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Emergency Preparedness and Response in Aquaculture

Simulation of Vessel Response Time for Sheltered and Exposed Fish Farms

Henrik Håkonsen

Marine Technology
Submission date: June 2017
Supervisor: Bjørn Egil Asbjørnslett, IMT

Norwegian University of Science and Technology
Department of Marine Technology

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

MASTER'S THESIS

Emergency Preparedness and Response in Aquaculture

- Simulation of Vessel Response Time for Sheltered and Exposed Fish Farms

Henrik Dyrland Håkonsen

Submission date:	09.06.2017
Supervisor:	Bjørn Egil Asbjørnslett

Norwegian University of Science and Technology

Department of Marine Technology

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Preface

This master's thesis is written by Henrik Håkonsen in the spring of 2016 and accounts for 30 credits. The thesis is written at the Norwegian University of Science and Technology, Department of Marine Technology. The full task description of the thesis can be found in Appendix E – Task Description.

In the fall of 2016, a project thesis was written and served as a preliminary study to this thesis. The focus in the project thesis was to provide skills in modelling of simulation models. The project thesis also provided an introduction to emergency preparedness in the aquaculture industry.

The major part of the report has been written in the second half of the spring semester. In the beginning, the focus was on researching current emergency preparedness, as well as building the simulation model. The work process has been demanding, but has undoubtedly resulted in a great learning curve.

I would like to thank my advisor, Bjørn Egil Asbjørnslett, for valuable input on the thesis throughout the entire process.

Trondheim, 09.06.2017

Henrik Håkonsen

Henrik Håkonsen

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Summary

This master's thesis investigates emergency preparedness and response in Norwegian aquaculture using discrete-event simulation. The aquaculture industry is growing in terms of production, size, and technology, with the first exposed salmon farm expected in offshore waters by the end of 2017. One should therefore prepare and plan for new challenges. This thesis considers emergency preparedness and response for current and future aquaculture. The emergencies considered involve loss of biomass.

The system limitations are set to when salmon is located in cages at sea. Relevant literature considering emergency preparedness and response in aquaculture is evaluated. Emergency preparedness and response is defined as planning for emergency, and the reactive actions performed after emergency. To gain insight, relevant literature from other segments is also assessed.

A discrete-event simulation model is developed in SimEvents, to serve as a tool in the analysis. The model is developed as a generic basis to handle different emergency types. The modeled system is constructed to determine response time and time until the emergency is eliminated, based on various input data. The correlation between input data and calculations with the system is illustrated. The input data is mostly based on research, thereby causing variations in accuracy. The simulation model is used to evaluate emergency escape and emergency slaughter.

A case study with three cases is carried out to show the application and diversity of the simulation model. All three cases contain several scenarios with changing input data. The two first cases considers response time for wellboats and light diving vessels upon first arrival at the emergency site. With varying probability and distribution input, simulations are performed for one sheltered fish farm and one exposed fish farm. Further, the case study considers different fleet compositions to empty the two fish farms, with varying stock sizes.

Each simulation provides different output due to stochastic variables, such as wave height and mobilization time. The results show that it is possible to obtain the same response times for the exposed fish farm by increasing the availability of response vessels. Further, the case study shows that a significantly larger capacity is needed for emergency slaughter in exposed areas. Lastly, the case study shows that poor utilization decreases performance offshore when one large vessel is used, instead of several smaller vessels.

The thesis concludes that increased focus on preparedness and response in the growing aquaculture industry is needed. Both to improve procedures and planning, to prevent loss of biomass in emergency. The case study concludes that it is highly possible to achieve a satisfactory level of preparedness and response for exposed fish farming, but standby vessels may be necessary. Furthermore, increased incentives are suggested to improve current planning and communication procedures, level of standardization, as well as ensuring capacities before emergency occurs.

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Sammendrag

Denne masteroppgaven undersøker en tilnærming til beredskap i norsk fiskeoppdrett ved hjelp av diskret-hendelses simulering. Oppdrettsindustrien er i vekst når det gjelder produksjon, størrelse og teknologi, og det første havbaserte oppdrettsanlegget er ventet å være i produksjon før 2018. Med produksjonsveksten bør man være forberedt på et større antall nødssituasjoner og nye utfordringer. Denne masteroppgaven vurderer derfor beredskap med tanke på dagens, og fremtidens havbruk. Nødssituasjonene i denne oppgaven involverer tap av biomasse.

Systembegrensningene er satt til når laksen er plassert i merder i sjøvann. Relevant litteratur er evaluert for å gi en oversikt over dagens beredskapssituasjon. Beredskap er i denne oppgaven definert som planlegging og handlingene som blir gjort etter at nødssituasjonen har oppstått. Relevant litteratur er også vurdert for andre segmenter, for å gi bedre innsikt til temaet.

En diskret-hendelses modell er utviklet, for å bidra til beredskapsanalysen. Modellen er utviklet som et generisk grunnlag for å simulere forskjellige typer nødssituasjon. Simuleringsmodellen er utviklet for å finne responstid og tid til et anlegg er uslaktet, basert på varierende forutsetninger gitt av inngangsdata. Sammenhengen mellom inngangsdata og utregninger med systemet er illustrert. Inngangsdataen er basert på forskning og varierer derfor i nøyaktighet. I denne masteroppgaven er simuleringsmodellen brukt til å evaluere nødssituasjoner av typen rømming og utslakting.

Modellen anvendes i et eksempelstudie med tre forskjellige typer nødssituasjoner som inneholder flere scenarier der forutsetningene endres. De to første situasjonene tar for seg responstid for brønnbåter og dykkerfartøy ved første ankomst til oppdrettsanlegget i nød. I scenariene endres sannsynligheten som bestemmer hvor fort beredskapsfartøy ankommer. Simuleringer er gjort for et skjermet og et værutsatt oppdrettsanlegg. Videre vurderes forskjellige flåtesammensetninger i en utslaktingssituasjon for begge oppdrettsanleggene med varierende fiskebestand.

Simuleringene gir varierende resultater som følger av stokastiske variabler, som for eksempel signifikant bølgehøyde og mobiliseringstid. Resultatene viser at det er fullt mulig å oppnå samme beredskapsnivå for havbasert oppdrett, når man øker tilgjengeligheten til fartøyene, men at fartøy i konstant beredskap er nødvendig for å oppnå samme gjennomsnittsverdi for responstid. Videre viser eksempelstudiet at det er behov for betydelig større kapasitet for å tømme er havbasert oppdrettsanlegg. I tillegg viser studiet at dårlig utnyttelse reduserer ytelsen når et stort fartøy brukes, i stedet for tre mindre fartøyer med samme totalkapasitet.

Masteroppgaven konkluderer at et økt fokus på beredskap er nødvendig for å forbedre rutiner og planlegging som forhindrer tap av biomasse i nødssituasjoner. Eksempelstudiet konkluderer at det er fullt mulig å oppnå et tilstrekkelig beredskapsnivå for havbasert oppdrett, men at fartøy i konstant beredskap må vurderes. Videre foreslås økte insentiver for å forbedre dagens planleggings- og kommunikasjonsprosedyrer, nivå av standardisering, samt sikring av tilstrekkelig kapasitet i nødssituasjoner.

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1. Introduction

Background

This master’s thesis is the result of increased focus on aquaculture at the Norwegian University of Science and Technology. The aquaculture industry has been exposed to serious growth in the latest years in terms of production, technology, and size. The industry stakeholders have no intentions of stopping this growth, and increasing production by a five-fold before 2050 have been mentioned on several occasions. Additionally, the industry is considering the possibility of salmon farming in more exposed areas. To reach this goal, increased innovation will likely occur, thereby resulting in more research on the topic. Assuming such a growth will result in more emergency situations, part of this innovation and research must deal with emergency preparedness and response. Proper safety measures may be crucial when considering exposed aquaculture and production increase. Thus, this thesis will investigate some of the important research questions considering current and future emergency preparedness and response for the aquaculture industry.

Objective

The objective of this thesis is to develop a generic simulation model to assess preparedness in emergency situations, and to identify response times for sheltered and exposed fish farms, based on varying input data. The model will serve as a tool to analyze and evaluate current versus future emergency preparedness and response in Norwegian aquaculture.

Limitations

The focus will be on defining what emergency preparedness and response implies for Norwegian aquaculture. Therefore, the probability of an emergency occurring will not be considered, but rather the preparedness and reactive consequence mitigation barriers. These barriers represent emergency preparedness and response in this research. Additionally, preparedness will only be considered in the Norwegian aquaculture industry. All emergencies will be limited to when the salmon is in cages in seawater. In other words, from smolt is put into saltwater pens, until they are harvested. Additionally, this thesis will only deal with emergency preparedness in terms of loss of biomass. Hence, emergency preparedness regarding human lives is excluded, assuming this will be at a satisfactory level. Lastly, the simulation model will be limited to events demanding response from wellboats or diving vessels. Simulations will therefore only be executed for situations of fish escape and situations demanding emergency slaughter.

State-of-the-art

The aquaculture industry is currently moving towards fish farming in exposed areas. The first offshore fish farm will soon be launched, thereby starting a new era in salmon farming. In order to be successful in this new era, other key contributors in the supply chain answers with bigger and better services. The capacity and technology of vessels transferring salmon is developing, with the largest and most complex ones yet to come. This also applies to providers of service vessels, fish farms, and other key parts of the industry.

Structure

The thesis will start with a short description of the system boundaries, and some of the most important entities. Following, the problem at hand will be described. Afterwards, a literature review of emergency response in aquaculture and other segments will be presented. After the literature review, the thesis will move on to the technical part. Discrete-event simulation is assessed before the developed simulation model is thoroughly described. Following, the simulation model will be applied in a case study involving three separate cases of emergency. The results from the three cases will be presented with simple graphs and plots. Finally, discussions of the literature review and simulation output will be carried out to provide conclusions and recommendations, as well as some suggestions for further work.

2. System Description and Important Entities

To better understand the problem at hand, it is necessary to consider the aquaculture supply chain. This chapter provides a description of the relevant steps in the aquaculture supply chain where emergency preparedness is considered in this thesis. Figure 1 illustrates the system boundaries, followed by a thorough description.

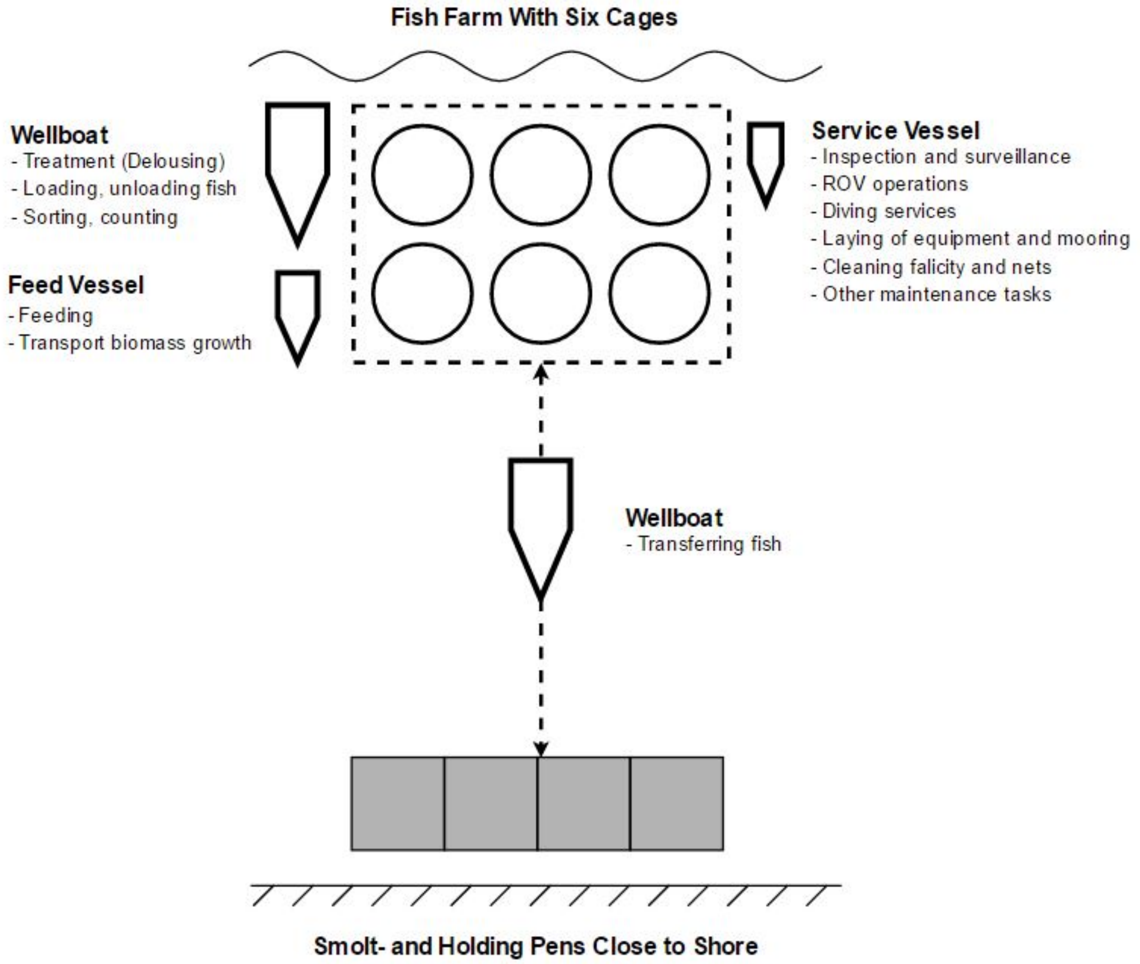

Figure 1: System limitations and some important entities and common services they provide (Ulvan, 2017).

The illustration presents the boundaries in which this study considers emergency preparedness and response. In the aquaculture value chain, salmon is partly raised in fresh water tanks on land. At this stage, they are not able to survive in salt water. When they reach a weight of 60-80 grams, they are ready for the smolt stage (MarineHarvest, 2017). At this stage, the salmon go through a biologic change, enabling them to live in seawater. At first, they are put into smolt pens close to shore, as shown in the illustration. It is from this point in time, emergency preparedness is considered in this thesis.

When the salmon is sufficiently large, a vessel called a wellboat, or live fish carrier, transfers the live salmon to fish farms at sea. Here, salmon is unloaded into cages, where they stay for approximately two years. During these two years, the salmon requires regular feeding, which is done by feeding vessels and barges. Also, they may be transferred between different cages.

When a weight of 4-6 kilos is reached, the salmon is ready for slaughter (ErkoSeafood, 2017). At this stage, wellboats are utilized to transfer salmon to slaughter. Close to shore, the live cargo is unloaded into holding pens at the slaughter facility, and further harvested onto the landbased slaughter facility. In this study, emergency preparedness is considered until the salmon is moved from seawater and into the slaughter facility. In other words, emergency preparedness is considered from the smolt stage, until slaughter.

Figure 1 illustrates the system boundaries, but also some of the most important entities in the aquaculture supply chain. Five entities are considered in this system, and the following descriptions are inspired by Ulvan (2017). Some of these may contain certain important entities within them, such as a fish farm containing several cages.

2.1 Wellboats

As mentioned, these are the vessels that transfer fish to and from the facilities. All Norwegian salmon are aboard a wellboat 2-4 times in its lifecycle, which clearly demonstrates the importance of such vessels in the aquaculture supply chain. Apart from transferring live fish, they also perform other important tasks. Among these are treatment of fish-disease, delousing, and emergency slaughter. According to Hauvik (2015), ten percent of the normal operation goes to transferring smolt, thirty percent to treating salmon, and sixty percent goes to harvest and transfer.

Today, the Norwegian fleet of wellboats consists of approximately 60 vessels, as shown in the database in Appendix B. The latest years, we have seen a significant development in technology, size, and capacity for this type of vessel. This is demonstrated in Figure 2, where capacity versus build year is plotted.

As seen in the plot, the obvious trend is to build vessels with larger capacity. Between year 2000 and 2005, the normal was below 1000 cubic meters, while it is typically above 3000 cubic meters after year 2012. The fleet is still in development both in terms of size and technology, with several new builds on the way. Among these is Ronja Storm, with an expected capacity of 7450 cubic meters, almost double of what has been normal to build in the last decade (Sysla, 2017). Admittedly, it is not going to operate in Norway, but clearly illustrates the direction of the development for such vessels. Moreover, Hauvik (2015) describes that several relatively new vessels are in danger of being phased out, due to new regulations.

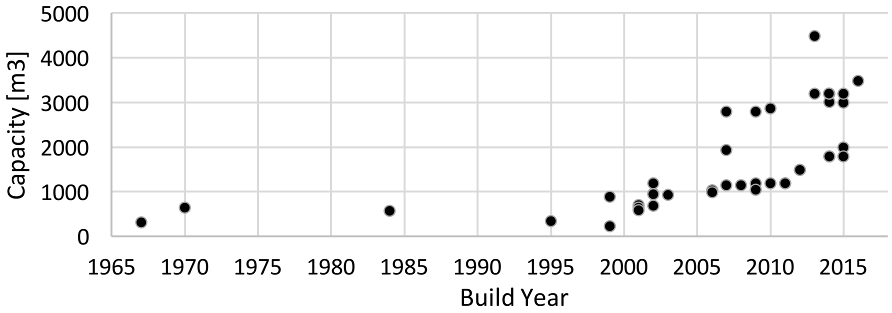

Figure 2: Trend of cargo capacity versus build year for wellboats.

2.2 Feed Vessels and Barges

These vessels transfer the entire feed biomass of approximately 1.8 million tonnes. In 1990, a fleet of 100 tonnes was considered large, while today, one would expect a capacity of over 1000 tonnes. A clear development is going on also in this segment of the supply chain. In addition to development in size, there are significant technological changes in the fleet. For instance, several new vessels are now powered by environmentally friendly LNG engines.

2.3 Service Vessels

The service vessels are arguably the ones keeping production running as efficiently as possible. A vast selection of these types of vessels exist. Among them are ribs, catamarans and more, all performing various service operations in the aquaculture supply chain. Some key functions include ROV operations, inspection, mooring, cleaning, and maintenance. They also perform diving operations to fix broken nets and perform other under water service operations.

2.4 Holding and Slaughter Pens

Pens in close proximity to the slaughter facility are used to store salmon until they are ready for slaughter, or transfer to fish farm. Typically, the salmon spend 2-3 days in these pens before slaughter. This is partly to calm the fish after transfer, and to release transport capacity.

2.5 Fish Farm

The fish farm is arguably the most important entity in the aquaculture supply chain. When ready for salt water, the salmon is put into cages at sea. The farms typically consist of several individual cages, depending on allowed capacity at the specific location. The farms are designed, dimensioned, installed and operated based on regulations from NYTEK and the standard, NS 9415 (Lovdata, 2012). Approximately 1300 fish farms can currently be found along the Norwegian coast, with a maximum allowed capacity of 8580 tonnes at a single location (Fiskeridirektoratet, 2017a). In most cases, a single farm consists of several cages, each with a maximum capacity of 780 tonnes.

