a)+...
737         x*(TimeFromDepot(Location(Store1(c)),a)...
738         +8+TimeFromDepot(Location(j),a))+t)>=...
739         TimeWindow(j,2)&& A(j,numRoutes-z-...
740         length(Store1)+c-length(Store2)) == 0 &&...
741         JobShipCompatibility(a,JobType(j)) == 1....
742         && t>0
743     A(:,numRoutes) = []; %Remove column from A matrix
744     Time(:,numRoutes) = []; %Remove column from time
745     Cost(:,numRoutes) = []; %Remove column from cost
746     %Reduce number of feasible routes by 1
747     numRoutes=numRoutes-1;
748 end
749 end
750 end
751 %Move new jobs in store to first store matrix
752 Store1 = Store2;
753 Store2 = []; %Empty second store matrix.

```



```

754
755     end
756
757     n = n+1; %Update counter
758 end
759
760 %Check if current time is greater than time window for new
761 %job because of hours waited for bad weather
762 elseif TimeFromDepot(Location(i),a)+t >= TimeWindow(i,2) &&...
763     JobShipCompatibility(a,JobType(i)) == 1 ...
764     && sum(A(:,numRoutes)) == 1
765     A(:,numRoutes)=[]; %Remove column from A matrix
766     Time(:,numRoutes)=[]; %Remove column from time
767     Cost(:,numRoutes) = []; %Remove column from cost
768     numRoutes= numRoutes-1; %Reduce number of feasible routes by 1
769 end
770 end
771
772 A( :, ~any(A,1) ) = []; %removing zero-columns
773 Time( :, ~any(Time,1) ) = []; %removing zero-columns
774 Cost(Cost==0) = []; %removing zero-columns
775
776 %Add time and cost for sailing back to port
777 for x=1:size(A,2) %For number of columns in A matrix
778     for y = 1:size(A,1) %For number of rows in A matrix
779         if Time(y,x) == max(Time(:,x))
780             %Add cost for sailing from last job to port
781             Cost(x) = Cost(x) + CostFromDepot(Location(y),a);
782             %Add time for sailing from last job to port
783             Time(y,x) = Time(y,x) + TimeFromDepot(Location(y),a);
784         break
785     end
786 end
787
788 end
789

```

---

```

790 %Add additional costs. Cost for leasing vessel, for starving salmon
791 %before delousing operations and fuel used during anchor handling
792 %operations
793 for x=1:size(A,2) %For number of columns in A matrix
794     for y = 1:size(A,1) %For number of rows in A matrix
795         if A(y,x) == 1
796             %Add cost for leasing vessel
797             Cost(x) = Cost(x) + LeasingCostVessel(a)*JobDuration(y,a);
798         elseif A(y,x) == JobType(y)
799             %Check if start time of jobs performed is greater than time
800             %window for that job
801             if Time(y,x)-JobDuration(y,a)-TimeWindow(y,1)>0
802                 %Add cost for starving salmon this extra amount of time
803                 Cost(x) = Cost(x) + (4.5-4.5/(1+GrowthRate)^(Time(y,x)-...
804                     0.5*JobDuration(y,a)-TimeWindow(y,1)))*NumberSalmon...
805                     (y)*63;
806             end
807         elseif A(y,x) == 1 && (JobType(y) == 2 || JobType(y) == 9)
808             %Add cost for fuel used during anchor handling operations
809             Cost(x) = Cost(x) + JobDuration(y,a)*FuelCostAH(a);
810         end
811     end
812 end
813
814 %Store A matrix, time matrix, number of feasible routes and cost vector for
815 %each vessel in own matrices.
816 if a == 1
817     A1 = A;
818     Time1 = Time;
819     numRoutes1 = numRoutes;
820     Cost1 = Cost;
821 elseif a== 2
822     A2 = A;
823     Time2 = Time;
824     numRoutes2 = numRoutes;
825     Cost2 = Cost;

```

```
826     elseif a == 3
827         A3 = A;
828         Time3 = Time;
829         numRoutes3 = numRoutes;
830         Cost3 = Cost;
831     elseif a == 4
832         A4 = A;
833         Time4 = Time;
834         numRoutes4 = numRoutes;
835         Cost4 = Cost;
836     end
837 end
838 %Sum total number of feasible routes created for each vessel type
839 numRoutesTot = numRoutes1 + numRoutes2 + numRoutes3+numRoutes4;
840 %Create datafiles to be used for optimization model in Xpress
841 numJobs = length(JobType); %Number of jobs to performed
842 A = [A1,A2,A3,A4]; %All A matrices
843 Cost = [Cost1, Cost2, Cost3,Cost4]; %All cost vectors
844 Time = [Time1, Time2, Time3, Time4]; %All time matrices
845 fopen('Datafile.txt','wt'); %Open datafile to write data to
846 fileID = fopen('Datafile.txt','w'); %Create file ID
847 %Write total number of routes to datafile
848 fprintf(fileID,'numRoutesTotal : %2d \n',numRoutesTot);
849 %Write number of feasible routes for each vessel to datafile
850 fprintf(fileID,'numRoutes1 : %2d \n',numRoutes1);
851 fprintf(fileID,'numRoutes2 : %2d \n',numRoutes2);
852 fprintf(fileID,'numRoutes3 : %2d \n',numRoutes3);
853 fprintf(fileID,'numRoutes4 : %2d \n',numRoutes4);
854 %Write number of jobs to be performed to datafile
855 fprintf(fileID,'numJobs : %2d \n',numJobs);
856 %Write number of vessel types to datafile
857 fprintf(fileID,'numVesselType : %2d \n',length(LeasingCostVessel));
858 %Write A matrix to datafile
859 fprintf(fileID,'A : [ \n');
860 for i = 1:size(A,1)
861     for j = 1:size(A,2)
```