Traditionally, fish farms are located in sheltered areas along the coast, where weather and sea conditions are favorable. Today, there is a shortage of such locations, thereby forcing the industry to farm at locations exposed to worse conditions. Consequently, more robust constructions are required to perform the necessary work. Significant technological and structural developments are needed to withstand these changes in weather conditions.

Recently, this has started what may be described as a technological evolution in the aquaculture industry. Several major companies are presenting new concepts, capable of salmon farming in exposed conditions (EXPOSED, 2017a). Some of the concepts have been given grants, while others are already in production. However, none of these farms are currently in operation. For this reason, it is necessary to evaluate the different emergencies that may occur. Moreover, it may be crucial to evaluate the possible outcomes of such emergencies, and how to be prepared. Thereby, leading to the problem of this master's thesis.

3. Problem Description

In recent years, increasing production and export by a fivefold within 2050, have been mentioned on several occasions. The Minister of Fisheries, Per Sandberg is one of the positive actors on the matter. In the beginning of 2017 he expressed that an increase in exported value by a fivefold might be a modest goal (Sandberg, 2017). However, such an increase will require an extensive expansion of the industry, as well as development in technology and research. Such a growth may also bring forth new challenges in terms of risk and emergency. Consequently, this thesis investigates emergency preparedness and response when considering the near and distant future of the industry.

To better grasp the context of the problem, it is necessary to consider the significance of such a growth. Increasing the production will require higher capacities in all parts of the value chain. Today, fish farms of different kinds are represented along the entire Norwegian coastline. Most of these are located in sheltered areas along the coast, with low impact from weather conditions. Such locations are in short supply, thereby providing incentives to farm in more exposed locations.

As a result, the Centre for Research-based Innovation in Norway has started a research program considering exposed aquaculture. The objective is to “develop knowledge and technologies for EXPOSED aquaculture operations, enabling a sustainable expansion of the fish farming industry” (EXPOSED, 2017a). Naturally, such developments will also affect emergency preparedness, therefore requiring research on the subject.

An assumption made in this thesis is that, the number of emergency situations may increase, as production increases. Additionally, it is arguable that the exposed locations will cause more severe and comprehensive emergencies. For instance, due to worse weather conditions and further sailing distances, which also will affect the response time and logistical challenges. Furthermore, the design and structure of these exposed fish farms are brand new, and have not yet been tested in real life. This will likely present new and unknown challenges both for normal operations and in emergency situations.

One of these new projects is SalMar’s, Ocean Farm 1, which will start production in Frohavet in the third quarter of 2017 (Eide, 2016). The structure is robust, and claimed to have very low risk of fish escape (SalMar, 2017). Although the risk of emergency is low, it is necessary to consider the possible loss of biomass in case an emergency occurs. Example emergencies causing loss of biomass are fish escape, fish disease, excessive louse population, and mass death. A more detailed analysis of possible emergencies can be found in Appendix C. Figure 3 illustrates the sea conditions of a buoy close to the exposed area where Ocean Farm 1 will operate.

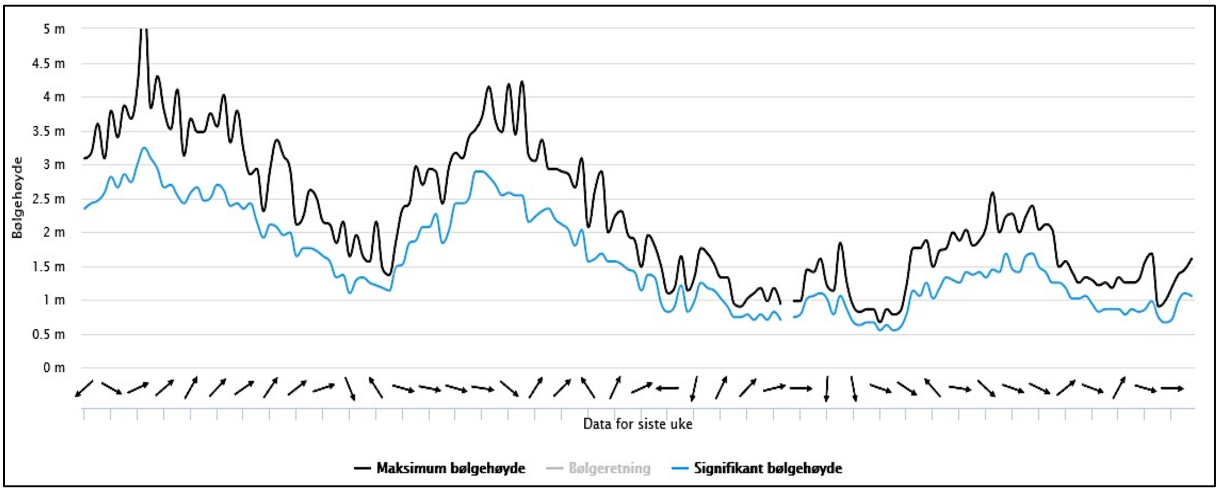

Figure 3: One week of wave data from Marine Harvest's buoy close to Ocean Farm 1's expected location. The blue line shows significant wave height, and the black line shows maximum wave height (EXPOSED, 2017b).

The buoy is owned by Marine Harvest, and shows wave data for one week. The illustration shows wave height in the vertical axis versus data for the last week in the horizontal axis. The blue line illustrates the significant wave height, which reaches a maximum of over three meters for that week. Recently, Bjelland (2016) stated that the most exposed fish farm currently in operation reaches a maximum significant wave height of 2.5 meters. These two values highlight the major difference in conditions exposed fish farming can expect.

Since few aquaculture operations have been performed in such weather conditions, it may be essential to have the proper emergency preparedness and response procedures figured out. However, since exposed fish farming is in an early stage, it is impossible to foresee exactly which emergencies will occur. Therefore, this thesis is an attempt to evaluate and analyze if it is possible to achieve a similar level of preparedness for exposed farming, as for sheltered farming. More specifically, simulations are carried out considering response time and fleet composition. This is to determine necessary improvements for exposed farming to reach the same level of preparedness as for sheltered farming.

The problem is analyzed using a developed discrete-event simulation model. The simulation model provides quantitative output for emergency preparedness, for different emergency types and system states. By studying the provided output and findings in literature, the following five research questions considering emergency preparedness and response are assessed.

- Which adjustments are needed to achieve the same response times for exposed farming as for sheltered salmon farming?
- Is it necessary to consider implementing standby vessels for emergency response?
- Is the cost of adequate preparedness too large?
- What are clear problems in the current procedures of emergency preparedness?
- Is there a satisfactory amount of available research on the subject?

4. Literature Review

The literature review in this thesis provides an overview of the most relevant findings on emergency preparedness and response. Due to limited scientific research, some findings are from reports, news articles, guides, and similar publications, in addition to academic work and research articles. The chapter is structured so that the reader first obtains an understanding of what is meant by emergency preparedness and response in this thesis. Following, findings considering preparedness and response in aquaculture emergency is presented, followed by relevant findings in other segments, such as the oil and gas industry. Lastly, literature concerning simulation in general and in accordance with emergency preparedness and response is reviewed.

4.1 Defining Emergency Preparedness and Response

In this thesis, emergency preparedness and response is defined as planning for emergency and the actions done after an emergency has occurred. As previously mentioned, the probability of an emergency is therefore neglected. Nevertheless, to fully understand how this thesis defines the term, it may be beneficial to consider the full risk picture. This is often done with a bow tie diagram. The diagram visualizes the risk of events in one simple illustration. Figure 4 illustrates a general composition of a bow tie diagram.

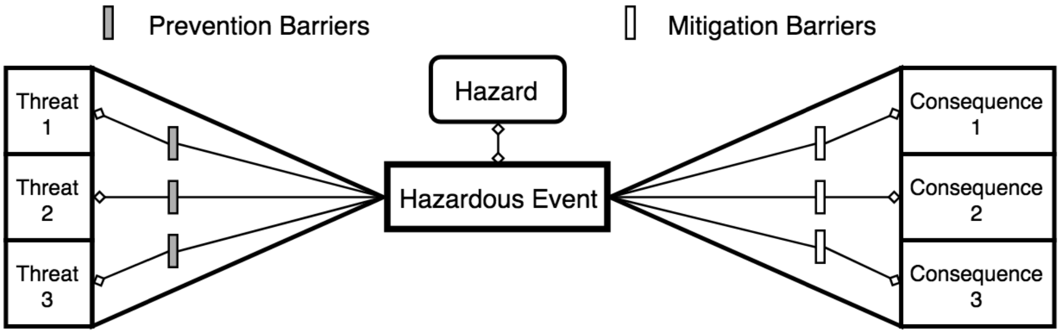

Figure 4: Typical bow tie diagram illustrating the full risk picture for hazards/emergencies, inspired by CGERiskManagementSolutions (2017).

The diagram illustrates that a hazardous event or an emergency may occur due to several causes, often referred to as threats. Commonly, the starting point is to identify a hazard, which may be as simple as a wellboat drifting towards a net cage containing salmon. The hazard may lead to the hazardous event, for instance a collision causing a hole in the net. Causes to this could be harsh weather conditions or system failure. The grey barriers represent measures to prevent the hazardous event from occurring, for instance periodical maintenance on the system. One of the resulting consequences may be escaping salmon. The white barriers represent measures to reduce and mitigate the outcome of the consequence, for instance by planning for emergency or calling for a diving vessel to fix the damage.

This thesis primarily considers the mitigation, or consequence reducing barriers. These are referred to as emergency preparedness and response. To determine the most important aspects to consider, a brief Preliminary Hazard Analysis (PHA) is performed. First, the possible hazards are determined, such as rough weather and structural errors. Secondly, the resulting undesired events and consequences are defined, such as fish escape. Finally, some consequence reducing measures are proposed, such as calling for diving vessel to fix the net. The analysis is performed to obtain an overview of the possible events requiring emergency preparedness and response. The analysis can be found in its entirety in Appendix C.

4.2 Aquaculture

This chapter presents some relevant findings considering emergency preparedness and response in the aquaculture industry. The focus is mainly on emergencies related to loss of biomass, such as disease, mass death, excessive louse population, and escape.

Regarding the industry stakeholders' view, emergency preparedness was the main subject in an annual conference held by TEKMAR (Sunde, 2009). The conference was held in 2009, with 155 participants, where 70 percent represented the industry. Based on previous experience with sudden changes in demanded capacities in various situations, the question that is thoroughly debated is, which threats the industry faces and how to mitigate consequences. Threats in the form of specific situations and themes are discussed among the participants through brainstorming sessions. One of the themes discussed is pumping and sorting of large quantities of fish. Possible solutions mentioned are to implement known procedures and technologies already used in the oil and gas industry. Additionally, thorough discussions are carried out on the possibility of suddenly being imposed to slaughter 5000 tonnes due to an approaching oil spill. Although standby wellboats provide the best solution in terms of response, it is found that cost is excessive. Furthermore, the possibility of sharing preparedness resources is mentioned as a solution. However, if several sites face the same emergency simultaneously, it will ultimately come down to shortage in capacity, either for the fleet or slaughter facility. Other discussion topics include handling mass death, delousing, slaughter at farm, and transporting salmon over long distances. General solutions and improvement areas found at the conference are to develop better technology, standardizing and training on procedures, sharing resources, improved preparedness plans, and the ability to decide and act quicker.

The Research Council of Norway published a news article stating that the most common escape cause is due to equipment failure (Hanssen, 2013). Researchers evaluates all reported escape situations from 2006-2009. In the process, it is found that structural errors accounts for 68 percent of escaped salmon, while human errors in conjunction with operations covers 11 percent. Further, they find that two out of three escape situations in the reviewed period are caused by holes in the cage net. By studying the escape situations, which are mandatory to report, the researchers propose solutions that will help reach the zero-escape vision. However, the article does not mention the actions made to secure the remaining stock, which is a part of the mandatory escape reports.

Regarding emergency preparedness in escape situations, a guide is developed to prevent and prepare for emergency (FHL et al., 2010). With the purpose of providing input to the industry on how to prepare for escape, the guide summarizes important parts of regulations and recommendations on how to fulfil them. Considering limiting the damage, mentioned measures are to lift the net hole above the waterline, sewing using divers, securing with chains, and calling for necessary service vessels. Also, the authors state the importance of "thinking ahead" to minimize the extent of the emergency. The guide also presents a recommended analysis consisting of six phases. Among these phases are "discover"," mobilize", and "handle". The authors emphasize the importance of considering that people are reluctant in declaring emergencies. Thus, recommending to implement definitions of when a situation is classified as an emergency into the preparedness plan. Moreover, the guide presents examples on how to construct such preparedness plans and what it should contain.

Regulations forces the fish farmers to always keep an updated preparedness plan (Lovdata, 2015). This is to contribute to safeguarding fish health and risk of infection in emergencies, such as disease and mass death. With instructions on how to handle certain operations, such as loading, treatment, transport, escape, and slaughtering, the farmer receives an overview on how to react in emergencies. Some of the preparedness plans are public, for instance the preparedness plans of "Kobbevik og Furuholmen Oppdrett AS" and "Engesund Fiskeoppdrett AS" (Kobbevik, 2013, Engesund). Although these are in geographical proximity to each other, the plans vary both in layout and content. Ultimately, the content of both plans seem to cover the necessaries. However, the differences indicate an extensive variation in preparedness plans along the Norwegian coast.

Sintef published an article in 2011 considering increased focus on escape in previous years. Aarhus (2011) states that this focus mainly is connected to ecological consequences, such as genetic threats to wild salmon and spread of disease. However, the article also comments on the potential economic loss for the affected fish farm, thereby increasing incentives to prevent escape. An example situation is presented with an estimated loss of 10 million NOK, where half of the loss is due to biomass. The other half is spent on counting the remaining stock, evaluating the damage extent, and recapture. Thereafter, three possible scenarios are presented with cost estimates. One of these considers escape from a net hole of one hundred thousand fish, resulting in a loss of 15.5 million NOK. The increased focus on escape that the article describes resulted in a decrease of escaped salmon from 921 000 in 2006 to 131 000 in 2016 (Fiskeridirektoratet, 2017b).

In addition to the previous findings, news articles are frequently used in this thesis. For instance, following outbreak of ILA-disease it is stated that all salmon must be slaughtered within 80 days (Johansen and Nikolaisen, 2013).

Although research on Norwegian Aquaculture is increasing, the author finds that there is a lack of scientific research considering certain emergency types in aquaculture. For instance, the author experienced an unsatisfactory amount of research considering emergency slaughter.

4.3 Other Segments

Josefsen et al. (2016) studies response time in emergency oil spills in artic conditions in his master's thesis. Due to the remote areas in the Arctic, he investigates the possibility of utilizing vessels from the operational fleet in emergency as opposed to standby vessels. The thesis concludes that a satisfactory level of safety in terms of response time may be achievable by using operational vessels instead of standby vessels.

Regarding how different stakeholders communicate during oil spills, Walker et al. (2015) review and assess, "current oil spill preparedness and response practices for community and stakeholder engagement, including related institutional and operational constraints". The authors define The Deepwater Horizon (DWH) emergency as a central event when defining response options. When concluding, the authors emphasize the importance of communication in emergency between public, responders, and communities. By studying the weaknesses of DWH, five examples of communication practices during oil spills are suggested.

Following Hurricane Sandy, Powell et al. (2012) considers common failures, such as the difficulties of securing "situational awareness". More specifically, the information required to construct the required planning and response decisions. They also state that the proper authorities did not "take charge to coordinate strategic decisions", even though they had claimed control beforehand. Further, the future of emergency preparedness is considered, stating the importance of developing protocols and ensuring capacities. Lastly, they emphasize that disasters are inevitable, therefore calling for better preparation and planning ahead of the emergency from authorities.

4.4 Simulation

This chapter presents relevant findings within discrete-event simulation and modelling. Some literature is related to other fields of study, but consider important challenges using discrete-event simulation systems. Some of the reviewed literature uses simulation to assess emergency response.

Josefsen et al. (2016) develops a discrete-event simulation model using MATLAB in his thesis. The model is used in a case study where simulations are carried out to determine response time for various fleet compositions. The author concludes that the model is capable of serving as a tool to analyze the possibility of using operational vessels in emergency.

In investigations of ambulances in Singapore, a discrete-event simulation model is developed and applied to reduce response times. Performance of various strategies are simulated to evaluate both response time and utilization. Wei Lam et al. (2014) conclude that they improved response times by reallocating ambulances more effectively. Moreover, the article describes discrete-event simulation as a “risk-free and practical platform for testing new operational policies”.

Regarding the increasing interest in clean energy of public transport, Sebastiani et al. (2016) consider the challenges of battery recharging and bus energy consumption. A discrete-event event simulation model evaluating the energy consumption is presented, taking various stochastic variables into account. By coupling a discrete-event simulation model with optimization the authors present possible solutions for a given case.

As a part of the course module “Ocean Systems Simulation” at NTNU, a compendium is issued as a guide for developing simulation models (NTNU, 2016). The compendium starts by introducing basic concepts regarding simulation. A description of SimEvents in general is provided, followed by simple model examples and guides on development. Gradually, the compendium increases the complexity of its examples, providing new solutions. The compendium is regularly used as a guide in this thesis.

The author finds that there is a satisfactory amount of academic research regarding discrete-event simulation. Additionally, course material and accumulated knowledge within the subject is a major contribution to the upcoming simulation part of the thesis.

5. Methodology of Discrete-Event Simulation

Discrete-event simulation is an effective tool in providing quantitative output to analyze flow systems containing stochastic variables (Gray, 2007). Thus, the goal is to develop a model representing a real-life system. Such models provide fast and acceptable output, representing the various states of the system. In the simulation model, entities flow through a predefined path of events. In each event the necessary calculations are done, thus affecting the flow of each entity. A properly designed discrete-event simulation provides accurate and relevant estimates without being computationally prohibitive (Caro et al., 2010). A major challenge in simulation is to maintain a balance of the detail in the model and complexity of the input data. To provide fast and accurate output, it is often important to design the model as simple as possible.

A simple system may be exemplified by a car representing an entity, moving through a traffic junction representing an event. The traffic junction contains a certain value of cars in queue, which determine how long the entity must wait, or if it can go straight through. In simulation, such values are often represented by stochastic variables, which are subject to random variations. These variables are often represented by statistical measures.

The discrete-event simulation engine used in this thesis is SimEvents, which provides possibilities of conducting operational research for capacity-planning, supply-chains and more (MathWorks, 2017). In addition to the engine, a library is provided, containing components such as queues, servers, switches, and other blocks. These are the building-blocks of the real-life system, which is to be constructed. They provide crucial services, such as generating entities, defining each event and the flow of the system. Figure 5 illustrates a simple example of how a model can be developed in SimEvents by using the component library.

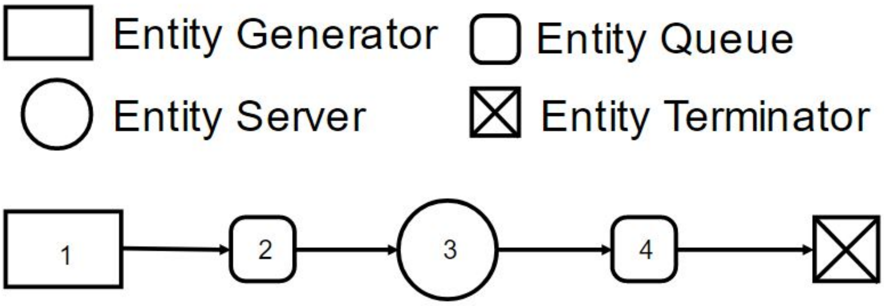

Figure 5: Simple Example Simulation Model in SimEvents with common blocks.

The illustration presents four of the most commonly used blocks in SimEvents. In this example, the first block enables the user to generate entities, for instance one or several cars. The car is assigned attributes, such as speed, breaking power, and fuel consumption. The next block is a queue, providing the ability to regulate the number of cars allowed to pass through. In this case, it may represent the number of lanes. Following, the entity enters the server, which may represent the traffic junction. At this stage, stochastic variables may determine the duration the car must wait before passing the junction. The next queue is only added to control the flow of entities, only allowing one car to pass at once. Lastly, the entities are terminated to stop the simulation.

SimEvents is one of many software programs capable of developing such models. Other software frequently used are Java and MATLAB. However, these do not provide the same drag-and-drop functions and graphical user interface as SimEvents.

6. Model Applied for Simulation

The simulation model is developed in SimEvents, which is one of several MathWorks products. They also provide a product called MATLAB, which allows for more extensive and technical computations. It would be possible to develop the model using MATLAB. However, it is decided that SimEvents is more suitable based on the author's background and knowledge. Additionally, SimEvents is customized for developing and simulating discrete-event systems, therefore often providing a more intuitive user interface.

The objective of the modelled system is to provide results when simulating different emergency situations in the aquaculture industry. Expected output include response time upon first arrival at the emergency site and necessary fleet characteristics. Most importantly, each simulation provides information on how long it will take to solve the emergency. The results vary based on changing input data and stochastic variables for the relevant scenario.

The simulation model is based on a previous project thesis, but has significant modifications. The earlier model simulated both the normal operation and emergency, which demanded a logistical model simulating the normal operation of wellboats. During testing, it was experienced that such a model demanded substantial computational power, thereby causing the simulation time to increase. Moreover, it was found that simulating a random operational state for the relevant vessels is more befitting than applying the logistical model. As a result, the model is simplified, while providing virtually the same output.

A single simulation model is developed as a generic basis to handle different types of emergencies. Based on the type of situation, the entities follow a predefined path. The process varies based on two types of emergency situations, as illustrated in Figure 6.

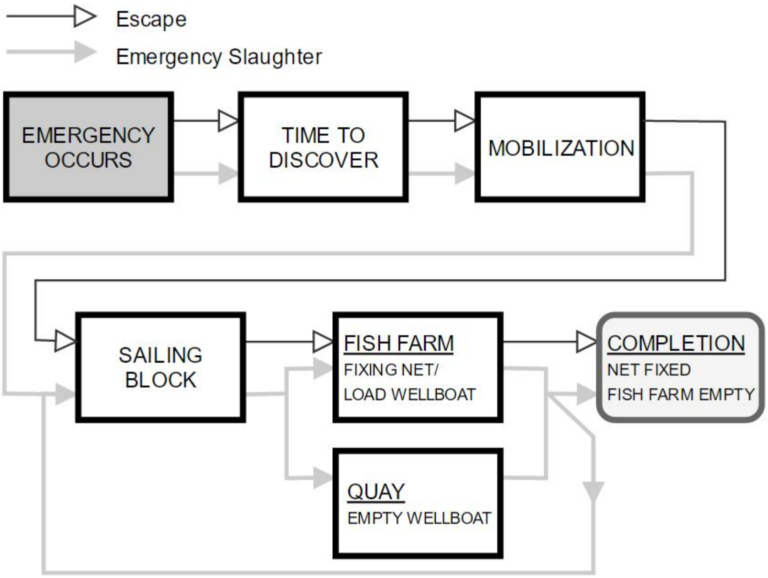

Figure 6: Process and predefined path for two types of emergency, and events affecting the flow of vessels.

Based on input data from an Excel file, the simulation model initiates the process matching the predetermined emergency. Situations involving slaughter forces the entities to flow between the fish farm block and the quay block until all fish is removed. As for the escape situations, the entities only enter the fish farm block once. When leaving the fish farm block, the damage is fixed and no more fish escape. A flowchart representing the structure and flow upon first arrival at the emergency site for both situations is illustrated in Figure 7.

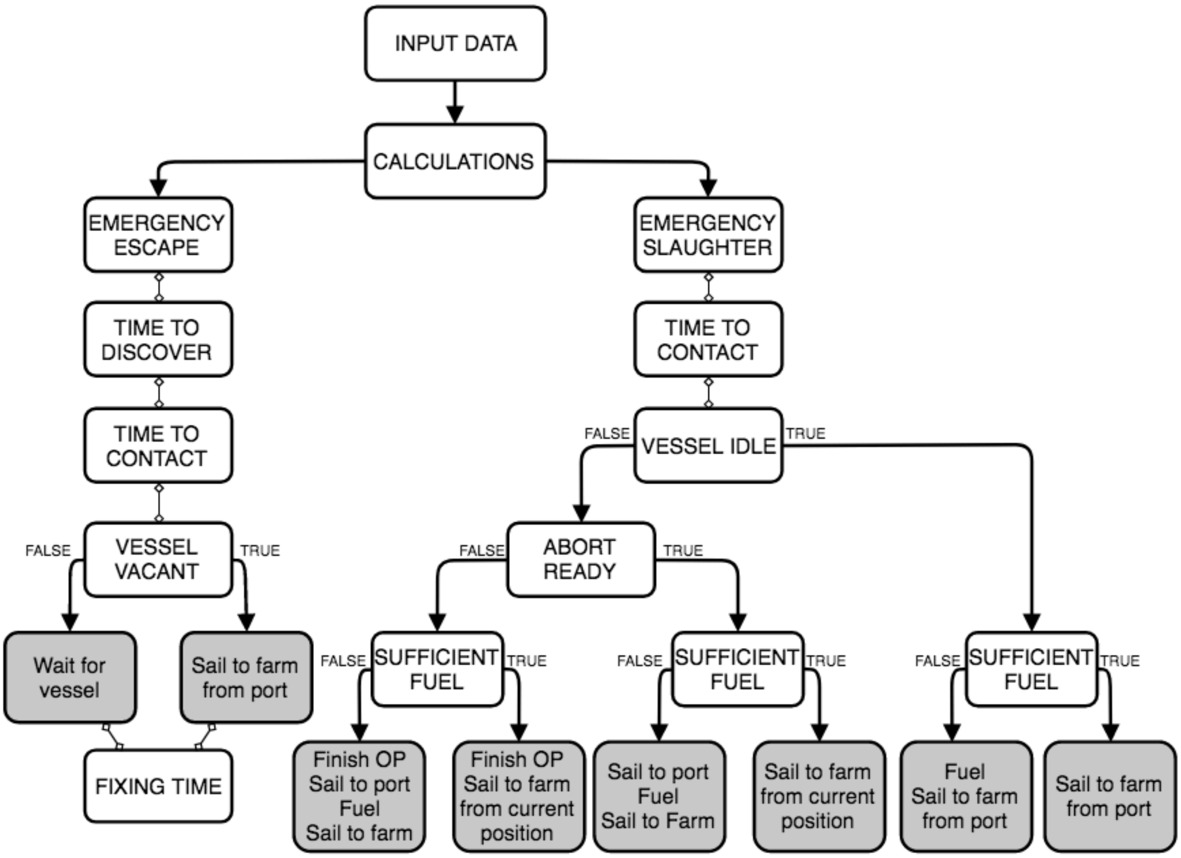

Figure 7: Diagram showing all possible selection outcomes for the simulation model for two emergency types.

The diagram illustrates the process all vessels go through in each simulation. The time usage and selection process for the unfilled squares are dependent on input probability and probability distributions, as described in Chapter 6.1.7. The diagram only considers the events before wellboats start emptying the fish farm. In contrast, the entire process is illustrated for emergency escape.

For emergency slaughter, this process addresses the mobilization phase for acquiring wellboats. Since emergency slaughter regularly is imposed on the farmer, the discovery time is left out, thereby assuming the responsible preparedness personnel starts mobilizing immediately. The first event is contacting necessary actors to acquire help. Afterwards, the model selects if the vessel is idle, meaning it is either in operation or not. If idle, the vessel is assumed in port and either sails directly or fills the entire fuel tank before sailing to the emergency site. If not idle and abort ready, the fuel level determines if the vessel must sail to port to refuel or sail directly from the current position. If not abort ready, the vessel must finish the operation and possibly head back to port based on the fuel level.

For emergency escape, the discovery time is added, as this may contribute to a large part of the biomass loss. Afterwards, the contacting time is selected, followed by vessel vacancy. The probability of a vessel being vacant may depend on several factors. Such factors include weather conditions, distance, and if compatible vessels are in operation. For instance, a light diving vessel may be out of reach of an exposed farm and lack the required operational criterion in terms of wave height and damage extent. At this point, the model selects whether the farm must wait for a suitable vessel or not. Lastly, the fixing time is selected based on a probability distribution, as illustrated in Figure 9.

6.1 Input Data

Most of the input data used in the simulations is retrieved from separate Excel files containing matrices. However, certain input is inserted directly into the SimEvents software. By using the function *xlsread()*, the entire value matrices are retrieved. The matrix size is defined, followed by definitions of row number and column number of the required value. Such files are also retrieved in the same way in the MATLAB workspace. In SimEvents however, the function must be declared, which is done by using the *extrinsic* function. As mentioned, this model is constructed as a generic emergency response model for aquaculture. The Excel file is made with several sheets to differentiate between the types of emergency. The sheet to be run must be moved to the far left before saving and then running the model.

When all input data is defined the simulation model is ready to run. At the simulation start, the data is retrieved. Further, as the entities flow through the model, the input is used in the different system events. The input is used to perform the necessary calculations to replicate real-life situations. To develop a model capable of simulating real-life systems, the input data is obviously essential in order to achieve representable output. Figure 8 illustrates the connections between all the input data and calculations with the modeled system.

As illustrated, the input and calculations affect the different parts of the system. In the illustration, the system is divided into four parts. Before reaching the emergency site for the first time, the vessels go through the selection process illustrated in Figure 7. At this point, the type of emergency is predefined as either escape or slaughter. Another part is the port, or slaughter facility, which only wellboats use in the system. The sailing and fish farm applies for both types of emergency. However, the vessels in emergency escape sail, and enter the fish farm only ones. Matrices containing the input data can be found in Appendix D.

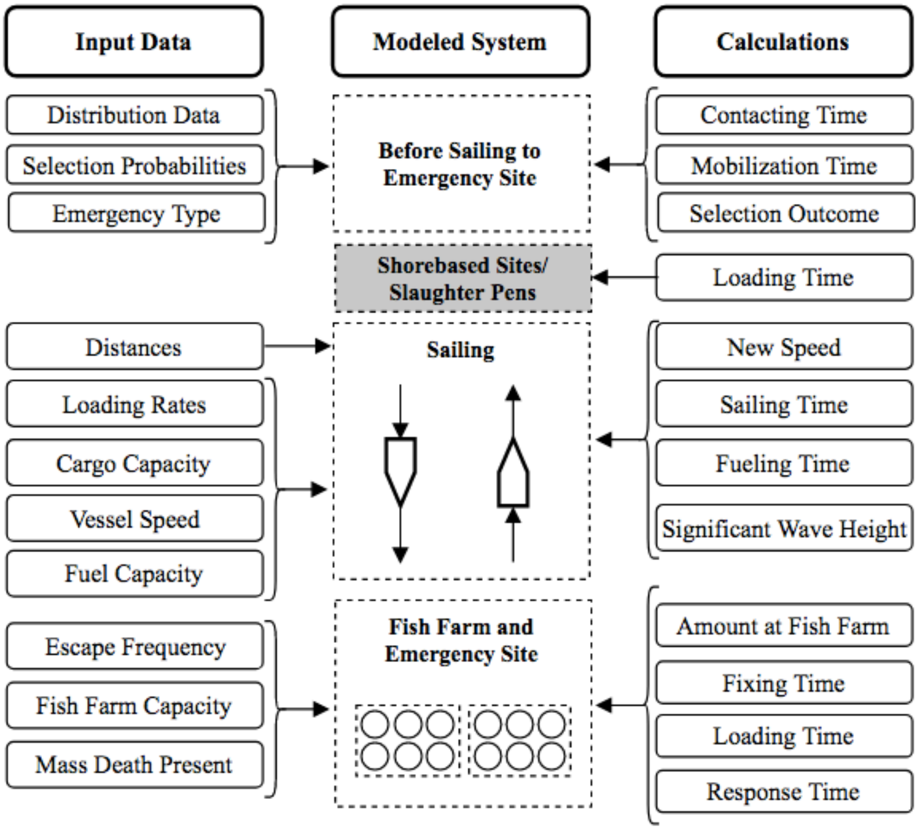

Figure 8: All input data and calculations performed in the simulation, and their correlation with the modeled system.

6.1.1 Emergency Type and Mass Death

At first, it is necessary to state if the emergency occurs due to escape or slaughter for the specific simulation. Similarly, it is required to declare if the emergency includes mass death of the biomass. This is simply done using integers, as shown in Table 1.

Table 1: Integer value in input data to declare emergency type, and if mass death is present.

Emergency Type	Mass Death Control	Integer Value
Emergency escape	Mass death present	1
Emergency slaughter	Mass death not present	2

6.1.2 Fleet Size

Secondly, the size of the fleet is determined. In this model, the maximum fleet size is set to four vessels. Only one vessel is used in escape situations. For emergency slaughter, it is possible to use more vessels, thereby simulating for different fleet compositions.

6.1.3 Vessel Speed

Only one speed mode is used for the simulations in this thesis. The vessels are set to service speed for emergency slaughter and maximum speed for emergency escape. This input can easily be changed, for instance if it is required to simulate on maximum speed for wellboats. The vessel speed is given in knots.

6.1.4 Cargo and Farm Capacity

Capacity is only given for emergency slaughter requiring wellboats. Most of the vessels in the database in Appendix B are given a capacity in cubic meters. In contrast, the capacity of fish farms is mostly given in tonnes. Tonnes are used in the simulation model, so for the vessels with a given value in cubic meters, a factor of 6.5 is used to convert to tonnes. The factor is found using the vessels with given values in both tonnes and cubic meters and then determining the mean value of several obtained factors. The fish farm capacities are found using Barentswatch (2017) and Fiskeridirektoratet (2017a).

6.1.5 Loading Rates

The loading and unloading rates are given in tonnes per hour. These rates differ depending on several factors in the real system, thus providing unnecessary complications to the simulation model. Both to simplify the simulations and due to limited information on the correct rates, only one constant value is used for loading rates. These parameters are only used for vessels required in emergency slaughter. The rates are determined by observing AIS-data for operational wellboats at MarineTraffic (2017). By dividing capacity with the approximate time spent at a fish farm for a specific vessel, a rough loading rate is determined. Table 2 presents the process of obtaining the loading rates.

Table 2: Determining loading rates based on AIS-data, and cargo capacity.

Vessel	Capacity [tonnes]	Average Time Observed [hrs]	Loading Rate [tonnes/hrs]
Ro Fjord	400	2.50	160
Havtrans	500	3.33	150

The time observed is an average of several stops made by the same vessel. When observing the AIS-data, no information is provided on which type of operation the wellboat is performing. However, the sailing pattern strongly indicates that the vessels are transporting slaughter ready salmon. Thereby, loading and unloading live cargo. To compensate for unknown factors, such as loaded amount per stop, the loading rates are adjusted to a more conservative value at 100 tonnes per hour.

6.1.6 Locations and Distances

In this simulation model, the locations of interest are given by latitude and longitude in the separate Excel File. However, due to the need of frequent circumnavigation along the Norwegian coast, the distances are found using GoogleMyMaps (2017) to better represent the real system. The routes are assumed by analyzing regular sailing patterns for similar vessels. The distances are inserted in kilometers in the separate Excel file.

6.1.7 Selection Probability and Probability Distribution Data

Stochastic variables are used to better represent the changing variables of events in the selection process. For escape situations, these include time of discovery, time to contact diving vessel, vessel vacancy, and time to fix the damage. As for the slaughter situations, varying parameters include time to contact slaughter vessel, if vessel is idle, abort ready, and sufficient fuel level. Table 3 presents the different events that require input probability or input to create probability distributions.

Table 3: Events requiring Input values for probability, or to create probability distribution.

Type of Emergency	Input Values	Event
Emergency escape	μ, σ	Time of discovery
		Time to contact light diving vessel
		Wait for vessel
	0-1	Time to fix damage
		Vessel vacant
Emergency slaughter	μ, σ	Time to contact wellboat
		Time to finish current operation
	0-1	Vessel idle
		Abort ready
		Sufficient fuel

For the parameters that either are true or false, a uniform distribution is used to determine the outcome combined with the input value between zero and one, which represent probability. The parameters that determine time usage vary depending on half normal distributions. Optimally, statistics should be used for each event, but due to missing information assumptions are made until the required statistics become available. Exact values used in this thesis are presented in Chapter 7.1. The half normal distribution is dependent on two values in MATLAB and SimEvents. These are μ and σ. Figure 9 illustrates an example of three half normal distributions.

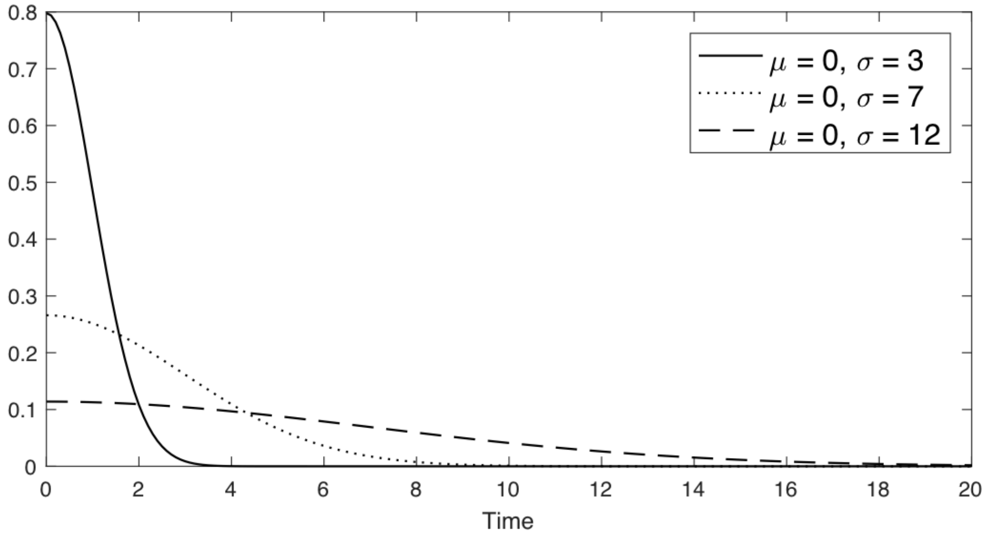

Figure 9: Three examples of half normal distributions with varying σ.