```
862         fprintf(fileID, '%2d', A(i, j));
863     end
864     fprintf(fileID, '\n');
865 end
866 fprintf(fileID, ' ]\n');
867 %Write cost vector to datafile
868 fprintf(fileID, 'Cost : ');
869 for i = 1:length(Cost);
870     fprintf(fileID, '%12.2f', Cost(i));
871 end
872 fprintf(fileID, ' ]\n');
873 %Write penalty for not doing a job to datafile
874 fprintf(fileID, 'Penalty : [\n');
875 for i = 1:length(JobType)
876     fprintf(fileID, '%2d\n', Penalty(i));
877 end
878 fprintf(fileID, ' ]\n');
879 %Write investment cost for each vessel type to datafile
880 fprintf(fileID, 'CostNewVessels : [40202 86434 117274 213126] \n');
881
882 fclose(fileID); %Close datafile
883
884 moselexec RouteOpt.mos %Run optimization model in Xpress
885
886 OptimalRoutes = load('Result.dat'); %Load optimal routes found in Xpress
887
888 clearvars min max %Clear variables
889 %Create zero matrix for optimal routes
890 OptRot = zeros(length(JobType), length(OptimalRoutes));
891 %Create zero matrix for time during each route
892 AscTime = zeros(length(JobType), length(OptimalRoutes));
893 for i = 1:length(OptimalRoutes)
894     AscTime(:, i) = sort(Time(:, OptimalRoutes(i)));
895 end
896 %Put time after each job is finished in matrix
897 for i = 1:length(OptimalRoutes)
```

---

```

898     t = 1;
899     for j = 1:length(JobType)
900         if AscTime(j,i) >0
901             for m = 1:length(JobType)
902                 if AscTime(j,i) == Time(m,OptimalRoutes(i))
903                     OptRot(t,i) = m;
904                     t = t+1;
905                 end
906             end
907         end
908     end
909 end
910 %Display optimal routes in command window
911 disp('Optimal routes:')
912 disp(transpose(OptRot))
913 %Results = 'Results';
914 %Create zero matrix for time after each job is finished
915 TimeafterJob = zeros(5,length(OptRot(:,1)));
916 %Create zero matrix for duration of each route
917 MaxTime = zeros(5,length(OptRot(:,1)));
918 %Create zero matrix for optimal routes travelled
919 RoutesTravelled = zeros(5,length(OptRot(:,1)));
920 for i = 1:length(OptimalRoutes) %For number of optimal routes found
921     disp('Total duration of route:')%Display total duration of routes
922     disp(max(Time(:,OptimalRoutes(i))))
923     %Create matrix for duration of each route
924     MaxTime(i) = max(Time(:,OptimalRoutes(i)));
925     %Display time afetr each job is finished
926     disp('Time after each job completed:')
927     disp(transpose(sort(Time(:,OptimalRoutes(i)))))
928     %Create matrix for time after each job is finished
929     TimeafterJob(i,:) = transpose(sort(Time(:,OptimalRoutes(i))));
930     %Create matrix for routes travelled
931     RoutesTravelled(i,:) = transpose(OptRot(:,i));
932 end
933

```

---

```
934 %Create text vectors to be written to a excel file for easier
935 %interpretation of results
936 A = {'OptimalRoutes';'OptimalRoutes';'OptimalRoutes';'OptimalRoutes';...
937      'OptimalRoutes'};
938 B = {'Duration';'Duration';'Duration';'Duration';'Duration'};
939 C = {'Time after Job';'Time after Job';'Time after Job';'Time after Job'...
940      ';Time after Job'};
941 D = {'Total Cost'};
942 E = {'Vessels used';'Vessels used';'Vessels used';'Vessels used';...
943      'Vessels used'};
944 F = {'Jobs not performed';'Jobs not performed';'Jobs not performed'};
945 %Write results to excel file
946 xlswrite('Resultater hysesong optimering.xlsx',A,'Ark1','A1')
947 xlswrite('Resultater hysesong optimering.xlsx',B,'Ark1','A6')
948 xlswrite('Resultater hysesong optimering.xlsx',C,'Ark1','A11')
949 xlswrite('Resultater hysesong optimering.xlsx',D,'Ark1','A16')
950 xlswrite('Resultater hysesong optimering.xlsx',E,'Ark1','A17')
951 xlswrite('Resultater hysesong optimering.xlsx',F,'Ark1','A22')
952 xlswrite('Resultater hysesong optimering.xlsx',RoutesTravelled,'Ark1'...
953      , 'B1')
954 xlswrite('Resultater hysesong optimering.xlsx',MaxTime,'Ark1','B6')
955 xlswrite('Resultater hysesong optimering.xlsx',TimeafterJob,'Ark1','B11')
956 %Load cost for each route from Xpress
957 CostRoutes = load('CostRoutes.dat');
958 xlswrite('Resultater hysesong optimering.xlsx',CostRoutes,'Ark1','N1')
959 %Load total cost for whole week from Xpress
960 TotalCost = load('Cost.dat');
961 %Load vessels used for each route from Xpress
962 Vessels = load('Vessels.dat');
963 %Load jobs not performed from Xpress
964 NotPerformed = load('NotPerformed.dat');
965 xlswrite('Resultater hysesong optimering.xlsx',Vessels,'Ark1','B17')
966 %Read in penalty for not performing a job.
967 Penalty1 = xlsread('Lokasjoner Salmar.xlsx','Ark1','Q26:Q37');
968 if isempty(NotPerformed) == false %If there are jobs that are not performed
969     xlswrite('Resultater hysesong optimering.xlsx',NotPerformed,'Ark1',...
```

---