As σ increases, the curve becomes less steep, providing a broader range of possibilities for the time axis. As time increases, the probability declines, thereby leading to a higher probability of ending up in a time interval closer to zero when generating random numbers. For instance, when generating close to an infinite amount of random numbers for the dashed curve, the mean value is 5.58 while the maximum value is approximately 42 hours. The μ value determines the lowest possible time value. In this thesis, such curves are applied since time usage is undesired and based on the assumption that a high time value occurs less frequently. A drawback of using these distributions is that a limit is set for the highest possible value.

In MATLAB script, it is possible to generate random numbers directly and obtain new values each time. When using simulation in SimEvents, it is often desirable to obtain the same random value for every run. Therefore, when generating random numbers, the value is only random in the first run. To solve this problem, the described distributions are introduced to the simulation model. Further, a random number is retrieved from the distribution instead of generating random numbers directly in script.

Uniform distributions are applied to select between true or false in events with input probability between zero and one. The distributions also provide a random number between zero and one. These values are used in the selection process by assigning probabilities to the parameters in Table 3. An example of the selection process is illustrated in Table 4.

Table 4: Example of the selection process in one simulation using random numbers from uniform distributions and assigned probability.

Emergency	Parameter	Probability	Random value	Outcome
Emergency escape	Vessel vacant	0.70	0.34	True
Emergency slaughter	Vessel idle	0.30	0.65	False
	Abort ready	0.66	0.45	True
	Sufficient fuel	0.55	0.89	False

In this example, the vessel is vacant in the escape situation since the random value is in the probability interval. For slaughter, the vessel is not idle, is abort ready, but must fuel. Therefore, the model forces the wellboat to sail to port from current position to fuel, before heading toward the emergency site. The script for the entire selection process can be found in the sailing time server in Appendix A.

6.1.8 Metocean Data

The last stochastic value is retrieved from historical metocean data. In design and engineering, such data is frequently used in analysis, providing valuable information when evaluating durability, installations, and other operations. The data comprises statistical measurements on wind, wave height, and more. In this thesis, the significant wave height data is used as input in the simulation model. Due to the short sailing distances in aquaculture, only one set of data is used to provide variations in the output and to show how wave data may be applied in the simulation model. Due to confidentiality agreements for the used data, the values are randomized between zero and three in the attached wave data file.

6.1.9 Fuel Capacity

The fuel capacity is given in cubic meters and is only required for wellboats. Fuel capacity is seldom provided information in the shipyard's fleet catalogue. However, Sølvtrans (2017), the world's largest wellboat company provides fuel capacity values for several of their wellboats. The capacity is plotted versus length over all in Figure 10.

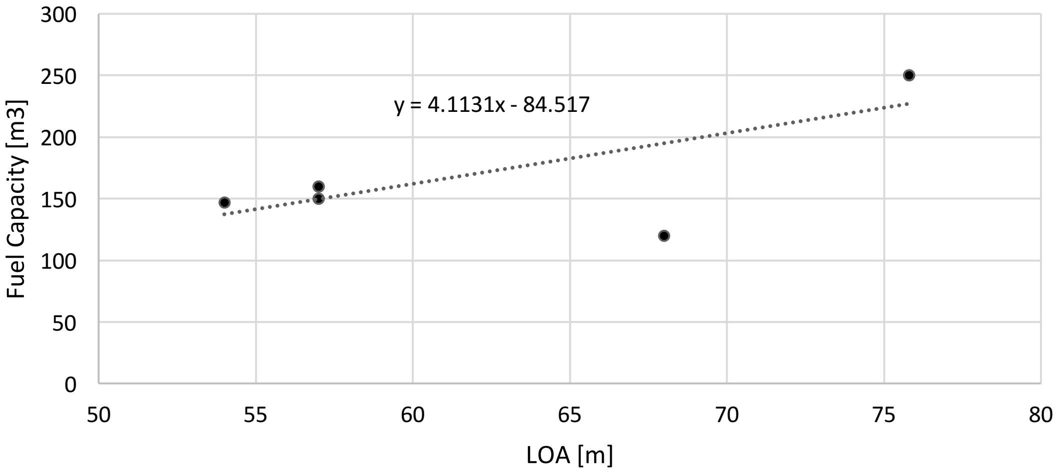

Figure 10: Fuel capacity versus length over all for known vessels and trend line formula to determine fuel capacity.

As illustrated, a linear trend line is added together with the coherent formula where y represents fuel capacity and x represents length over all. The formula is used to determine fuel capacity for vessels lacking such information.

6.2 Calculations in the Simulation Model

After initializing the simulation, as the entities flow through the model, certain calculations affecting the duration are performed. These are derived from vessel characteristics and other input data, such as sailing distances and farm capacity. This chapter provides descriptions of calculations throughout the simulations.

6.2.1 Loading Time

The loading and unloading rates are set as equal in this thesis. Light diving vessels are not given capacity or loading rates since no transport of biomass is necessary. Thus, only wellboats are given these parameters. The loading time is given by,

$$Loading\ Time = \frac{Capacity}{Loading\ Rate}$$

The capacity is fully utilized for every leg in the modelled system, while the loading rates are constant. The loading time is given in hours.

6.2.2 Distance Calculations

As mentioned, the distances are determined in advance of the simulation process to include circumnavigation. However, an option of using coordinates is added in the simulation model. By using this option, distances are calculated using the great circle arc to find distances in degrees. The functions *deg2nm* and *km2nm* are used to convert to nautical miles.

6.2.3 New Speed and Sailing Time

The vessel speed at sea suffers due to increased resistance in deteriorating weather conditions. This is implemented in the simulation model by adopting wave data. The wave data is from the previously described buoy owned by Marine Harvest. The data is retrieved by Sintef. In this thesis, significant wave height is used. The initial input speed is affected by a random value from the wave data for each sailing leg. In turn, this leads to an increased sailing time given by

$$Sailing\ Time = \frac{Distance}{Current\ Speed} * 1{,}02^{Hs}$$

As seen in the equation, the sailing time increases by an exponential factor as the significant wave height increases. Due to a short time span in each simulation, the vessel sails in the same conditions for each sailing leg. Generally, it is important to consider seasonal changes when using wave data. In this thesis data is used for the whole year, as emergencies may occur at all times and all possible wave heights must be considered.

6.2.4 Time Usage to First Arrival at Emergency Site

The time usage before the vessel reaches the emergency site for the first time varies due to several factors. Figure 7 and Table 3 illustrate the events that affect the response time. Depending on the outcome of the selection process, the vessels are forced to perform different operations before they can sail to the fish farm in emergency. Table 5 illustrates the calculations done in the model depending on which state the vessel is in at simulation start.

Table 5: Time usage of processes a vessel may go through before arriving at the emergency site for the first time.

Process	Calculation formula in simulation model
Sail to emergency from port	(Distance/Speed)*(1.02)^Hs
Sail to port from current position	((Distance*random number[0-1])/Speed)*(1.02)^Hs
Sail to emergency from current position	((Distance*random number[0.5-2])/Speed)*(1.02)^Hs
Fueling time	Fuel Capacity/150

When a vessel must sail to port from a current operational position, the initial distance between emergency site and farm is multiplied by a random number between zero and one. In other words, an operational area with a radius equal to the input distance is assumed. If a vessel must sail to the emergency from a current position, the initial input distance is multiplied by a random number between 0.5 and 2. Thereby assuming that it does not operate within a radius of half the input distance. However, it may be positioned as far away as twice the input distance. All possible distance outcomes are illustrated in Figure 11.

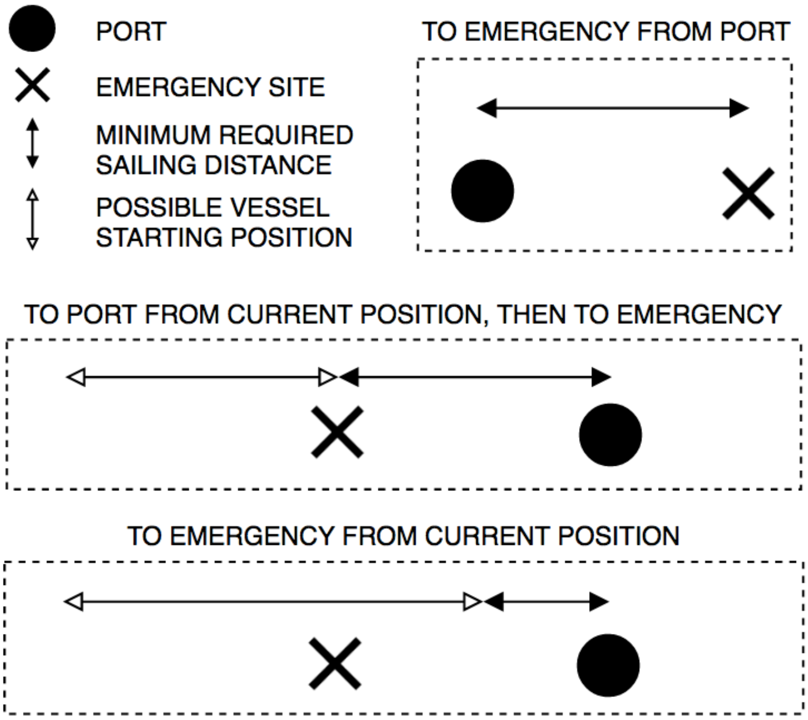

Figure 11: All possible sailing distances prior to the first arrival at the emergency site.

The upper scenario represents all outcomes for light diving vessels in escape situations and scenarios where a wellboat is idle. However, the wellboat may need refueling before it can sail to the emergency. The middle scenario represents outcomes where the wellboat is in operation and lacks sufficient fuel. Thereby, requiring vessels to sail to port to refuel before heading to the emergency. The bottom scenario represents outcomes where the vessel is in operation, but has sufficient fuel. It may need to finish the current operation if not abort ready. However, since the vessel has sufficient fuel, it sails directly to the emergency site.

6.3 Model Architecture and Flow

This chapter provides insight to the flow and architecture of the simulation model. The simulation model is constructed to keep the complexity to a minimum, while being able to provide representable output. Consequently, it has a customizable interface, thereby providing a broader range of applications than escape and slaughter situations. Figure 12 illustrates all events affecting the vessels in the simulation model. All coding within the different blocks can be found in Appendix A.

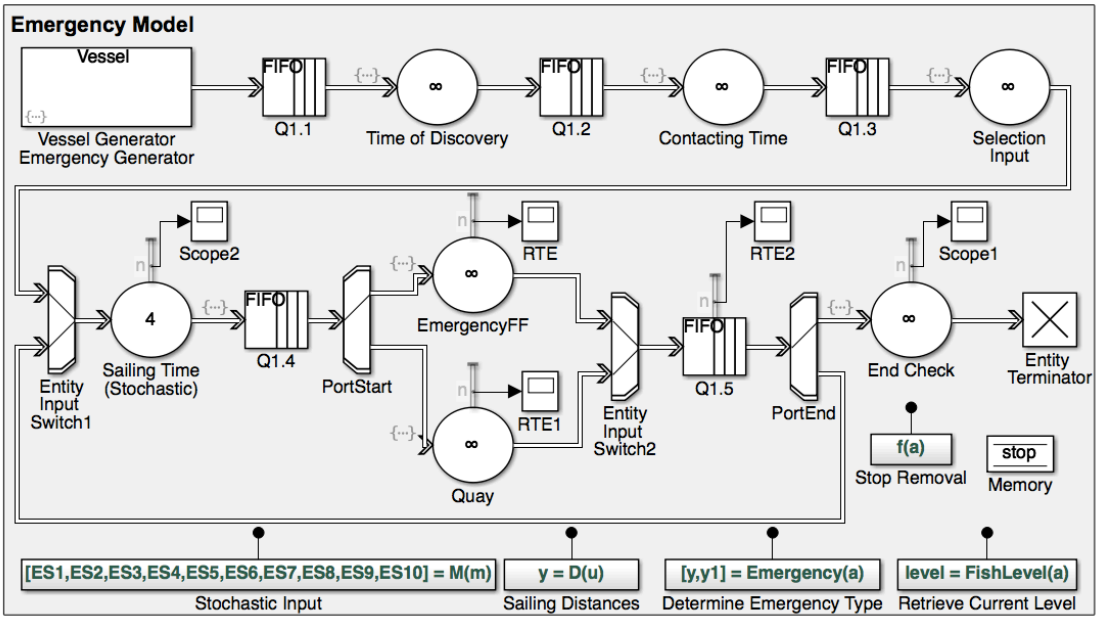

Figure 12: Architecture and entity flow of the main part of the simulation model developed in SimEvents.

The bottom blocks contain *Simulink Functions* which provide several possibilities, such as generating random numbers, creating global variables, and converting coordinates to distances. As previously mentioned, uniform distributions are made to further generate random values between zero and one. This is done in such blocks, to actually retrieve new values for each simulation run.

The initial block in the simulation model is the *Entity Generator*, which is responsible for generating the entities representing vessels. In this block, the required input is retrieved and assigned to the vessels. For instance speed, capacity, and loading rate. Attributes for the selection process are also generated in this block. This is to retrieve random numbers later in the model from the stochastic input block in the bottom left corner. After leaving the first block, the entities pass the first *Entity Queue*. The queues are only added to the model to control the flow of entities and to provide the possibility of spot checking the time an entity passes it.

The next block is the first *Entity Server*, which are blocks determining time usage in the simulations. The first and second server retrieves a random number based on half normal distributions in the stochastic input block. These values determine how much time the entities spend inside the blocks. In the selection input server, random values are also retrieved from the bottom left block. However, in this case they are assigned to the entities created at the starting block. This action could be performed in the sailing block, but since the entities only passes the selection input block once, the simulation time is decreased considerably for slaughter cases.

Next is the sailing block, which arguably holds the most important function in the simulation model. Based on the input probabilities and random numbers assigned in the prior server, the selection process is performed to determine the sailing time prior to the first arrival at the emergency site. This server also includes time to finish current operation and refueling time. Additionally, the wave data is retrieved in this server along with sailing distances and speed to determine sailing time. As illustrated, the maximum allowed number of entities is four.

Following, the entities are forced to follow the upper path in the *Entity Output Switch*, therefore entering the server representing the emergency fish farm. For escape situations, the vessel retrieves a random number from a half normal distribution representing the fixing time. For emergency slaughter, the vessel fully loads its maximum cargo capacity. This server logs all arrivals in the connected scope, but most importantly it logs the first arrival. If emergency escape, the simulation is finished and the entities pass the end check server and is removed in the *Entity Terminator*. If emergency slaughter, the wellboat entities enter the sailing time server, now calculating the sailing time from emergency to port. Following, the entities enter the quay server which simulates unloading at port. This process is repetitive until the emergency fish farm is emptied. Figure 13 illustrates the model architecture of the emergency fish farm.

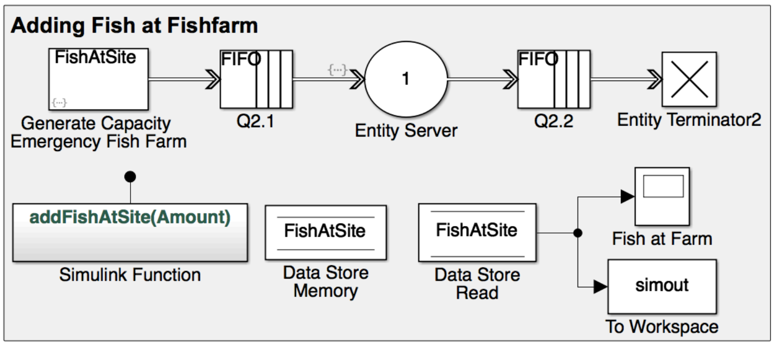

Figure 13: Architecture of the part representing the fish farm in the simulation model developed in SimEvents.

This illustrated process generates the input fish farm capacity at simulation start. In the bottom left *Simulink Function*, a *Global Variable* is generated representing the amount of fish at the farm. The scope plots time versus amount at farm for each time unit during the simulation, while the *To Workspace* block saves the plotted values in MATLAB for later use. Figure 14 illustrates the process enabling modifications to the total amount of fish at the farm during simulation.

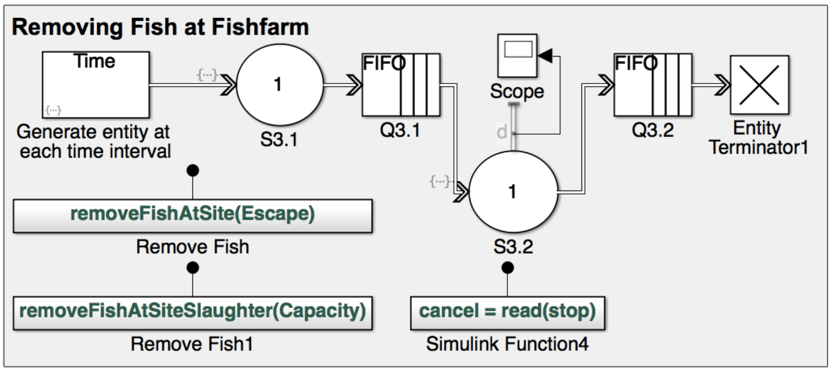

Figure 14: Architecture of the part removing biomass from the fish farm in the simulation model developed in SimEvents.

The upper left block generates one entity for each time unit if emergency escape is simulated or mass death is added in the input data. The two servers control the entity flow by only letting the entities through if one of the mentioned scenarios are fulfilled. The frequency of the removal is determined in the two *Simulink Functions*, by subtracting the input frequency from the global variable at each time unit (one hour). For instance, if the input frequency is set to five, a total of five tonnes is subtracted from the fish farm every hour until it is empty or the damage is fixed. The bottom left block is also connected to the emergency fish farm server in Figure 12. Each time a wellboat is in the fish farm server, an amount equal to its capacity is removed from the global variable.

The simulations are run from a separate MATLAB script. The wanted number of runs are defined in the script. The necessary output data is logged by creating a string for the sequence. By saving the data as arrays in MATLAB from the scopes, the script logges the required values for each run. When simulation is finished, all values are logged as a vector in MATLAB workspace. After each run, the vector is manually saved for later use. An example script of how to run one of the case study simulations from MATLAB script can be found in the bottom of Appendix A. Descriptions of all code for each block is also found included in Appendix A.

7. Case Study

This chapter provides a case study to demonstrate the application of the simulation model. Additionally, its diversity is displayed by applying it to various possible real-life events. Some of the applied input remain unchanged through the study while some selected input parameters are adjusted through the procedure. Applied input data for two of the scenarios is presented in Appendix D.

7.1 Input Data Used in Case Study

For all simulations, some of the input is constant, such as locations, thereby distances. The geographical locations used in the case study are presented in Figure 15. The map is created in My Maps, which is a service provided by Google, enabling the user to develop custom maps.

Figure 15: Map showing all locations and sailing routes used in the case study (GoogleMyMaps, 2017).

The two upper markers represent the fish farms used in the case study, while the other two represent what is referred to as ports. The grey lines represent the sailing pattern in emergency escape, while the white lines are used in emergency slaughter. Ocean Farm 1 is placed at the locality, Håbranden. This is the approved location for the farm. Ørnøya represents the sheltered location in the case study. Both farms and the slaughter facility is owned by Salmar, thereby providing a more realistic case (Eide, 2016). Abyss (2017) is a Kristiansund based company providing various services to the the aquaculture industry. They drift several diving vessels and provide around the clock preparedness in suspicion of for instance escape. Table 6, presents the distance input in the case study.

Table 6: Input distances used in the case study.

Port	Fish Farm	Distance
Slaughter Facility	Ørnøya	8.4 km
Slaughter Facility	Ocean Farm 1	44.2 km
Abyss	Ørnøya	52.0 km
Abyss	Ocean Farm 1	74.5 km

When sailing from Abyss, the emergency type is of escape. For each emergency type, a further distance is intentionally chosen for the exposed fish farm. All scenarios in the case study are based on these distances. The fleet utilized in slaughter situations is presented in Table 7.

Table 7: Fleet used in the case study for emergency slaughter and assigned input parameters (Rostein, 2017).

Vessel Number	Vessel Name	Service Speed [knots]	Cargo Capacity [tonne]	Loading Rates [tonne/hrs]	Fuel Oil [m3]
1	Ro Chief	12	180	100	140
2	Ro Fjord	11	400	100	210
3	Robas	10	130	100	105
4	Ro Fjell	11	700	100	275

The four vessels are used for emergency slaughter in the case study. The input is partly determined by evaluating certain regularities, such as fuel oil and converting cargo capacity from cubic meters to tonnes, as previously described in Chapter 6.1.4. All vessels are built by Rostein, a Norwegian shipyard.

7.1.1 Case 1: Response Time First Arrival for Several Probability Scenarios

In the first case, response time is evaluated for the sheltered and exposed farm for emergency slaughter. The case study considers response time for first arrival at the emergency site for different probability scenarios of obtaining a wellboat. The scenarios and probabilities are presented in Table 8.

Table 8: Four probability scenarios of obtaining wellboat in emergency slaughter for sheltered and exposed.

Event	**Prob. Scenario 1 (Sheltered)**	**Prob. Scenario 2 (Exposed)**	**Prob. Scenario 3 (Exposed)**	**Prob. Scenario 4 (Exposed)**
Vessel idle	0.20	0.20	0.70	1.0
Abort ready	0.50	0.50	0.70	1.0
Sufficient fuel	0.75	0.75	0.70	1.0

The first scenario is performed for the sheltered fish farm with low probability of a vessel being idle. Following, the same scenario is simulated for the exposed farm. In the third scenario, the probability of the wellboat being idle, and abort ready is increased. The probability of sufficient fuel is decreased slightly. Lastly, simulations are done for a wellboat on standby, thus always ready to sail to the emergency when contacted. For all scenarios, some of the input data is constant, as illustrated in Table 9.

Table 9: Constant input for case 1 in the case study with assigned σ and μ values for probability distributions.

Vessel Speed [knots]	**Fuel Oil [m3]**	**Contact Time μ**	**Contact Time σ**	**Finish Op. μ**	**Finish Op. σ**
12	140	0	2	1	3

The speed and fuel capacity are the only required input parameters for the vessel in the first case. With the presented input parameters for contacting time, the maximum and mean value for ten thousand runs in MATLAB is approximately 7.5 hours and 1.5 hours, respectively. For time to finish current operation, the maximum and mean is approximately 13.3 hours and 3.4 hours, respectively.

7.1.2 Case 2: Response First Arrival with Varying Probabilities and Discovery Time for Emergency Escape

For the second case, response time is simulated for the sheltered and exposed farm for emergency escape. The case study considers response time including both fixing time and the time to discover the damage. Two scenarios are simulated with varying input data, as presented in Table 10.

Table 10: Two scenarios with varying input data for emergency escape in sheltered and exposed locations.

Event	Scenario 1 (Sheltered)	Scenario 2 (Exposed)
Vessel vacant	0.50	1.00
Discovery σ	12	9

For the first scenario, the sheltered fish farm is considered with a 0.5 probability that a vessel is vacant. If not, the emergency site must wait for a vessel to be available. The discovery time in the first scenario ranges from zero to approximately 51 hours with a mean value of 9.5 hours. For the exposed scenario, the input value for the discovery distribution is reduced. This leads to a decreased range of zero to 42 hours with a mean value of 7 hours. The vessel is also on standby in the exposed scenario, thereby eliminating waiting time. The constant input for the emergency escape case is presented in Table 11.

Table 11: Constant input for the second case, with assigned σ and μ values for probability distributions.

Speed [knots]	Escape Frequency	Contact Time μ	Contact Time σ	Waiting μ	Waiting σ	Fixing μ	Fixing σ
35	1	0	3	1	3	0	4

The vessel speed is set at a high value for all scenarios. This can easily be changed if the desired varying variable in simulation is speed. For the three scenarios, the frequency of escape is set at one tonne of fish per hour. The escaped amount is not considered in this case study due to lacking information on statistics for escape frequencies.

7.1.3 Case 3: Necessary Fleet Composition for Emergency Slaughter of Varying Amount at Fish Farm in 5 days

The third case looks into how different fleet compositions perform in emergency slaughter. The applied fleet can be found in Table 7, while the probability of obtaining a wellboat is the same as scenario 1 in Table 8. The five scenarios simulated in case 3 is presented in Table 12.

Table 12: Five scenarios with varying fleet composition, amount to slaughter, and fish farm server capacity.

Event	Scenario 1 (Sheltered)	Scenario 2 (Sheltered)	Scenario 3 (Exposed)	Scenario 4 (Exposed)	Scenario 5 (Exposed)
Fish amount [tonnes]	780	5000	6240	6240	6240
Vessels used	1	1, 3	1, 3	1, 2, 3	4
Server capacity	1	2	1	1	1

The first scenario represents emergency slaughter of one full cage at the sheltered farm. Secondly, the slaughter amount is increased at the same fish farm. Also, the fish farm server capacity is increased, so that the two vessels can load fish simultaneously. In the three last scenarios, the exposed farm must slaughter its maximum capacity of 6240 tonnes. For the exposed farm, the two vessels used in scenario 2 are tested first. Following, one more vessel is added. Finally, the largest wellboat with 700 tonne capacity is simulated. The total available capacity in the two last scenarios differ by only ten tonnes. Only one wellboat is allowed to load at a time in the scenarios simulating emergency at the exposed farm.

7.2 Results from the Case Study

This chapter presents the results from the three cases in the case study. For each scenario in the two first cases, three hundred simulation runs are performed. In the third case, only one simulation run is performed for each scenario.

For the two first cases, the Cumulative Distribution Function (CDF) obtained by the response times is presented for all scenarios. Additionally, a normalized histogram is presented for the scenarios. For the final case, a graph is presented showing the amount at the fish farm over time for all five scenarios. Lastly, the utilization at the fish farm is considered for the last two scenarios in the third case.

The CDF illustrates the cumulative probability of retrieving the response time values along the horizontal axis. This is for instance used to determine the 0.9 probability of responding faster than a certain time value.

The normalized histograms show the density of the response times obtained in a given time range. This is illustrated by columns typically covering a range of one hour. The tallest column represents the time interval the response time will most likely be in compared to all other intervals of one hour. The utilization graph illustrates how efficiently the fish farm is used over time. If the plotted graph reaches a value of 1.0, a wellboat is always loading salmon.

7.2.1 Case 1: Response Time First Arrival for Varying Selection Probabilities

Scenario 1 considers emergency at the sheltered farm with a relatively low probability of a vessel being idle. This scenario is set as a base scenario to compare with the exposed farm. The probabilities of this scenario are assumed close to real-life operational values. The results from the three hundred simulation runs are presented in Figure 16. The CDF shows a 0.9 probability of responding faster than 7 hours. The density plot shows that most response times are in the range of 1 to 5 hours. The CDF plot shows a 0.6 probability of responding in this range.

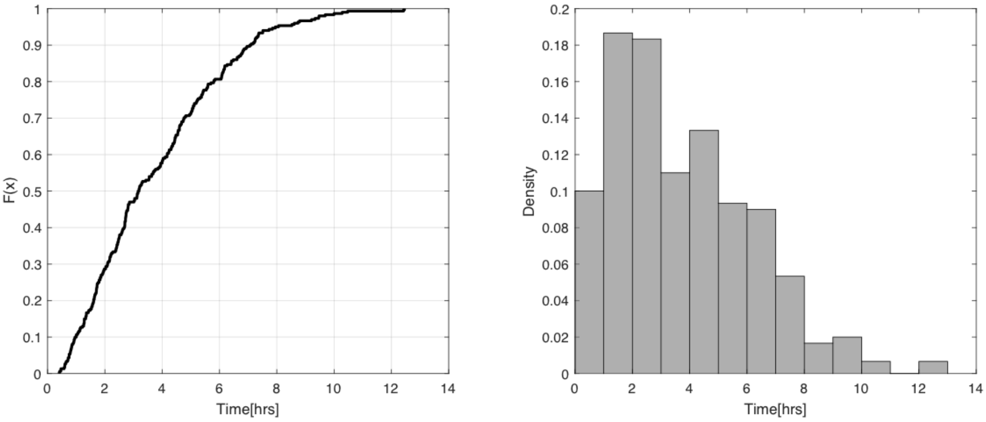

Figure 16: CDF plot and density plot for response times from probabiliy scenario 1, emergency slaughter.

Scenario 2 considers emergency response time for the exposed emergency farm. In this simulation, the probabilities are identical to the first scenario. The simulation results are presented in Figure 17. The CDF shows a 0.9 probability of being below 10 hours. The density plot shows that most response times are in the range of 3 to 7 hours. By studying the CDF, it is apparent that there is around a 0.6 probability of responding in this range. The maximum and minimum response times are approximately 15 hours and just under 2 hours. As expected, the CDF is almost identical to scenario 1, but has shifted to the right along the horizontal axis.

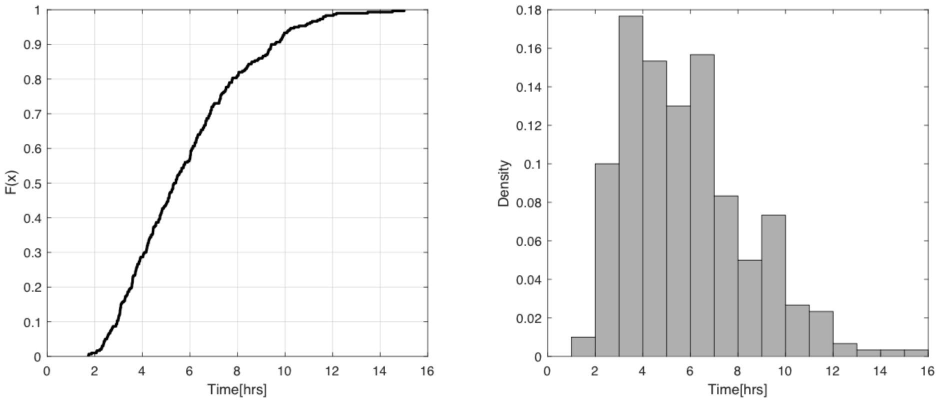

Figure 17: CDF plot and density plot for response times from probabiliy scenario 2, emergency slaughter.

The third scenario considers response time for the exposed farm with an increased probability of a vessel being idle and abort ready. The probability of having sufficient fuel is slightly decreased. The simulation results are presented in Figure 18. With increased probability of obtaining a vessel, the CDF shows a 0.9 probability of responding in 7 hours or faster. Compared to the second scenario, this is an improvement of 3 hours in the same probability range. The density plot shows a more compact result compared to the previous scenarios. Although the minimum and maximum response times are close to the previous scenario, there is now a 0.8 probability of responding in the interval 2 to 6 hours.

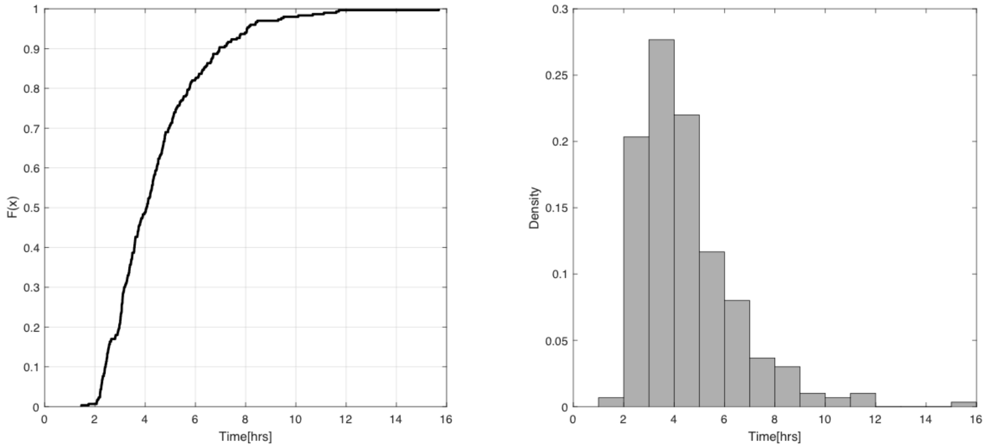

Figure 18: CDF plot and density plot for response times from probabiliy scenario 3, emergency slaughter.

In the final scenario presented in Figure 19, all probabilities are set to 1.0, meaning the wellboat is on standby at the port with sufficient fuel. By studying the maximum values in both plots, it is apparent that the exceedingly high response times are eliminated. The minimum response is two hours because of the distance to the emergency site. Therefore, the major part of the response times is within the range of 2 to 4 hours. With a standby vessel, the CDF and density plot shows a 0.9 probability of responding in the range from 2 to 5.5 hours based on the presented input data in Chapter 7.1.1.

The mean response time for each scenario in emergency slaughter is presented in Table 13. To reach the same mean value as for the sheltered scenario, the wellboat is required on standby.

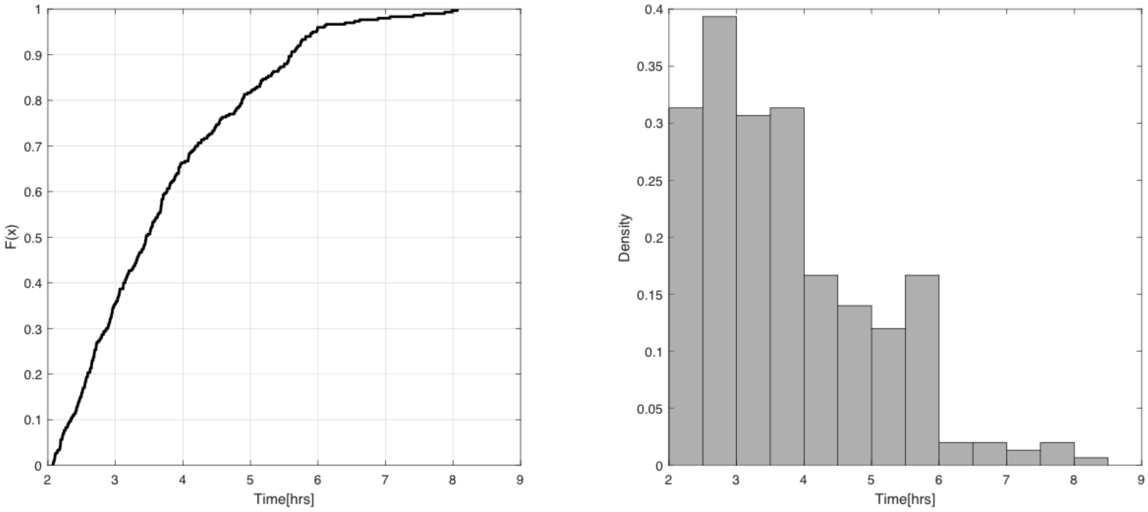

Figure 19: CDF plot and density plot for response times from probabiliy scenario 4, emergency slaughter.

Table 13: Mean response time for all probability scenarios in case 1.

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
Mean Response Time [hrs]	3.75	5.81	4.44	3.74

7.2.2 Case 2: Varying Probability and Discovery Input in Emergency Escape

The first scenario in the second case considers emergency at the sheltered farm, with a probability of 0.5 to avoid waiting for a vacant vessel. As seen in the plots in Figure 20, there is now a much larger range of response times compared to emergency slaughter. This is due to the added values of discovery time, fixing time, and waiting time. The CDF shows a 0.9 probability of responding in 25 hours or less, while the maximum response time is close to 40 hours. The histogram shows a high density of response times between 9 to 17.5 hours. From the CDF, there is approximately a 0.5 probability of responding in this range. The high values are mostly cause by the high σ presented in the input data.

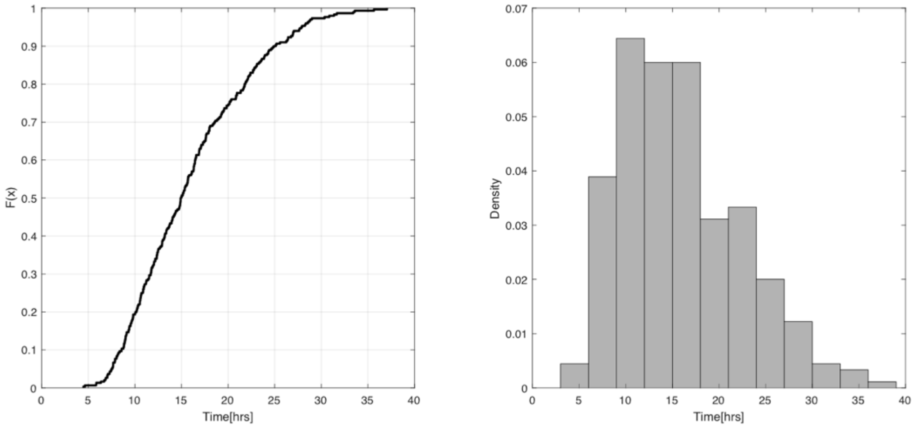

Figure 20: CDF plot and density plot for response times from probabiliy scenario 1, emergency escape.

Figure 21 illustrates the sorted values of three hundred runs, considering discovery time versus total response time including fixing time. The filled area represents discovery time, while all area under the light grey line represents the total time. The plot clearly shows that the discovery time stands for a large part of the response time. For the first scenario, the discovery time covers about 51 percent of the total time used.