```

970         'B22')
971     for i = 1:length(NotPerformed)
972         %Adjust value of total cost for each route. Replace penalty used in
973         %Xpress for not doing a job with actual penalty. Penalties used in
974         %Xpress are very big in order to make sure all jobs that are possible
975         %to perform are performed regardless of the cost
976         TotalCost = TotalCost-Penalty(NotPerformed(i))+Penalty1(...
977             NotPerformed(i));
978     end
979 end
980 xlswrite('Resultater hysesong optimering.xlsx',TotalCost,'Ark1','B16')
981 %Create plot of the significant wave heights the routes are exposed to.
982 figure(1)
983
984 subplot(2,2,1)
985 set(gca,'FontSize',14)
986 hold on
987 plot(Hs(1:ceil(max(max(Time(:,OptimalRoutes))))))
988 title('Simulated significant waveheight week 1')
989 xlabel('Time [hours]')
990 ylabel('Significant waveheight [m]')
991 %Create zeros matrix for job types performed for the optimal routes
992 OptJobType = zeros(size(OptRot));
993 %Create zero matrix for locations for the optimal routes
994 OptLocation = zeros(size(OptRot));
995 %Create matrices for job types and locations visited on the optimal routes
996 %travelled
997 for i = 1:size(OptRot,1)
998     for j = 1:size(OptRot,2)
999         if OptRot(i,j) >0
1000             OptJobType(i,j) = JobType(OptRot(i,j));
1001             OptLocation(i,j) = Location(OptRot(i,j));
1002         end
1003     end
1004 end
1005 %Display job types and locations visited on each route travelled

```

```
1006 disp('Jobtypes:')
1007 disp(transpose(OptJobType))
1008 disp('Locations:')
1009 disp(transpose(OptLocation))
1010
1011
1012
1013 %Create plots showing the routes travelled on a google map.
1014
1015 figure(2)
1016
1017 set(gca, 'FontSize', 16)
1018
1019 hold on
1020 route=zeros(1, size(OptLocation, 2));
1021 for i = 1:size(OptLocation, 2)
1022     x = [];
1023     y = [];
1024     labels=[];
1025     for j = 1:size(OptLocation, 1)
1026         if OptLocation(j, i)>0
1027             x(j) = Lat(OptLocation(j, i));
1028             y(j) = Lon(OptLocation(j, i));
1029         end
1030     end
1031     a = find(OptLocation(:, i));
1032     %Create vector containing lateral coordinates for locations
1033     %visited on optimal routes
1034     x = [Portx(OptLocation(1, i), :), x, fliplr(Portx(OptLocation(a(end), i)...
1035         , :))];
1036     %Create vector containing longitudinal coordinates for locations
1037     %visited on optimal routes
1038     y = [Porty(OptLocation(1, i), :), y, fliplr(Porty(OptLocation(a(end), i)...
1039         , :))];
1040     labels = cellstr(num2str([1:(length(x)-10)]));
1041     plot(y(6:length(y)-5), x(6:length(x)-5), 'o')
```



```
1042 %If vessel type is 1
1043 if OptimalRoutes(i) <=numRoutes1
1044     route(i)=plot(y,x,'--b','DisplayName','Route 15 m cat');
1045     text(y(6:(length(y)-5)),x(6:(length(x)-5)),labels,...
1046         'VerticalAlignment','bottom','HorizontalAlignment',...
1047         'right','color','blue')
1048 %If vessel type is 2
1049 elseif OptimalRoutes(i) >numRoutes1 && OptimalRoutes(i) <=(...
1050     numRoutes1+numRoutes2)
1051     route(i) = plot(y,x,'--k','DisplayName','Route 25 m cat');
1052     text(y(6:(length(y)-5)),x(6:(length(x)-5)),labels,...
1053         'VerticalAlignment','bottom','HorizontalAlignment',...
1054         'left','color','black')
1055 %If vessel type is 3
1056 elseif OptimalRoutes(i)>(numRoutes1+numRoutes2) && OptimalRoutes(i)...
1057     <=(numRoutes1+numRoutes2+numRoutes3)
1058     route(i) = plot(y,x,'--r','DisplayName',...
1059         'Route 25 m cat with delouser');
1060     text(y(6:(length(y)-5)),x(6:(length(x)-5)),labels,...
1061         'VerticalAlignment','top','HorizontalAlignment',...
1062         'right','color','red')
1063 %If vessel type is 4
1064 else
1065     route(i)= plot(y,x,'--m','DisplayName','Route 40 m mono');
1066     text(y(6:(length(y)-5)),x(6:(length(x)-5)),labels,...
1067         'VerticalAlignment','top','HorizontalAlignment',...
1068         'left','color','magenta')
1069 end
1070 end
1071 plot_google_map %Use plotting script found online to plot routes
1072 %Set legend, title, x- and y-label
1073 legend([route],'Location','northwest')
1074 title('Routes travelled week 1')
1075 xlabel('Longitude','FontSize',16)
1076 ylabel('Latitude','FontSize',16)
1077 toc %Record time used by algorithm
```

1078

1079

1080 FeasibleRoutesNew2; %Run route generation algorithmn for week 2

1081 FeasibleRoutesNew3; %Run route generation algorithmn for week 3

1082 FeasibleRoutesNew4; %Run route generation algorithmn for week 4

---

# I Xpress script for optimization

```
!Script for finding cost optimal routes

model master_thesis

options explterm !Line break does not separate expressions
options noimplicit !Everything except indices must be declared

uses "mumxprs"; !Use library with optimizer

!Set which datafile parameters should be retrieved from
parameters
    inputfile = 'Datafile.txt'; !Set the name of input data file
end-parameters

!Declare the different paramaters needed
declarations
    numJobs:           integer;
    numRoutesTotal:   integer;
    numRoutes1:       integer;
    numRoutes2:       integer;
    numRoutes3:       integer;
    numRoutes4:       integer;
    numVesselType:    integer;
    !numVessels:       integer;
end-declarations

!Read in parameters from datafile
initializations from inputfile
    numJobs;
    numRoutesTotal;
    numRoutes1;
    numRoutes2;
    numRoutes3;
    numRoutes4;
    numVesselType;
    !numVessels;
end-initializations

!Declare the different sets needed
declarations
    Routes : set of integer;
    Jobs   : set of integer;
    Vessels : set of integer;
end-declarations
```

---

```

!Define the size of the sets
Routes := 1..numRoutesTotal;
Jobs := 1..numJobs;
Vessels := 1..numVesselType;

!Finalize the sets
finalize(Routes);
finalize(Jobs);
finalize(Vessels);

!Declare additional parameters and the variables used
!Declare the objective function and constraints
declarations
  Penalty:      array(Jobs) of integer;
  Cost:         array(Routes) of real;
  CostNewVessels: array(Vessels) of integer;
  !Revenue:    array(Routes) of integer;
  x:           dynamic array(Vessels, Routes) of mpvar;
  y:           dynamic array(Jobs) of mpvar;
  A:           array(Jobs, Routes) of integer;
  totalCost:   linctr;
  ObligJobs:   array(Jobs) of linctr;
  !OptNodes:   array(nodes) of linctr;
  MaxRoutes1:  linctr;
  MaxRoutes2:  linctr;
  MaxRoutes3:  linctr;
  MaxRoutes4:  linctr;
  MaxJobs:     array(Vessels, Routes) of linctr;
  ShipType1:   array(Routes) of linctr;
  ShipType2:   array(Routes) of linctr;
  ShipType3:   array(Routes) of linctr;
  ShipType4:   array(Routes) of linctr;
end-declarations

!Read in additional parameters from datafile
initializations from inputfile
  Cost;
  Penalty;
  CostNewVessels;
  !Revenue;
  A;
end-initializations

!Create binary variable x
forall(v in Vessels, i in Routes) do
  create(x(v, i));
  x(v, i) is_binary;
end-do

```

```

!Create binary variable y
forall(j in Jobs) do
    create(y(j));
    y(j) is_binary;
end-do
!State objective function
totalCost :=
    sum(i in Routes, v in Vessels) (Cost(i)*x(v,i)+CostNewVessels(v)*x(v,i))
    + sum(j in Jobs) (Penalty(j)*y(j));

!Make sure all jobs are performed. If not make sure variable y is set to
! 1 for that job
forall(j in Jobs) do
ObligJobs(j) :=
    sum(i in Routes, v in Vessels) (A(j,i)*x(v,i)) + y(j) = 1;
end-do

!Make sure vessel type 1 can only travel routes compatible for that vessel
! type
forall(i in Routes|i>numRoutes1) do
ShipType1(i) :=
    x(1,i) = 0;
end-do

!Optional constraint: Make sure vessel type 1 can only travel 1 route
MaxRoutes1:=sum(i in Routes)x(1,i)=1;

!Make sure vessel type 2 can only travel routes compatible for that vessel
! type
forall(i in Routes|i<=numRoutes1 or i>(numRoutes1+numRoutes2)) do
ShipType2(i) :=
    x(2,i) = 0;
end-do

!Optional constraint: Make sure vessel type 2 can only travel 1 route
MaxRoutes2:=sum(i in Routes)x(2,i)=1;

!Make sure vessel type 3 can only travel routes compatible for that vessel
! type
forall(i in Routes|i<=(numRoutes1+numRoutes2) or i>(numRoutes1+numRoutes2+
numRoutes3))
do
ShipType3(i) :=
    x(3,i) = 0;
end-do

!Optional constraint: Make sure vessel type 3 can not be used
!forall(i in Routes) do
!ShipType3(i) :=
!    x(3,i) = 0;
!end-do

```

---

```

!Make sure vessel type 4 can only travel routes compatible for
!that vessel type
forall(i in Routes|i<=(numRoutes1+numRoutes2+numRoutes3)) do
ShipType4(i) :=
    x(4,i) = 0;
end-do

!Optional constraint: Make sure vessel type 4 can only travel 1 route
MaxRoutes4:=sum(i in Routes)x(4,i)=1;

!Optional constraint: Make sure vessel type 4 can not be used
!forall(i in Routes) do
!ShipType4(i) :=
!    x(4,i) = 0;
!end-do

!Optional constraint: Make sure each route can perform a max unumber
!of jobs per route
!forall(v in Vessels, i in Routes) do
!MaxJobs(v,i):= sum(j in Jobs) A(j,i)*x(v,i) <=5;
!end-do

!State goal. Minimize cost
minimize(totalCost);

!Write objective value to output
writeln("Total cost: ", getobjval);

!Write routes travelled, jobs performed, vessels used and costs
!for each route to output
forall(v in Vessels,i in Routes) do
    if(getsol(x(v,i)) > 0) then
        write('Vessel type: ',v,', Route number: ',i,', Job number: ');
        forall(j in Jobs)
            if(A(j,i)>0) then
                write(j,', ');
            end-if
        writeln('Cost: ',Cost(i));
    end-if
end-do

!Write jobs not performed to output
forall(j in Jobs) do
    if(getsol(y(j))>0) then
        writeln('Job number ',j,' not performed. Cost: ',Penalty(j));
    end-if
end-do

```

```
!Create datafile with optimal routes to import to MATLAB
fopen("Result.dat", F_OUTPUT);
forall(v in Vessels,i in Routes) do
    if(getsol(x(v,i)) > 0) then
        write (i);
        writeln;
    end-if
end-do

!Close datafile
fclose(F_OUTPUT);

!Create datafile with objective value to import to MATLAB
fopen("Cost.dat", F_OUTPUT);
writeln(getobjval);
fclose(F_OUTPUT);

!Create datafile with vessels used to import to MATLAB
fopen("Vessels.dat", F_OUTPUT);
forall(v in Vessels,i in Routes) do
    if(getsol(x(v,i)) > 0) then
        writeln(v);
    end-if
end-do
fclose(F_OUTPUT);

!Create datafile with jobs not performed to import to MATLAB
fopen("NotPerformed.dat", F_OUTPUT);
forall(j in Jobs) do
    if(getsol(y(j))>0) then
        writeln(j);
    end-if
end-do
fclose(F_OUTPUT);