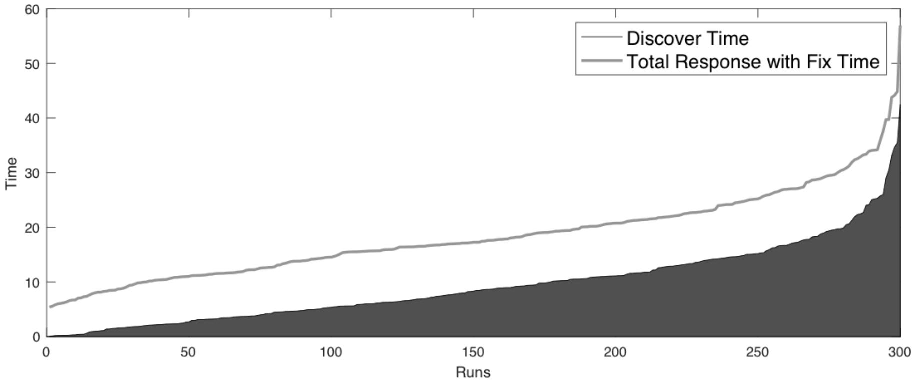

Figure 21: Area of discovery time for three hundred runs versus area of total response time.

In the second scenario, the σ value is decreased, assuming an exposed farm has better inspection procedures. Figure 22 presents the results from the second scenario. The probability of a vacant diving vessel is increased to 1.0, meaning the vessel is on standby. The CDF shows a 0.9 probability of responding in 25 hours or less. To achieve similar results as for the sheltered scenario, the time to discover the damage must decrease by a mean value of 2.5 hours, while a vessel must always be vacant.

Table 14 presents the mean response times for the two scenarios in case 2. The mean response times show that it is possible to achieve similar results for the exposed farm by having a diving vessel on standby and decreasing probability of obtaining a high discovery time.

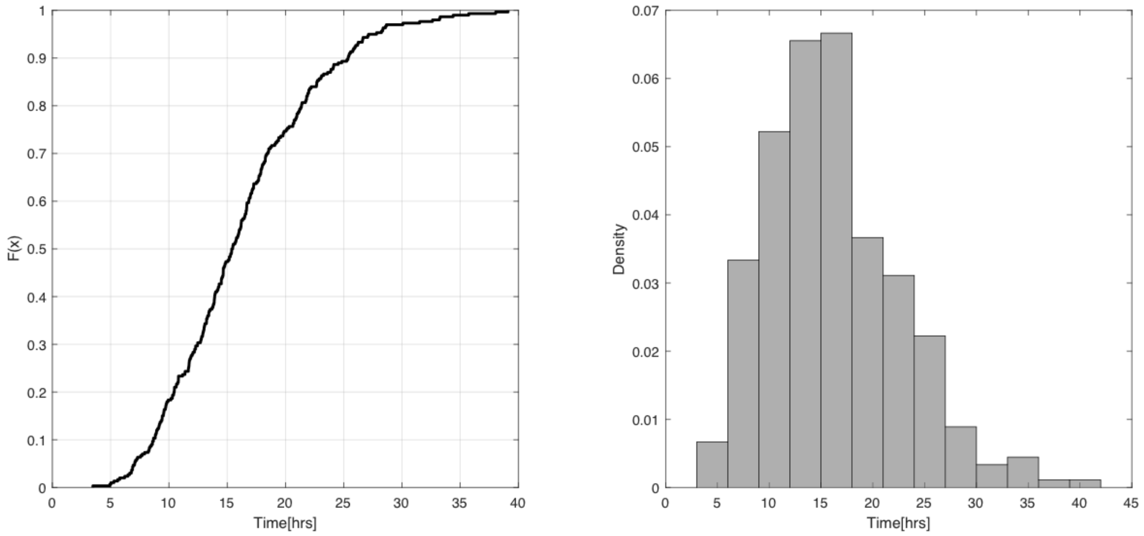

Figure 22: CDF plot and density plot for response times from probabiliy scenario 2, emergency escape.

Table 14: Mean response time for the two scenarios in case 2, emergency escape.

	Scenario 1	Scenario 2
Mean Response Time [hrs]	15.9	16.2

7.2.3 Case 3: Necessary Fleet Composition for Emergency Slaughter of Varying Amount at Fish Farm in 5 days

The third case studies the possibility of imposed slaughter of large amounts of stock in a short time span. A fleet of four vessels is available to solve the emergency. The case starts by simulating an emergency for one sheltered cage, followed by a more extensive emergency of slaughtering 5000 at the sheltered site. Lastly, three fleet compositions are simulated to empty the exposed farm when fully capacitated. Since the construction of the exposed farm consists of only one large cage, only one vessel is allowed to load salmon in this case study. The amount of fish over time until the farm is emptied is presented for all scenarios in Figure 23.

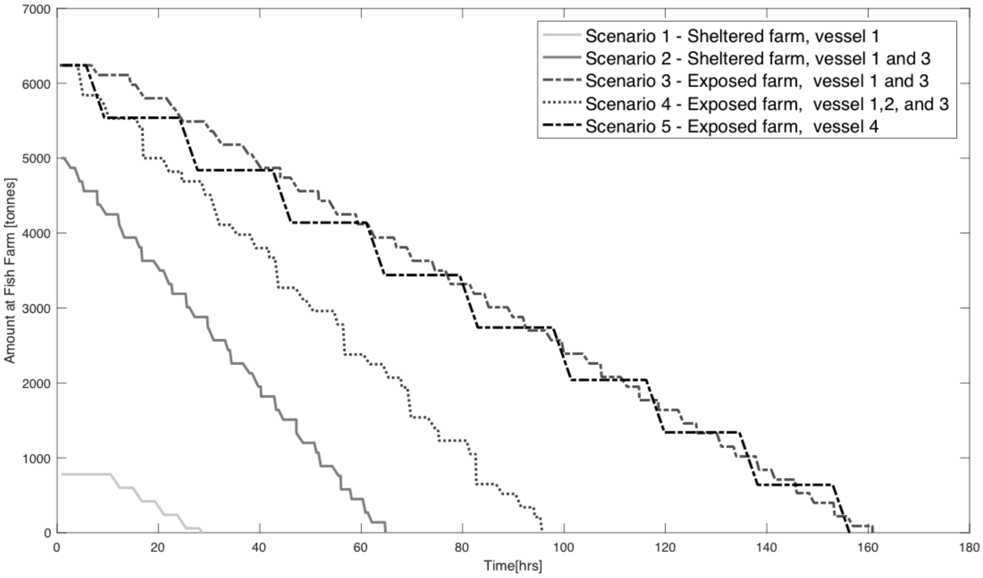

Figure 23: Time to empty fish farm for five scenarios with varying amount to slaughter and fleet composition.

In the first scenario, the one cage at the fish farm is emptied approximately 30 hours after the emergency occurred. When the amount required to slaughter increases and a second vessel is added to the fleet, the farm is emptied in just over 60 hours after occurrence. When moving to the exposed farm, the exact same fleet is unable to load the entire stock in 120 hours, failing by just over 40 hours. When adding a third wellboat, the fleet succeeds to empty the affected exposed farm. When the fleet of three vessels is replaced by a single vessel with similar cargo capacity, the performance recedes drastically. As seen in the plot, the one vessel is barely capable of performing better that the fleet of two vessels in the third scenario. This is much due to a low utilization at the fish farm, as presented in Figure 24.

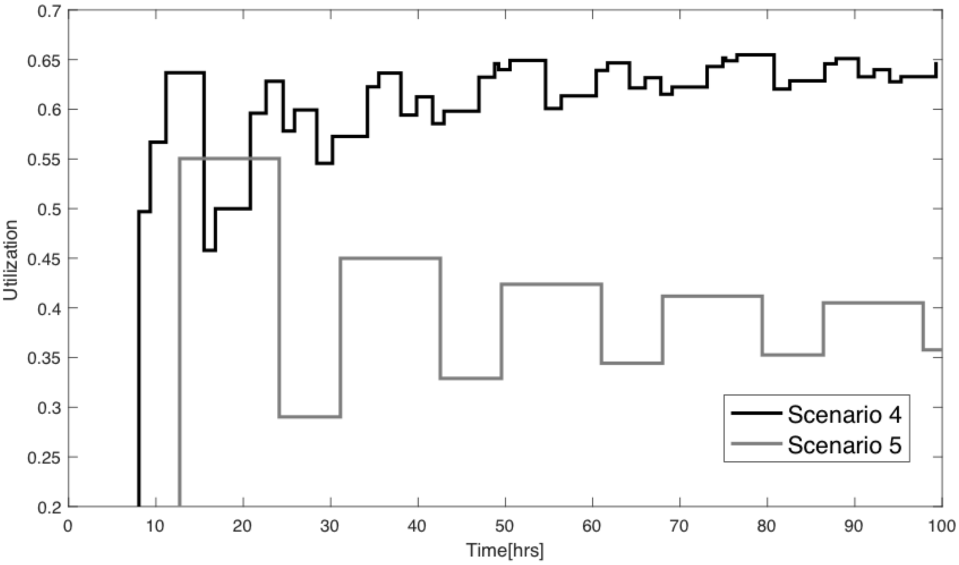

Figure 24 Utilization over one hundred hours at the exposed fish farm for a fleet of three vessels and one vessel.

As previously described, the two scenarios simulated holds similar available capacity. Nevertheless, the single vessel performs much worse than the fleet, even though the performance of the fleet suffers due to the restriction of simultaneous loading at the farm. The graphs clearly illustrate that a major contribution to the contrast in performance is due to utilization at the fish farm. The single vessel has better performance at the start of the simulation at 0.55 utilization. This is because the three vessels in scenario already finished loading once, and are thereby transferring cargo when the larger vessel arrives. Over time, the utilization when using one large vessel oscillates toward under 0.4, while the fleet ends up with 0.65 utilization. Figure 23 shows that the difference in utilization contributes to a deviation in performance of approximately 60 hours.

8. Discussion

Throughout the thesis, a simulation model is developed and applied in a case study. The results from the case study shows that the model can present various output for different cases of emergency. However, the simulation model has some drawbacks, as well as the input data, which is the basis for providing representable results. Therefore, this chapter discusses some major drawbacks affecting the validity of the simulation model and input data. Further, the provided output is evaluated, followed by some interesting connections between findings in literature and simulation results. Lastly, an assessment is presented, considering the previously presented research questions.

The simulation model is developed with some major simplifications, both due to lack of sufficient input data and because of the underlying purpose of the model. The purpose in this thesis is only to use the model as a tool in the investigations of emergency preparedness and response. For instance, the model is constructed without a logistical model simulating the normal operation before emergency occurs. Instead, the model starts by defining an operational state of the vessels based on input probability and random values from probability distributions. This may affect the credibility of the vessel starting point in emergency poorly. However, such a logistical model would demand highly advanced modeling and accurate input to provide representable output.

Moreover, the simulation model can only be run for one emergency site at a time, thereby eliminating emergencies at several fish farms. Also, weather conditions do not affect operations performed by the vessels, such as loading and net fixing. In certain real-life situations, the weather may impose the vessels to wait for a weather window. Furthermore, capacity at the slaughter facility is assumed infinite, thereby eliminating the fact that it may be the bottleneck in certain emergency slaughter cases. After first arrival at the emergency site, infinite fuel is assumed for emergency slaughter. Additionally, the vessels sail in the same wave height during each sailing leg and is based on the same metocean data for sheltered and exposed emergency. These simplifications are done due to the short time span and short sailing distances in each simulation. However, by using separate wave conditions for sheltered and exposed emergency, larger differences in response time would likely occur, thereby providing a conservative approach in this thesis.

As for the input data, major assumptions are made due to lack of scientific information and statistical data. The entire mobilization and selection phase is based on assumptions drawn from research and knowledge. In addition to the input data used upon first arrival, input values to develop a probability distribution for fixing time are also drawn from such assumptions. Moreover, only three hundred simulation runs are done for each scenario, which may lead to output not representing all possible outcomes.

It is also necessary to comment on the simulations done for the third case. Since only one simulation is performed for each scenario, unwanted deviations may occur due to the stochastic variables in the mobilization phase and significant wave height. However, the presented scenarios in this thesis contain a low level of deviation due to relatively short sailing distances, and similar time usage in the mobilization phase.

All the stated simplifications and assumptions affect the validity of the resulting output. However, since this thesis focuses on the comparison of exposed and sheltered emergency, the validity may suffer less than expected. The same preconditions apply to both cases when uncertainty is present and simplifications are made. Therefore, in most cases, the results are conservative when looking at the contrast in response times for sheltered and exposed emergency. For instance, the exposed time usage would increase by adding wave data in operation.

Even though the simulation model contains the mentioned drawbacks, the case study clearly shows high adaptability and diversity. The three cases of emergency performed in the case study indicates that the model is generic and can provide output for different system states and emergency types. However, since the model is constructed so that new random numbers is obtained for each simulation run, it is not possible to end up with the same results. In some cases, this might cause problems if reproducibility is desired to compare changes in input for similar conditions in the system.

With the assumptions and simplifications in mind, the results provide useful information when considering the research questions presented in Chapter 3. One of these questions asks which adjustments are needed to achieve similar response times for exposed as for sheltered emergency. Another question asks if it is necessary to implement standby vessels in exposed emergency.

In the first case of emergency, four probability scenarios of obtaining a vessel are simulated for emergency slaughter. When looking at the first and third scenario, the probability of a vessel being idle and abort ready is increased by 0.5 and 0.2, respectively. The probability of having sufficient fuel is decreased by 0.05. The results for both scenarios show a 0.9 probability of responding in 7 hours or less. However, the mean response time is 0.69 hours longer for the exposed farm in the third scenario. To obtain similar mean response times for the exposed farm, the wellboat must be on standby. For emergency escape, the second case presents the results for two scenarios with changing probability of vacancy and input value for discovery time. By increasing the probability of a vessel being vacant from 0.5 for sheltered escape to 1.0 for exposed escape and decreasing discovery time, both scenarios show a 0.9 probability of responding in 25 hours or less. Also, the mean response time only differs by 0.3 hours for the two scenarios.

In other words, based on the input data used in the case study, it is highly possible to achieve similar response times for exposed salmon farming. This may be done by increasing the availability of required vessels and by improving procedures to discover if escape is present. Improving other events in the mobilization phase, such as contacting time would also provide faster response. When considering the regulatory preparedness plans and major difference in layout for the two reviewed plans described in Chapter 4.1.1, such improvements may be achievable for several fish farms along the Norwegian coast. For instance, by providing more standardized templates for such plans, including clear definitions of when to declare an emergency, thereby achieving faster decision times. However, for both emergency types, it is necessary to implement standby vessels in order to achieve the same mean response time.

This leads us to the third research question, which asks if the cost of adequate preparedness is too large. If defining adequate preparedness as achieving the same mean response time, standby vessels are required. However, in the conference held by TEKMAR in 2009 described in Chapter 4.1.1, the participants found that the cost would be excessive. They also discuss the possibility of shared recourses at the conference. If one considers the results of the exposed farm from the third case in the case study, the utilization at the fish farm is better when using a fleet of three vessels compared to one large vessel with similar capacity. Also, Hauvik (2015) describes that several relatively new vessels are in danger of being phased out due to new regulations. These vessels will typically be of smaller capacity than what is expected in newer vessels, as seen in the wellboat trend in the same chapter. Therefore, possibilities may open to implement the vessels that will be phased out as shared resources, thereby implementing standby wellboats as shared resources, likely with a lower cost than previously.

The fourth research question asks what clear problems are in current procedures when considering emergency preparedness. For emergency escape, the second case in the case study shows that 51 percent of the time used in response is due to discovery time based on the input data. In the real world, these are likely escapes with small net holes, which are hard to detect. More frequent inspections may be a possible solution to this problem. Moreover, Chapter 4.1.1 presents an increased focus on escape in the last decade, resulting in a significant reduction in loss of biomass. The reduction was mostly caused by incentives connected to ecological threats. Also, it is stated that a fish farm with ILA disease is required slaughtered within 80 days, which may be defined as a long time to solve an emergency. In certain cases, the salmon farmer may use this time window to wait with slaughter in order to grow the salmon. In other words, stronger incentives may be beneficial for emergency slaughter, as is proven for escape. For instance, by decreasing the time window from 80 days. Moreover, the difference in layout of preparedness plans may indicate a low level of standardization.

The final research question asks if a satisfactory amount of scientific research is found regarding emergency preparedness and response for aquaculture. Due to the large focus in previous years, a significant part of the research naturally addresses emergency escape. On the other hand, it is arguable that research considering emergency slaughter is scarce. Even though it is thoroughly addressed in the conference held by TEKMAR, it is important to consider that the conference was held almost ten years ago.

With the aquaculture industry entering a new era, it may be crucial to increase the focus on emergency preparedness and response before disaster strikes. In Chapter 4.1.2, two studies are reviewed, which look at weaknesses and failures in preparedness and response after The Deepwater Horizon and Hurricane Sandy. In the reviews, the authors emphasize the importance of communication, planning, developing protocols, securing situational awareness, and ensuring capacities. Emergencies are inevitable, and it is therefore imperative to learn from situations such as these, also for the aquaculture industry.

9. Conclusions and Recommendations

Norwegian aquaculture is increasing both in terms of production and size. Consequently, focus increases on research and technological improvements. Due to lack of sheltered areas to perform salmon farming, the industry is entering a new era of offshore salmon farming in exposed areas. One should therefore prepare for new and unknown challenges. Hence, this thesis investigates emergency preparedness and response in aquaculture.

The generic discrete-event simulation developed in this thesis, is applied in a case study containing three cases of emergency. Although major assumptions and simplifications are made for both the simulation model and input data, it is found that the resulting output is representable when comparing sheltered and exposed emergency.

In the problem description of this thesis, the following research questions were presented.

- Which adjustments are needed to achieve the same response times for exposed farming as for sheltered salmon farming?
- Is it necessary to consider implementing standby vessels for emergency response?
- Is the cost of adequate preparedness too large?
- What are clear problems in the current procedures of emergency preparedness?
- Is there a satisfactory amount of available research on the subject?

The case study results show that it is possible to achieve similar response times for exposed salmon farming, by improving vessel availability and decreasing discovery time in emergency escape. To achieve the same mean response time, standby vessels are required for the given case study and input data. Also, even though larger vessels are expected these days, a fleet of smaller vessels with similar total capacity may perform better in emergency slaughter. However, the cost of standby vessels has been excessive in the past. If possible, phased out wellboats should be considered for use as standby vessels in emergency, preferably as shared resources to decrease cost.

Clear problems in current procedures include low levels of standardization and too few incentives to improve preparedness and response times. It is therefore recommended that a higher level of standardization is implemented, followed by stronger incentives to improve response times by ensuring capacities, developing protocols, and improving planning and communication procedures. All to secure control before emergency strikes.

A lack of scientific research considering emergency preparedness and response in aquaculture is found, especially for emergency slaughter. As aquaculture enters a new era of salmon farming, a new conference with key industry stakeholders is recommended, with emergency preparedness as the main theme. The thesis concludes that increased focus on emergency preparedness and response going into this new era of salmon farming is necessary, as emergencies are inevitable.

9.1 Further Work

Further work required to improve this thesis include developments of the simulation model and input data. Applying a logistical model running normal operation may present a more realistic starting point in emergency, if sufficient complexity is provided. To achieve more representable output, fuel consumption, operational limits, and separate wave data for sheltered and exposed emergency should be added. Moreover, the application area of the model can be improved by adding more fish farms, and capacity constraints at the slaughter facility. Regarding the input data, there is a large area of improvement. Such input includes, selection probabilities, developing more accurate distribution functions for time usage, escape frequency and more. Moreover, keeping a frequent dialog with industry stakeholders to obtain more representable input may increase the authenticity of the output in future simulations.