!Create datafile with cost for each route to import to MATLAB
fopen("CostRoutes.dat", F_OUTPUT);
forall(v in Vessels,i in Routes) do
    if(getsol(x(v,i)) > 0) then
        writeln(Cost(i));
    end-if
end-do
fclose(F_OUTPUT);

end-model
```

## J Matlab script for simulation

```

1  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Running the Simulink model from matlab
   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
2  % This script simulates the SivEvent model 100 times where a weather
3  % sceanario is simulated in order to check the robustness of the optimized
4  % solution.
5  % When the simulation is complete, all data from the simulation are
6  % stored in .mat files.
7
8
9  clear all;
10 k=100;    % Number of simulations
11 n=1250;   % hours of simimulation. Have 50 days in the simulation
12 num_states=10; % Number of states in the markov chain
13
14 % Obtaining data of time windows, type of job, vessel, duration of each job,
15 % factor and wave limits for each vessel
16 Typ=xlsread('Duration_for_Simulation', 'Type', 'A1:J20');
17 Twind=xlsread('Duration_for_Simulation', 'TimeWindow', 'A1:A45');
18 Twind2=xlsread('Duration_for_Simulation', 'TimeWindow', 'B1:B45');
19 VesseL=xlsread('Duration_for_Simulation', 'Vessel', 'A1:A20');
20 Lim=xlsread('Duration_for_Simulation', 'Limit', 'A1:A5');
21 Work=xlsread('Duration_for_Simulation', 'Job', 'A1:F45');
22 factor=xlsread('Duration_for_Simulation', 'Factor', 'A1:A19');
23
24
25
26 %% % Simulation of the weather scenarios based on Markov chains
27 % Choose between the two weather scenarios. Comment out the one that are
28 % not needed.
29 % %High Season: Markov chain transition probability matrix
30 %P= [0.915  0.083  0.001  0.001  0  0  0  0  0  0;
31 %    0.086  0.825  0.085  0.003  0.001  0  0  0  0  0;
32 %    0  0.182  0.702  0.113  0.002  0  0  0  0  0;

```



```

33 %      0.005  0.027  0.253  0.591  0.118  0.005      0      0      0      0;
34 %      0  0.015  0.015  0.354  0.462  0.154      0      0      0      0;
35 %      0      0      0      0  0.268  0.512  0.220      0      0      0;
36 %      0      0      0      0      0  0.500  0.444  0.056      0      0;
37 %      0      0      0      0      0      0  0.125  0.750  0.125      0;
38 %      0      0      0      0      0      0      0  0.333  0.333  0.333;
39 %      0      0      0      0      0      0      0      0  0.333  0.667];
40
41 % Winter: Markov chain transition probability matrix
42 P=[0.333  0.583      0      0  0.083      0      0      0      0      0;
43     0.017  0.778  0.198  0.007      0      0      0      0      0;
44     0  0.140  0.706  0.152  0.002      0      0      0      0;
45     0  0.005  0.239  0.611  0.137  0.008      0      0      0;
46     0.004      0  0.004  0.194  0.626  0.166  0.007      0      0;
47     0      0      0  0.005  0.270  0.546  0.178      0      0;
48     0      0      0      0  0.016  0.266  0.565  0.153      0;
49     0      0      0      0      0      0  0.218  0.621  0.161      0;
50     0      0      0      0      0      0      0  0.424  0.424  0.152;
51     0      0      0      0      0      0      0      0  0.833  0.167];
52
53
54 simMC=zeros(1,n);
55 datk=zeros(n,k);
56 states=zeros(n,1);
57
58 %Making a matrix with numbers from 0 to one to use in the simulation
59 % to randomly choose duration of each job within the ranges
60
61 Random=rand(1100,100);
62
63 for b=1:k
64     r=rand;
65
66     % SimMC(1) chooses the probability to start in each state.
67
68     % only valid for High Season

```

```
69 % Retrieved from the Markov chains simulation
70 simMC(1)=sum(r >= cumsum([0, 0.3587, 0.3537 ,0.1621 ,0.0699, ...
71     0.0249, 0.0162, 0.0073, 0.0039, 0.0016]))-1;
72
73 % %only valid for Winter
74 % %The values are obtained from the Markov chains simulation
75 simMC(1)=sum(r >= cumsum([0, 0.0057, 0.1969, 0.2821, 0.1801, ...
76     0.1327, 0.0853, 0.0575, 0.0410, 0.0158, 0.0029]))-1;
77
78 % Simulate the weather based on the transition matrix
79 for t=2:n
80
81     % Using Monte Carlo simulation to find the probability of which
82     % state that should be the next.
83     simMC(t)=randsample(num_states,1,true,P(simMC(t-1)+1,:))-1 ;
84 end
85
86 datk(:,b)=transpose(simMC);
87
88 end
89
90
91 % Generating zero matrices to reduce the simulation time
92 %Week 1
93 W1R1=zeros(20,k);
94 W1R2=zeros(20,k);
95 W1R3=zeros(20,k);
96 W1R4=zeros(20,k);
97 W1R5=zeros(20,k);
98 %Week 2
99 W2R1=zeros(20,k);
100 W2R2=zeros(20,k);
101 W2R3=zeros(20,k);
102 W2R4=zeros(20,k);
103 W2R5=zeros(20,k);
104 %Week 3
```

```
105 W3R1=zeros(20,k);
106 W3R2=zeros(20,k);
107 W3R3=zeros(20,k);
108 W3R4=zeros(20,k);
109 W3R5=zeros(20,k);
110 % Week 4
111 W4R1=zeros(20,k);
112 W4R2=zeros(20,k);
113 W4R3=zeros(20,k);
114 W4R4=zeros(20,k);
115 W4R5=zeros(20,k);
116 % Finishing routes
117 Exit_time=zeros(20,k);
118
119
120 % Make two .mat files to store data to reduce the simulation time and
121 % be able to clear them when they are not needed.
122 DataR= 'Retrieve_sim_data';
123 excelR='excelR_used_for_sim';
124
125 save(DataR, 'W1R1', 'W1R2', 'W1R3', 'W1R4', 'W1R5', 'W2R1', 'W2R2', 'W2R3', ...
126         'W2R4', 'W2R5', 'W3R1', 'W3R2', 'W3R3', 'W3R4', 'W3R5', 'W4R1', 'W4R2', ...
127         'W4R3', 'W4R4', 'W4R5', 'Exit_time');
128
129
130 clearvars b count n P r t v w num_states simMC
131 %% Running the simulation
132 %Normally, the first few simulations requires more simulation time.
133
134 for i =1:k
135
136     tic
137
138     % Load the SimEvent model to avoid having to open it.
139     load_system('discretetime');
140
```