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Appendix A – Simulation Model Script

In each block there are several tabs to perform various actions. All script and code is provided in the following appendix. Most of the queues are only added to control the flow of entities. All blocks containing code is added in the appendix.

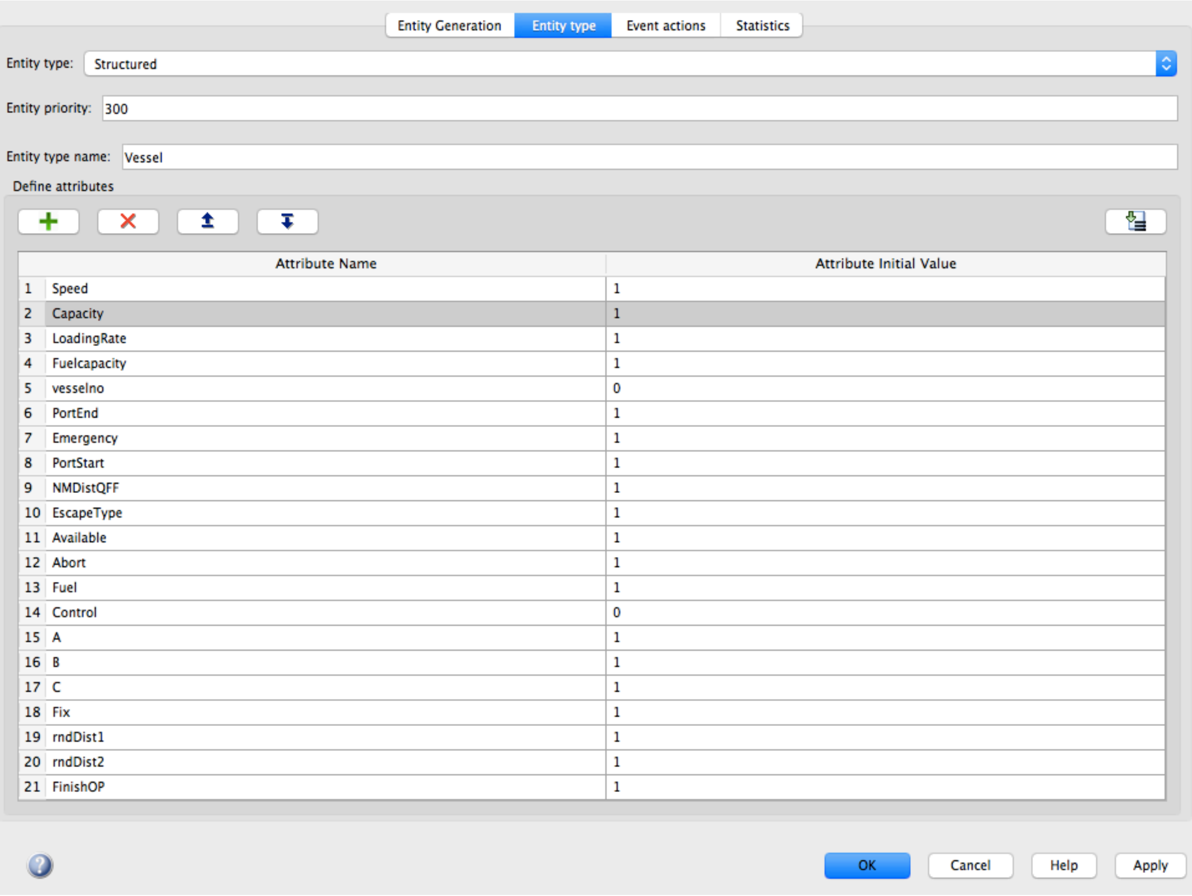
BLOCK (Entity Generator): Vessel Generator/ Emergency Generator

Tab: Entity Generation

```
% Generating vessels for given time intervals
persistent count igt;
% Generate one entity/vessel at time unit 0. To generate more
vessels, add zeros before inf (ex : igt = [0 0 0 0 inf] to
generate four vessels at simulation start)
if isempty(igt)
    igt = [0 inf];
    count = 1;
end

dt = igt(count);
count = count +1;
```

Tab: Entity Type



Entity type: Structured

Entity priority: 300

Entity type name: Vessel

	Attribute Name	Attribute Initial Value
1	Speed	1
2	Capacity	1
3	LoadingRate	1
4	Fuelcapacity	1
5	vesselno	0
6	PortEnd	1
7	Emergency	1
8	PortStart	1
9	NMDistQFF	1
10	EscapeType	1
11	Available	1
12	Abort	1
13	Fuel	1
14	Control	0
15	A	1
16	B	1
17	C	1
18	Fix	1
19	rndDist1	1
20	rndDist2	1
21	FinishOP	1

Figure A1: All attributes assigned to the vessel entity

Tab: Event Action

```
%% Implementing input data from Excel, and assigning the
values to entities.

% Enable SimEvents to implement data from Excel
coder.extrinsic('xlsread');
% Create matrix of zeros
A = zeros(4,17);
% Assigning values to matrix A from input Excel file
A = xlsread('InputEPR.xlsx');
% Retrieving matrix for Speeds [knots]
Speeds = A(:,1);
% Retrieving matrix for Capacities [tonne]
Capacities = A(:,3);
% Retrieving matrix for Loading/Unloading rates [tonne/hrs]
Rates = A(:,4);
% Retrieving matrix for Loading/Unloading rates [tonne/hrs]
Fuelcapacities = A(:,10);

% Probabilities used in selection process, A = Vessel
idle/Vessel vacant, B = Abort ready, C = Sufficient fuel
entity.A = A(1,15);
entity.B = A(2,15);
entity.C = A(3,15);

% Developing a count for each Vessel
persistent Vessel;

 if isempty(Vessel);
     Vessel = 1;
end
% Assigning speed values to vessels [knots]
entity.Speed=Speeds(Vessel);
% Assigning capacity values to vessels [tonne]
entity.Capacity=Capacities(Vessel);
% Assigning Loading/Unloading rate values to vessels
[tonne/hrs]
entity.LoadingRate=Rates(Vessel);
% Assigning fuel capacity values to vessels [m3]
entity.Fuelcapacity=Fuelcapacities(Vessel);

entity.vesselno=Vessel;
Vessel=Vessel+1;

% Retrieving distances from simulink function
y = D(1);

% Retrieving distance from Quay to Fish Farm
entity.NMDistQFF   = y;

% Retrieving emergency type, Escape = 1, Slaughter = 2
entity.Emergency = Emergency(1);
```

BLOCK (Server) : Time of Discovery

Tab: Main

```
% Retrieving random numbers from probability distributions
(See Simulink Function: Stochastic Input)
[ES1, ES2, ES3, ES4, ES5, ES6, ES7, ES8, ES9] = M(1);

% Defining the random value to use in the server
TIME = ES1;

% If emergency escape the random value is used, if emergency
slaughter no time is used
if entity.Emergency == 1;
    dt = TIME;
else entity.Emergency == 2;
    dt = 0;
end
```

BLOCK (Server) : Contacting Time

Tab: Main

```
% Regardless of which emergency type, apply the random value
for time usage
if entity.Emergency == 1;
    dt = TIME;
elseif entity.Emergency == 2;
    dt = TIME;
else
    dt = TIME;
end
```

BLOCK (Server) : Selection Input

Tab: Event Actions

```
% Retrieving random numbers from probability distributions
(See Simulink Function: Stochastic Input)
[ES1, ES2, ES3, ES4, ES5, ES6, ES7, ES8, ES9] = M(1);
% Use random value between 0 and 1
entity.Available = ES3;
% Use random value between 0 and 1
entity.Abort = ES4;
% Use random value between 0 and 1
entity.Fuel = ES5;
% Use random value based on half normal distribution
entity.Fix = ES6;
% Use random value between 0 and 1
entity.rndDist1 = ES7;
% Use random value between 0.5 and 2
```

```
entity.rndDist2 = ES8;
% Use random value based on half normal distribution
entity.FinishOP = ES9;
```

BLOCK (Server) : Sailing Time (Stochastic)

Tab: Main

```
% Retrieving random value for significant wave height from
historical metocean data (In the delivered thesis, the actual
wave data Excel file is replaced by a vector of the same size
containing random values from 0-3 Hs)
w=W(1);
% Time usage for vessels sailing from the port to the
emergency fish farm
ToFarmFromPort      =
(entity.NMDistQFF/entity.Speed)*(1.02)^w;
% Time usage for vessels required to finish the current
operation
FinishOP            = entity.FinishOP;
% Time usage for vessels required to sail to port from current
operational location
ToPort              =
((entity.NMDistQFF*entity.rndDist1)/entity.Speed)*(1.02)^w;
% Time usage for vessels required to sail to emergency site
from current operational location
ToFarmCurrentPos    =
((entity.NMDistQFF*entity.rndDist2)/entity.Speed)*(1.02)^w;
% Time used for vessels lacking sufficient fuel
Fueling             = entity.Fuelcapacity/150;


% Following is the script developed to determine sailing times
for emergency slaughter based on the obtained random values,
and input probability
if entity.Control == 0 && entity.Emergency == 2;
    if      entity.Available >= entity.A && entity.Abort >=
entity.B && entity.Fuel >= entity.C;
            dt = FinishOP + ToPort + Fueling + ToFarmFromPort;
    elseif  entity.Available >= entity.A && entity.Abort >=
entity.B && entity.Fuel <= entity.C;
            dt = FinishOP + ToFarmCurrentPos;
    elseif  entity.Available >= entity.A && entity.Abort <=
entity.B && entity.Fuel >= entity.C;
            dt = ToPort + Fueling + ToFarmFromPort;
    elseif  entity.Available >= entity.A && entity.Abort <=
entity.B && entity.Fuel <= entity.C;
            dt = ToFarmCurrentPos;
    elseif  entity.Available <= entity.A && entity.Abort >=
entity.B && entity.Fuel >= entity.C;
            dt = Fueling + ToFarmFromPort;
    elseif  entity.Available <= entity.A && entity.Abort <=
```

```
entity.B && entity.Fuel >= entity.C;
            dt = Fueling + ToFarmFromPort;
    elseif  entity.Available <= entity.A && entity.Abort >=
entity.B && entity.Fuel <= entity.C;
            dt = ToFarmFromPort;
    elseif  entity.Available <= entity.A && entity.Abort <=
entity.B && entity.Fuel <= entity.C;
            dt = ToFarmFromPort;
    else
        dt=100; % To control that this option is not chosen
    end
else
    dt=100; % To control that this option is not chosen
end
% Following is the script developed to determine sailing times
for emergency escape based on the obtained random values, and
input probability
if entity.Control == 0 && entity.Emergency == 1;
    if      entity.Available >= entity.A;
            dt = ToFarmFromPort+FinishOP;
    elseif  entity.Available <= entity.A;
            dt = ToFarmFromPort;
  else
        dt=dt;
    end
else
    dt=dt;
end

% Following is the script determining the sailing times after
the vessels have been at the emergency site once
if entity.Control == 1 && entity.Emergency == 2;
    dt = ToFarmFromPort;
else
end

if entity.Control == 1 && entity.Emergency == 1;
    dt = ToFarmFromPort;
end
```

BLOCK (Server) : Sailing Time (Stochastic)

Tab: Main

```
% If emergency slaughter, time usage depends on cargo capacity
and loading rate. If emergency escape, use previously
retrieved random number from half normal distribution
if entity.Emergency == 2;
    dt = (entity.Capacity/entity.LoadingRate);
else
    dt = entity.Fix;
end
```

Tab: Event Actions

```
% Read the current amount of fish at the fish farm
level = FishLevel(1);
% If emergency escape, enter the port leading to termination
if entity.Emergency == 1;
    entity.PortEnd = 1;
end

% If there is still in the fish farm and it is emergency
slaughter, remove fish from the farm equivalent to the vessel
capacity, and sail back to the sailing time block, and then to
the quay/port to unload
if level >= 0 && entity.Emergency == 2;
   removeFishAtSiteSlaughter(entity.Capacity);
   entity.PortStart = 2;
   entity.PortEnd = 2;
% If the fish farm is emptied, enter the port leading to
termination
elseif level <= 0 && entity.Emergency == 2;
    entity.PortEnd ==1;
end
% Set value 1 to control that the vessel has entered the fish
farm before
entity.Control=1;
```

BLOCK (Server) : Quay (Port)

Tab: Main

```
% If emergency slaughter, time usage depends on cargo capacity
and loading rate.
if entity.Emergency == 2;
    dt = (entity.Capacity/entity.LoadingRate);
else
    dt = 100; % This value is set to control that it never is
used
end
```

Tab: Event Actions

```
% Tell vessels to return to sailing block, and then to fish
farm
entity.PortEnd = 2;
entity.PortStart = 1;

% Retrieve current amount of fish at the fish farm
level = FishLevel(1);

% If the fish farm is empty, sail to termination
if level <= 0 && entity.Emergency == 2;
    entity.PortEnd = 1;
end
```

BLOCK (Queue) : Q1.5

Tab: Event Actions

```
% Retrieve current amount of fish at the fish farm
level=FishLevel(1);
% If emergency slaughter, and the farm is empty, sail to
termination
if level <= 0 && entity.Emergency == 2;
    entity.PortEnd = 1;
end
% Comment out for case 3 (When time to empty farm is
considered)
entity.PortEnd = 1;
```

BLOCK (Server) : End Check

Tab: Event Actions

```
% Trigger value to use in order to stop removal of fish when
mass death or escape
f(1);
```

BLOCK (Entity Generator) : Generate Capacity Emergency Fish Farm

Tab: Entity Generation

```
% In this block, the option of generating entity at simulation
start is checked, dt=inf to avoid generating entities after
one is generated
dt=inf;
```

Tab: Entity Type

```
% This tab is used in a similar way as in Figure A1. One
attribute is created calle Amount
```

Tab: Event Actions

```
% Enable SimEvents to read Excel files
coder.extrinsic('xlsread');
% Create a matrix of zeros of the same size as the input data
A=zeros(4,17);
% Assign the values in the input file to the matrix
A=xlsread('InputEPR.xlsx');
% Assign the fish farm capacity/input value, to the generated
attribute
entity.Amount = A(1,11);
```

BLOCK (Entity Server) : Entity Server

Tab: Event Actions

```
% Add the previously retrieved amount to the Global Variable,
FishAtSite
addFishAtSite(entity.Amount);
```

BLOCK (Entity Generator) : Generate entity at each time interval

Tab: Entity Type

```
% This tab is used in a similar way as in Figure A1. Two
attributes are created calle Emergency and MassDeath
```

Tab: Event Actions

```
% Retrieve input values (Described in  BLOCK (Simulink
Function): Determine Emergency Type
[y,y1] = Emergency(1);
% Determine which emergency type based on input data
entity.Emergency = y;
% Determine if mass death is present based on input data
entity.MassDeath = y1;
```

BLOCK (Entity Server) : S3.1

Tab: Main

```
% Retrieve current amount of fish at the fish farm
level = FishLevel(1);

% If emergency slaugter, and mass death is not present, dont
let the entities pass by setting time to inf. Also set time to
inf is the fish farm is empty. If none of these apply, let the
entities pass through with no time usage
if entity.Emergency == 2 && entity.MassDeath == 2;
    dt=inf;
elseif level <= 0;
    dt=inf;
else
    dt=0;
end
```

BLOCK (Entity Server) : S3.2

Tab: Main

```
% Remove one unit from the Global Variable: FishAtSite, each
time an entity passes (every hour/time unit)
Escape=1;
removeFishAtSite(Escape);
% Read the triggered value (1) from the Server: End Check
K = read(1);

% If triggered in the Server and mass death is not present,
stop entities from passing through, else let the entities pass
if K == 1 && entity.MassDeath == 2;
    dt = inf;
else
    dt=0;
end
```

BLOCK (Simulink Function) : Waves

```
% This script will retrieve wave data from Excel, the file
used in the Case study is replaced by a same size vector of
random values from 0-3, % due to confidenciality agreement

% State function to send out value for u
function w  = fcn(u)
% Allow Simulink to read Excel files, and make distribution
coder.extrinsic('xlsread','makedist');
% Create matrix of zeros of the same size as values from the
input wave data
A=zeros(9807,3);
% Assign values to the matrix A
A=xlsread('WavesRnd0-3.xlsx');
% Create vector for the column containing Hs
B=A(:,2);
% Make a uniform distribution for values of the same size as
the wave data
% column. It is possible to just use functions to retrive a
random value
% from the vector, but in that case, the value would only be
random for the
% first simulation. This thesis requires random values for
each simulation
% run.
pd = makedist('Uniform','lower',1,'upper',9807);
% Create a matrix of one zero
m=zeros(1,1);
% Retrieve a random value from the uniform distribution (This
random value
% changes for each simulation run)
```

```
k = random(pd,1,1);
% Make the random value an integer number by rounding it
m = round(k);
% A random integer in the wave data vector interval is now
created. w is therefore assigned a random measured value in
the historical wave data
w=B(m,1);
```

BLOCK (Simulink Function) : Stop Removal

```
% State function
function fcn(u)
% Create stop as global variable to use to stop (Triggered in
End Check server
global stop
% Assign value of 1 to stop
stop = 1;
```

BLOCK (Simulink Function) : Stochastic Input

```
% State function and output
function [ES1,ES2,ES3,ES4,ES5,ES6,ES7,ES8,ES9] = fcn(u)
% Allow Simulink to read Excel files, and make distributions
coder.extrinsic('makedist','xlsread');
% Create matrix of zeros of same size as values from input
wave data
B = zeros(4,17);
% Assign values to the matrix B
B = xlsread('InputEPR.xlsx');
% Retrieve mu and sigma values from input data to create half
normal distributions
Waitmu              = B(1,16);
Waitsigma           = B(2,16);
Contactmu           = B(3,16);
Contactsigma        = B(4,16);
Fixmu               = B(1,17);
Fixsigma            = B(2,17);
FinishOPmu          = B(3,17);
FinishOPsigma       = B(4,17);
% Control that all output has values assigned to them
ES1 = 1;
ES2 = 1;
ES3 = 1;
ES4 = 1;
ES5 = 1;
ES6 = 1;
ES7 = 1;
ES8 = 1;
ES9 = 1;
% Create half normal distribution for Time of Discovery Server
```

```
pd = makedist('HalfNormal','mu',Waitmu,'sigma',Waitsigma);
% Generate random number from dist. when server is triggered
by entity
ES1 = random(pd,1,1);
% Create half normal distribution for Contacting Time Server
pd2 =
makedist('HalfNormal','mu',Contactmu,'sigma',Contactsigma);
% Generate random number from dist. when server is triggered
by entity
ES2 = random(pd2,1,1);
% Create uniform distribution
pd3 = makedist('Uniform','lower',0,'upper',1);
% Generate random number 0-1 when server is triggered by
entity
ES3 = random(pd3,1,1);
% Create uniform distribution
pd4 = makedist('Uniform','lower',0,'upper',1);
% Generate random number 0-1 when server is triggered by
entity
ES4 = random(pd4,1,1);
% Create uniform distribution
pd5 = makedist('Uniform','lower',0,'upper',1);
% Generate random number 0-1 when server is triggered by
entity
ES5 = random(pd5,1,1);
% Create half normal distribution for fixing time in escape
pd6 = makedist('HalfNormal','mu',Fixmu,'sigma',Fixsigma);
% Generate random number from dist. when server is triggered
by entity
ES6 = random(pd6,1,1);
% Create uniform distribution
pd7 = makedist('Uniform','lower',0,'upper',1);
% Generate random number 0-1 when server is triggered by
entity
ES7 = random(pd7,1,1);
% Create uniform distribution
pd8 = makedist('Uniform','lower',0.5,'upper',2);
% Generate random number 0.5-2 when server is triggered by
entity
ES8 = random(pd8,1,1);
% Create half normal distribution for vessels requiring
finishing operation
pd9 =
makedist('HalfNormal','mu',FinishOPmu,'sigma',FinishOPsigma);
% Generate random number from dist. when server is triggered
by entity
ES9 = random(pd9,1,1);
```

BLOCK (Simulink Function) : Sailing Distances

```
% State function and output
function NMDistQFF  = fcn(u)
% Allow Simulink to read Excel files, use distance functions
and convert
% kilometers to nautical miles
coder.extrinsic('xlsread','distance','km2nm');
% Create matrix of zeros of the same size as input data
B = zeros(4,17);
% Assign values to the matrix B
B = xlsread('InputEPR.xlsx');
% %Location of Quay (If coordinates are used, optional)
% %LocationQuay = [B(1,5),B(1,6)];
% %Location of Fish Farm (If coordinates are used, optional)
% %LocationFF = [B(1,7),B(1,8)];
% %Distance from Quay to Fish Farm or Slaughter to fish farm,
depending on type of emergency (If coordinates are used,
optional)
% %DistQFF  = distance('gc', LocationQuay, LocationFF);
% Get input value for distance in kilometers
DistQFF = B(1,13);
% Create matrix of one zero
NMDistQFF = zeros(1,1);
% Distances converted from kilometers to nautical miles
NMDistQFF  = km2nm(DistQFF);
```

BLOCK (Simulink Function) : Determine Emergency Type

```
% State function and output
function [y,y1] = fcn(u)
% Allow SimEvents to read Excel files
coder.extrinsic('xlsread');
% Retrieve input for type of emergency, and if mass death is
present
persistent A
if isempty(A)
    A = zeros(4,17);
    A = xlsread('InputEPR.xlsx');
end
    y  = A(1,12);
    y1 = A(1,14);
```

BLOCK (Simulink Function) : Simulink Function

```
% State function
function fcn(Amount)
%Creating a global variable FishAtSite
global FishAtSite;
% Assign the input fish farm amount to the global variable
FishAtSite = Amount;
```

BLOCK (Simulink Function) : Remove Fish

```
% State function
function fcn(Escape)
% Allow Simulink to read Excel files
coder.extrinsic('xlsread');
% Create matrix of zeros
B = zeros(4,17);
% Assign input values to matrix
B = xlsread('InputEPR.xlsx');
% Assign escape frequency input to F
F = B(1,9);
% Remove 1*F for every hour of damage or mass death
global FishAtSite;
FishAtSite = FishAtSite - ((Escape)*F);
```

BLOCK (Simulink Function) : Remove Fish1

```
% State function
function fcn(y)
% Using global variable.
global FishAtSite;
% Removing entity.Capacity for vessel loading at fish farm
FishAtSite = FishAtSite - (y);
```

BLOCK (Simulink Function) : Simulink Function4

```
% Global variable to stop escape or mass death when fixed or
emptied
function y = fcn(u)
global stop
y = stop;
```

MATLAB script: Run model from script

```
% Run from script, the model will run the input from the sheet
in Excel placed furthest to the left
clear all
close all
clc
w = warning ('off','all');
% Name of model, just to make function calls shorter
m = 'EmergencyPreparednessAndResponse';
% Get a list of all blocks in the model
blocks = find_system(m,'Type','Block');

set_param('EmergencyPreparednessAndResponse','StopTime','200')
;


% How many times to run the model
numModelRuns = 50;


for run = 1:numModelRuns
 % Run the model
 sim(m);
 % Logg values for each run
 Response(run) = ResponseTime(1,1);
 Responsewfix(run) = ResponseTime(2,1);
 Discover(run) = Discoverytime(1,1);
 TotalTime(run) = END(1,1);
 %plot(FishatFarm(2:end,1),FishatFarm(2:end,2))
 hold on
 run
end

% Automatic plot from simulations
figure
subplot(1,2,1)
cdfplot(Response)
h1 = cdfplot(Response);
set(h1,'Color',[0 0 0]);
title('')
xlabel('Time[hrs]')

subplot(1,2,2)
histogram(Response,'Normalization','pdf')
title('')
xlabel('Time[hrs]')
ylabel('Density')
```

Appendix B – Wellboat Database

	TONNAGES/DIMENSION			
Vessel Name (Company)	**GT [tonnes]**	**LOA [m]**	**Breadth [m]**	**Draught [m]**
Langsund (Rostein)	499	43,9	10,0	4,5
Ro Arctic (Rostein)	2696	75,5	15,5	5,0
Ro Chief (Rostein)	1066	53,3	12,0	6,5
Ro Fjell (Rostein)	3893	87,5	17,0	6,5
Ro Fjord (Rostein)	2310	72,2	15,0	7,0
Ro Master (Rostein)	2241	72,1	15,0	4,2
Ro Server (Rostein)		82,0	16,0	4,0
Robas (Rostein)	668	46,5	9,5	5,2
Robris (Rostein)	674	46,5	9,5	5,3
Rohav (Rostein)	805	56,8	10,0	5,0
Rostein (Rostein)	805	56,8	10,0	4,0
Ronja Commander (Sølvtrans)	1021	54	12	4,3
Ronja Harvester (Sølvtrans)	2043	68	14,1	5,9
Ronja Huon (Sølvtrans)	3566	75,8	16	6,9
Ronja Nordic (Sølvtrans)	1276	57	12	5,5
Ronja Pioner (Sølvtrans)	1040	57	12	5,1
Ronja Polaris (Sølvtrans)	3582	75,8	16	6,9
Ronja Skye (Sølvtrans)	497	40	10	4,6
Ronja Superior (Sølvtrans)	1276	57	12	5,1
Ronja Viking (Sølvtrans)	1276	57	12	5,0
Dønnalaks (Norsk Fisketransport)	670	51	9	5,0
Dønnland (Norsk Fisketransport)	1536	62,9	12	6,0
Havtrans (Norsk Fisketransport)	3654	84,8	17	6,5
Namsos (Norsk Fisketransport)	3957	84,8	16,9	5,0
Novatrans (Norsk Fisketransport)	1318	62,8	12	5,2
Sørdyrøy (Norsk Fisketransport)	611	50		

Veidnes (Norsk Fisketransport)	695	51,1	9,7	5,2
Viktoria Lady (Norsk Fisketransport)	1186	53,8	12,8	5,2
Viktoria Viking (Norsk Fisketransport)	1100	57	12	5,1
Viknatrans (Norsk Fisketransport)	1318	62	12	5,4
Øydrott (Bømlo Brønnbåtservice)	1226	62	12	5,1
Øyfjord (Bømlo Brønnbåtservice)	1718	69	12	5,9
Øylaks (Bømlo Brønnbåtservice)	1468	62,9	12	5,9
Øysund (Bømlo Brønnbåtservice)	1718	69,9	12	5,9
Øytind (Bømlo Brønnbåtservice)	1747	69,9	12	5,9
Frøystrand (Frøy Rederi)	1226	62	12	4,5
Frøytind (Frøy Rederi)	684	34,5	9,5	5,5
Gåsø Viking (Frøy Rederi)	3665	78	16	6,5
Hedda (Frøy Rederi)	392	44	7,8	
Christine (Intership Norge)	498	44	10	5,0
Inter Caledonia (Intership Norge)	2811	69,8	17	6,5
Haugbas (Scanbio Ingredients)	241	26	8	4,8
Haugfjord (Scanbio Ingredients)	499	45	10	4,5
Frøytrans (Barents Marine)	231	36		
Bjørg Pauline (Nordlaks Transport AS)	2189	70,0	15,0	6,4
Brudanes (Brudanes)	498	49,5	8	5,0
Gærda Sæle (Gærda Sæle)	445	36	12	4,5
Grip Transporter (Gripfisk Service)	1105	60	11	4,0
Grotanger (M/S Grotanger Brønnbåt Nord)	499	40	10	4,5
Havgull (Vestfjord Brønnbåtservice)	255	42		
Havørn (Aspøy)	391	39		
Lifjell (Brønnbåt Nord)	498	42		
Mowi Star (Mowi Star)	452	38		
Seigrunn (Seigrunn)	993	49		
Seivåg (Seivåg Shipping)				
Tauranga (Napier)	886	75		
Triton (Eli Star)	339	38		

	Wellboat Functions					
Vessel Name (Company)	**Cargo Capacity [m3]**	**Service speed [knots]**	**Live Salmon [tonnes]**	**Sorting [tonnes/hrs]**	**Fuel oil [m3]**	**Buildyear / Rebuilt***
Langsund (Rostein)	700	10,2	100	40-60		2002
Ro Arctic (Rostein)	3024	11,7	435			2014
Ro Chief (Rostein)	1200	8,1	180	80		2002
Ro Fjell (Rostein)	4500	5,8	700			2013
Ro Fjord (Rostein)	2800	11,2	400	100		2009
Ro Master (Rostein)	2800	9,7	380	100		2007
Ro Server (Rostein)	3500	9,6				2016
Robas (Rostein)	900	9,9	130	40-60		2006*
Robris (Rostein)	900	8,7	130	40-60		2006*
Rohav (Rostein)	1050	11				2011*
Rostein (Rostein)	1050	10,9				2010*
Ronja Commander (Sølvtrans)	940	7,9			147	2003
Ronja Harvester (Sølvtrans)	1950	9,3			120	2007
Ronja Huon (Sølvtrans)	3200	8,7			250	2014
Ronja Nordic (Sølvtrans)	1150	11,1			150	2008
Ronja Pioner (Sølvtrans)	1040	9,9			160	2006
Ronja Polaris (Sølvtrans)	3200	6,9			250	2013
Ronja Skye (Sølvtrans)	600	9				2001
Ronja Superior (Sølvtrans)	1150	10,5			150	2007
Ronja Viking (Sølvtrans)	1040	10,7			160	2006
Dønnalaks (Norsk Fisketransport)	970	7,9				2002
Dønnland (Norsk Fisketransport)	1500	8,8				2012
Havtrans (Norsk Fisketransport)	3200	10,7		200		2014
Namsos (Norsk Fisketransport)	3200	12	640			2015
Novatrans (Norsk Fisketransport)	1200	9,2				2011
Sørdyrøy (Norsk Fisketransport)		10,2				1966
Veidnes (Norsk Fisketransport)	950	11				2002
Viktoria Lady (Norsk Fisketransport)	1000	12				2006
Viktoria Viking (Norsk Fisketransport)	1050	11				2009
Viknatrans (Norsk Fisketransport)	1200	11				2011
Øydrott (Bømlo Brønnbåtservice)	1200	14	180	60		2010
Øyfjord (Bømlo Brønnbåtservice)	1800	12,5				2014
Øylaks (Bømlo Brønnbåtservice)	1500	12,5	225	60		2012
Øysund (Bømlo Brønnbåtservice)	1800	12,5				2014
Øytind (Bømlo Brønnbåtservice)	1800	12				2015
Frøystrand (Frøy Rederi)	1200	10,1				2009
Frøytind (Frøy Rederi)	900	7,9				1999

Gåsø Viking (Frøy Rederi)	3000	11,1				2015
Hedda (Frøy Rederi)	580	8,5				1984
Christine (Intership Norge)	705	10,5				2001
Inter Caledonia (Intership Norge)	2000	7,7				2015
Haugbas (Scanbio Ingredients)	350	7,2				1995
Haugfjord (Scanbio Ingredients)	700	8,4				2011*
Frøytrans (Barents Marine)						1963
Bjørg Pauline (Nordlaks Transport AS)	2870	8,9	300			2010
Brudanes (Brudanes)	650	9,1				1970
Gærda Sæle (Gærda Sæle)		9				2000
Grip Transporter (Gripfisk Service)		7,3				1993
Grotanger (M/S Grotanger Brønnbåt Nord)	650	8,5				2001
Havgull (Vestfjord Brønnbåtservice)	330					1967
Havørn (Aspøy)						1994
Lifjell (Brønnbåt Nord)	240					1999
Mowi Star (Mowi Star)						1996
Seigrunn (Seigrunn)						
Seivåg (Seivåg Shipping)						
Tauranga (Napier)						
Triton (Eli Star)						

This database is developed partly when writing the previous project thesis, and further developed during this process. The author does not acknowledge that all these values are exact. Some of the most important sources of information include MarineTraffic (2017), Sølvtrans (2017), (Rostein, 2017).

Appendix C – Preliminary Hazard Analysis

Brief Preliminary Hazard Analysis (PHA) for aquaculture emergency.

NO.	Hazard	Hazardous Event	Consequence	Consequence Mitigation
1.	Rough weather	Damage to cages at floating collar, net or mooring	**Fish escape**	Fast response time in fixing damaged material. Such as diving vessel to fix nets. Improved recapture plans. Move remaining stock with wellboat. Alarm systems/ROV inspections Preparedness plan
2.	Wellboat, Feeding vessel, Work vessel	Damage to cage from contact with vessel hull or propeller		
3.	Predators	Rip in net		
4.	Structural errors	Material damage to cage from for instance gnawing from chains on net		
5.	Other vessels	Collision		
6.	Human error	Operational error For instance faults when loading salmon, feeding, etc.		
7.	Operations	Sorting, Shifting and washing nets Handling dead fish Treatment Rip from crowding		
8.	Lice	Extensive louse population	Need for delousing, Emergency slaughter	Empty cage at fish farm Capacity wellboats
9.	Disease	Fish death, loss of biomass Spread	Emergency slaughter, Treatment, vaksine	Higher silage capacity at fish farm
10.	Oil spill	Moving towards fish farm	Need to move fish/cage Emergency slaughter	Ensure sufficient capacity Practice mobilization phase Act quickly/ fast decisions
11.	Algea/Jellyfish	Resurgence at fish farm	Emergency slaughter	Ensure sufficient capacity Practice mobilization phase Act quickly/ fast decisions

Appendix D – Simulation Input Data

Example of input data from case study, case 1, Scenario 2. In the Excel sheet, the upper row follows the letters A-Q, equivalent to 17 rows.

Service Speed [knots]	**Cargo Capacity [m3]**	**Cargo Capacity [tonne]**	**Loading Rates [tonne/hrs]**	**Latitude of Quay**
12	1200	180	100	63,710298
11	2800	400	100	
10	900	130	100	
11	4500	700	100	

Longitude of Quay	**Latitude Fish Farm**	**Longitude Fish Farm**	**Escape and mass death Frequency [tonne/hour]**	**Fuel Oil [m3]**	**Amount at Emergency Fish Farm [tonne]**
8,559691	63,942667	9,13192	1	140	6240
				210	
				105	
				275	

Emergency case [1=Escape, 2=Slaughter]	**Distance from Slaughter facility to farm [km]**	**Mass Death [1=Yes, 2=No]**	**Prob**	**1. Waitmu 2. WaitSigma 3. Contactmu 4. Contactsigma**	**1. Fixmu 2. FixSigma 3. FinishOPmu 4. FinishOPsigma**
2	44,2	2	0,2	0	0
			0,5	0	0
			0,75	0	1
				2	3

Example of input data from case study, case 2, Scenario 2. In the Excel sheet, the upper row follows the letters A-Q, equivalent to 17 rows.

Service Speed [knots]	Cargo Capacity [m3]	Cargo Capacity [tonne]	Loading Rates [tonne/hrs]	Latitude of Quay	Longitude of Quay
35				63,114888	7,758111
30					
25					

Latitude Fish Farm	Longitude Fish Farm	Escape Frequency [tonne/hour]	Fuel Oil [m3]	Amount at Emergency Fish Farm [tonne]	Emergency case
63,942667	9,13192	5		6240	1

Distance from Slaughter facility to farm [km]	Mass Death [1=Yes, 2=No]	Prob	1. Discoverymu 2. DiscoverySigma 3. Contactmu 4. Contactsigma	1. Fixmu 2. FixSigma 3. Waitmu 4. WaitSigma
74,5	2	0,50	0	2
			9	2
			0	0
			3	4

Appendix E – Task Description

MASTER'S THESIS IN MARINE TECHNOLOGY

SPRING 2017

For stud.techn.

Henrik Håkonsen

Emergency Preparedness and Response in Aquaculture

- Simulation of Vessel Response Time for Sheltered and Exposed Fish Farms

Background

This master's thesis is the result of increased focus on aquaculture at the Norwegian University of Science and Technology. The aquaculture industry has been exposed to serious growth in the latest years in terms of production, technology, and size. The industry stakeholders have no intentions of stopping this growth, and increasing production by a five-fold before 2050 have been mentioned on several occasions. Additionally, the industry is considering the possibility of salmon farming in more exposed areas. To reach this goal, increased innovation will likely occur, thereby resulting in more research on the topic. Assuming such a growth will result in more frequent emergency situations, part of this innovation and research must deal with emergency preparedness and response. Proper safety measures may be crucial when considering exposed aquaculture and production increase. Thus, this thesis will investigate some of the important research questions regarding current, and future emergency preparedness and response for the aquaculture industry.

Objective

The objective of this thesis is to develop a generic simulation model to assess preparedness in emergency situations, and to identify response times for sheltered and exposed fish farms, based on varying input data. The simulation model will serve as a tool to analyze and evaluate current versus future emergency preparedness and response in Norwegian aquaculture.

Tasks

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

a. Define limitations and important entities in the system.
b. Describe the problem, and present important research question.
c. Review state of art within the topic. That means to document what others have done and published previously.
d. Determine the required input data and calculations to use in simulation.
e. Develop a discrete-event simulation model in SimEvents, capable of simulating several typical emergency types in aquaculture.
f. Perform a case study to present the application, and diversity of the simulation model.
g. Present the simulation results for three cases of emergency, and discuss the validity of the results.
h. Carry out thorough discussions addressing the presented research questions and approach to emergency preparedness and response, based on the simulation output and literature review.

i. Provide realistic recommendations required to obtain a satisfactory preparedness level in future salmon farming.

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.
- In case computer programs have been made as part of the thesis work, the source code shall be included. In case of experimental work, the experimental results shall be included in a suitable electronic format.

Supervision:

Main supervisor: Bjørn Egil Asbjørnslett

Deadline: 11.06.2017