```
141 % Chooses column i of rand variables that is needed in the model.
142 tif=Random(:,i);
143 % Shows the weather states and that is needed for the model to run.
144 states=datk(:,i);
145
146 save(excelR,'Typ','Twind','Twind2','VesseL','Lim','Work',...
147      'factor','datk','i','k','Random');
148
149 % Remove all data that are not needed for the simulation.
150 % Will reduce the simulation time.
151 clearvars W1R1 W1R2 W1R3 W1R4 W1R5 W2R1 W2R2 W2R3 W2R4 W2R5...
152          W3R1 W3R2 W3R3 W3R4 W3R5 W4R1 W4R2 W4R3 W4R4 W4R5...
153          Exit_time DataR excelR datk Random
154
155 tout=zeros(1500,1);
156
157 %Run the SimEvent model
158 sim('discretetime');
159
160 % Retrieve the data that are needed to store data from the simulation
161 DataR= 'Retrieve_sim_data';
162 load(DataR);
163
164 % Get the data from the SimEvent model and storing them in a matrix
165 % The if sentence checks if a vessel executes the current route. If we had
166 % not checked, we would get an error due to trying to store data from an
167 % empty matrix.
168
169
170 if 0< VesseL(1)
171 % Week 1 Route 1
172     W1R1(1:2,i)=W1R1J1.Time;
173     W1R1(3:4,i)=W1R1J2.Time;
174     W1R1(5:6,i)=W1R1J3.Time;
175     W1R1(7:8,i)=W1R1J4.Time;
176     W1R1(9:10,i)=W1R1J5.Time;
```

```
177     W1R1 (11:12, i)=W1R1J6.Time;
178     W1R1 (13:14, i)=W1R1J7.Time;
179     W1R1 (15:16, i)=W1R1J8.Time;
180     W1R1 (17:18, i)=W1R1J9.Time;
181     W1R1 (19:20, i)=W1R1J10.Time;
182     Exit_time (1, i)=W1R1EX.Time;
183 end
184
185 if 0< VesseL(2)
186     % Week 1 Route 2
187     W1R2 (1:2, i)=W1R2J1.Time;
188     W1R2 (3:4, i)=W1R2J2.Time;
189     W1R2 (5:6, i)=W1R2J3.Time;
190     W1R2 (7:8, i)=W1R2J4.Time;
191     W1R2 (9:10, i)=W1R2J5.Time;
192     W1R2 (11:12, i)=W1R2J6.Time;
193     W1R2 (13:14, i)=W1R2J7.Time;
194     W1R2 (15:16, i)=W1R2J8.Time;
195     W1R2 (17:18, i)=W1R2J9.Time;
196     W1R2 (19:20, i)=W1R2J10.Time;
197     Exit_time (2, i)=W1R2EX.Time;
198 end
199
200 if 0< VesseL(3)
201     % Week 1 Route 3
202     W1R3 (1:2, i)=W1R3J1.Time;
203     W1R3 (3:4, i)=W1R3J2.Time;
204     W1R3 (5:6, i)=W1R3J3.Time;
205     W1R3 (7:8, i)=W1R3J4.Time;
206     W1R3 (9:10, i)=W1R3J5.Time;
207     W1R3 (11:12, i)=W1R3J6.Time;
208     W1R3 (13:14, i)=W1R3J7.Time;
209     W1R3 (15:16, i)=W1R3J8.Time;
210     W1R3 (17:18, i)=W1R3J9.Time;
211     W1R3 (19:20, i)=W1R3J10.Time;
212     Exit_time (3, i)=W1R3EX.Time;
```

```
213     end
214
215     if 0 < VesseL(4)
216         % Week 1 Route 4
217         W1R4(1:2,i)=W1R4J1.Time;
218         W1R4(3:4,i)=W1R4J2.Time;
219         W1R4(5:6,i)=W1R4J3.Time;
220         W1R4(7:8,i)=W1R4J4.Time;
221         W1R4(9:10,i)=W1R4J5.Time;
222         W1R4(11:12,i)=W1R4J6.Time;
223         W1R4(13:14,i)=W1R4J7.Time;
224         W1R4(15:16,i)=W1R4J8.Time;
225         W1R4(17:18,i)=W1R4J9.Time;
226         W1R4(19:20,i)=W1R4J10.Time;
227         Exit_time(4,i)=W1R4EX.Time;
228     end
229
230     if 0 < VesseL(5)
231         % Week 1 Route 5
232         W1R5(1:2,i)=W1R5J1.Time;
233         W1R5(3:4,i)=W1R5J2.Time;
234         W1R5(5:6,i)=W1R5J3.Time;
235         W1R5(7:8,i)=W1R5J4.Time;
236         W1R5(9:10,i)=W1R5J5.Time;
237         W1R5(11:12,i)=W1R5J6.Time;
238         W1R5(13:14,i)=W1R5J7.Time;
239         W1R5(15:16,i)=W1R5J8.Time;
240         W1R5(17:18,i)=W1R5J9.Time;
241         W1R5(19:20,i)=W1R5J10.Time;
242         Exit_time(5,i)=W1R5EX.Time;
243     end
244     if 0 < VesseL(6)
245         % Week 2 Route 1
246         W2R1(1:2,i)=W2R1J1.Time;
247         W2R1(3:4,i)=W2R1J2.Time;
248         W2R1(5:6,i)=W2R1J3.Time;
```

```
249     W2R1 (7:8, i)=W2R1J4.Time;
250     W2R1 (9:10, i)=W2R1J5.Time;
251     W2R1 (11:12, i)=W2R1J6.Time;
252     W2R1 (13:14, i)=W2R1J7.Time;
253     W2R1 (15:16, i)=W2R1J8.Time;
254     W2R1 (17:18, i)=W2R1J9.Time;
255     W2R1 (19:20, i)=W2R1J10.Time;
256     Exit_time (6, i)=W2R1EX.Time;
257 end
258 if 0< VesseL(7)
259     % Week 2 Route 2
260     W2R2 (1:2, i)=W2R2J1.Time;
261     W2R2 (3:4, i)=W2R2J2.Time;
262     W2R2 (5:6, i)=W2R2J3.Time;
263     W2R2 (7:8, i)=W2R2J4.Time;
264     W2R2 (9:10, i)=W2R2J5.Time;
265     W2R2 (11:12, i)=W2R2J6.Time;
266     W2R2 (13:14, i)=W2R2J7.Time;
267     W2R2 (15:16, i)=W2R2J8.Time;
268     W2R2 (17:18, i)=W2R2J9.Time;
269     W2R2 (19:20, i)=W2R2J10.Time;
270     Exit_time (7, i)=W2R2EX.Time;
271 end
272 if 0< VesseL(8)
273     % Week 2 Route 3
274     W2R3 (1:2, i)=W2R3J1.Time;
275     W2R3 (3:4, i)=W2R3J2.Time;
276     W2R3 (5:6, i)=W2R3J3.Time;
277     W2R3 (7:8, i)=W2R3J4.Time;
278     W2R3 (9:10, i)=W2R3J5.Time;
279     W2R3 (11:12, i)=W2R3J6.Time;
280     W2R3 (13:14, i)=W2R3J7.Time;
281     W2R3 (15:16, i)=W2R3J8.Time;
282     W2R3 (17:18, i)=W2R3J9.Time;
283     W2R3 (19:20, i)=W2R3J10.Time;
284     Exit_time (8, i)=W2R3EX.Time;
```

```
285     end
286     if 0 < VesseL(9)
287         % Week 2 Route 4
288         W2R4(1:2,i)=W2R4J1.Time;
289         W2R4(3:4,i)=W2R4J2.Time;
290         W2R4(5:6,i)=W2R4J3.Time;
291         W2R4(7:8,i)=W2R4J4.Time;
292         W2R4(9:10,i)=W2R4J5.Time;
293         W2R4(11:12,i)=W2R4J6.Time;
294         W2R4(13:14,i)=W2R4J7.Time;
295         W2R4(15:16,i)=W2R4J8.Time;
296         W2R4(17:18,i)=W2R4J9.Time;
297         W2R4(19:20,i)=W2R4J10.Time;
298         Exit_time(9,i)=W2R4EX.Time;
299     end
300
301     if 0 < VesseL(10)
302         % Week 2 Route 5
303         W2R5(1:2,i)=W2R5J1.Time;
304         W2R5(3:4,i)=W2R5J2.Time;
305         W2R5(5:6,i)=W2R5J3.Time;
306         W2R5(7:8,i)=W2R5J4.Time;
307         W2R5(9:10,i)=W2R5J5.Time;
308         W2R5(11:12,i)=W2R5J6.Time;
309         W2R5(13:14,i)=W2R5J7.Time;
310         W2R5(15:16,i)=W2R5J8.Time;
311         W2R5(17:18,i)=W2R5J9.Time;
312         W2R5(19:20,i)=W2R5J10.Time;
313         Exit_time(10,i)=W2R5EX.Time;
314     end
315
316     if 0 < VesseL(11)
317         % Week 3 Route 1
318         W3R1(1:2,i)=W3R1J1.Time;
319         W3R1(3:4,i)=W3R1J2.Time;
320         W3R1(5:6,i)=W3R1J3.Time;
```



```
321     W3R1 (7:8, i)=W3R1J4.Time;
322     W3R1 (9:10, i)=W3R1J5.Time;
323     W3R1 (11:12, i)=W3R1J6.Time;
324     W3R1 (13:14, i)=W3R1J7.Time;
325     W3R1 (15:16, i)=W3R1J8.Time;
326     W3R1 (17:18, i)=W3R1J9.Time;
327     W3R1 (19:20, i)=W3R1J10.Time;
328     Exit_time (11, i)=W3R1EX.Time;
329 end
330 if 0< VesseL(12)
331     % Week 3 Route 2
332     W3R2 (1:2, i)=W3R2J1.Time;
333     W3R2 (3:4, i)=W3R2J2.Time;
334     W3R2 (5:6, i)=W3R2J3.Time;
335     W3R2 (7:8, i)=W3R2J4.Time;
336     W3R2 (9:10, i)=W3R2J5.Time;
337     W3R2 (11:12, i)=W3R2J6.Time;
338     W3R2 (13:14, i)=W3R2J7.Time;
339     W3R2 (15:16, i)=W3R2J8.Time;
340     W3R2 (17:18, i)=W3R2J9.Time;
341     W3R2 (19:20, i)=W3R2J10.Time;
342     Exit_time (12, i)=W3R2EX.Time;
343 end
344 if 0< VesseL(13)
345     % Week 3 Route 3
346     W3R3 (1:2, i)=W3R3J1.Time;
347     W3R3 (3:4, i)=W3R3J2.Time;
348     W3R3 (5:6, i)=W3R3J3.Time;
349     W3R3 (7:8, i)=W3R3J4.Time;
350     W3R3 (9:10, i)=W3R3J5.Time;
351     W3R3 (11:12, i)=W3R3J6.Time;
352     W3R3 (13:14, i)=W3R3J7.Time;
353     W3R3 (15:16, i)=W3R3J8.Time;
354     W3R3 (17:18, i)=W3R3J9.Time;
355     W3R3 (19:20, i)=W3R3J10.Time;
356     Exit_time (13, i)=W3R3EX.Time;
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```
357     end
358     if 0 < VesseL(14)
359         % Week 3 Route 4
360         W3R4(1:2,i)=W3R4J1.Time;
361         W3R4(3:4,i)=W3R4J2.Time;
362         W3R4(5:6,i)=W3R4J3.Time;
363         W3R4(7:8,i)=W3R4J4.Time;
364         W3R4(9:10,i)=W3R4J5.Time;
365         W3R4(11:12,i)=W3R4J6.Time;
366         W3R4(13:14,i)=W3R4J7.Time;
367         W3R4(15:16,i)=W3R4J8.Time;
368         W3R4(17:18,i)=W3R4J9.Time;
369         W3R4(19:20,i)=W3R4J10.Time;
370         Exit_time(14,i)=W3R4EX.Time;
371     end
372
373     if 0 < VesseL(15)
374         % Week 3 Route 5
375         W3R5(1:2,i)=W3R5J1.Time;
376         W3R5(3:4,i)=W3R5J2.Time;
377         W3R5(5:6,i)=W3R5J3.Time;
378         W3R5(7:8,i)=W3R5J4.Time;
379         W3R5(9:10,i)=W3R5J5.Time;
380         W3R5(11:12,i)=W3R5J6.Time;
381         W3R5(13:14,i)=W3R5J7.Time;
382         W3R5(15:16,i)=W3R5J8.Time;
383         W3R5(17:18,i)=W3R5J9.Time;
384         W3R5(19:20,i)=W3R5J10.Time;
385         Exit_time(15,i)=W3R5EX.Time;
386     end
387
388     if 0 < VesseL(16)
389         % Week 4 Route 1
390         W4R1(1:2,i)=W4R1J1.Time;
391         W4R1(3:4,i)=W4R1J2.Time;
392         W4R1(5:6,i)=W4R1J3.Time;
```

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393     W4R1(7:8,i)=W4R1J4.Time;
394     W4R1(9:10,i)=W4R1J5.Time;
395     W4R1(11:12,i)=W4R1J6.Time;
396     W4R1(13:14,i)=W4R1J7.Time;
397     W4R1(15:16,i)=W4R1J8.Time;
398     W4R1(17:18,i)=W4R1J9.Time;
399     W4R1(19:20,i)=W4R1J10.Time;
400     Exit_time(16,i)=W4R1EX.Time;
401 end
402 if 0< VesseL(17)
403     % Week 4 Route 2
404     W4R2(1:2,i)=W4R2J1.Time;
405     W4R2(3:4,i)=W4R2J2.Time;
406     W4R2(5:6,i)=W4R2J3.Time;
407     W4R2(7:8,i)=W4R2J4.Time;
408     W4R2(9:10,i)=W4R2J5.Time;
409     W4R2(11:12,i)=W4R2J6.Time;
410     W4R2(13:14,i)=W4R2J7.Time;
411     W4R2(15:16,i)=W4R2J8.Time;
412     W4R2(17:18,i)=W4R2J9.Time;
413     W4R2(19:20,i)=W4R2J10.Time;
414     Exit_time(17,i)=W4R2EX.Time;
415 end
416 if 0< VesseL(18)
417     % Week 4 Route 3
418     W4R3(1:2,i)=W4R3J1.Time;
419     W4R3(3:4,i)=W4R3J2.Time;
420     W4R3(5:6,i)=W4R3J3.Time;
421     W4R3(7:8,i)=W4R3J4.Time;
422     W4R3(9:10,i)=W4R3J5.Time;
423     W4R3(11:12,i)=W4R3J6.Time;
424     W4R3(13:14,i)=W4R3J7.Time;
425     W4R3(15:16,i)=W4R3J8.Time;
426     W4R3(17:18,i)=W4R3J9.Time;
427     W4R3(19:20,i)=W4R3J10.Time;
428     Exit_time(18,i)=W4R3EX.Time;
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```
429     end
430     if 0 < VesseL(19)
431         % Week 4 Route 4
432         W4R4(1:2,i)=W4R4J1.Time;
433         W4R4(3:4,i)=W4R4J2.Time;
434         W4R4(5:6,i)=W4R4J3.Time;
435         W4R4(7:8,i)=W4R4J4.Time;
436         W4R4(9:10,i)=W4R4J5.Time;
437         W4R4(11:12,i)=W4R4J6.Time;
438         W4R4(13:14,i)=W4R4J7.Time;
439         W4R4(15:16,i)=W4R4J8.Time;
440         W4R4(17:18,i)=W4R4J9.Time;
441         W4R4(19:20,i)=W4R4J10.Time;
442         Exit_time(19,i)=W4R4EX.Time;
443     end
444
445     if 0 < VesseL(20)
446         % Week 4 Route 5
447         W4R5(1:2,i)=W4R5J1.Time;
448         W4R5(3:4,i)=W4R5J2.Time;
449         W4R5(5:6,i)=W4R5J3.Time;
450         W4R5(7:8,i)=W4R5J4.Time;
451         W4R5(9:10,i)=W4R5J5.Time;
452         W4R5(11:12,i)=W4R5J6.Time;
453         W4R5(13:14,i)=W4R5J7.Time;
454         W4R5(15:16,i)=W4R5J8.Time;
455         W4R5(17:18,i)=W4R5J9.Time;
456         W4R5(19:20,i)=W4R5J10.Time;
457         Exit_time(20,i)=W4R5EX.Time;
458     end
459
460     % Save the new obtained data from the simulation.
461     DataR= 'Retrieve_sim_data';
462     save(DataR, 'W1R1', 'W1R2', 'W1R3', 'W1R4', 'W1R5', 'W2R1', 'W2R2', ...
463           'W2R3', 'W2R4', 'W2R5', 'W3R1', 'W3R2', 'W3R3', 'W3R4', 'W3R5', ...
464           'W4R1', 'W4R2', 'W4R3', 'W4R4', 'W4R5', 'Exit_time');
```

```
465
466     % Not necessary, but interesting to see the progress of the
467     % simulation and how much time each simulation takes.
468     Tid=i
469     toc
470
471     % Clear all variables to remove all unnecessary global variables
472     % that are increasing the simulation time.
473     clear all;
474
475     % Retrieve the variables that are needed for the simulation and
476     % for loop to proceed the simulation
477     excelR='excelR_used_for_sim';
478     load(excelR);
479 end
480 clear all;
```

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