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Major Accidents in Exposed Fish Farming

A quantitative collision risk analysis

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Marine Technology
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Preface

This document represents my master thesis. It has been written to fulfill the graduation requirements of the Norwegian University of Science and Technology. My thesis will explore the risk picture of fish farming in exposed areas, which is a highly relevant topic for the Norwegian fish farming industry.

I realized early in the working process that information from the fish farming industry would be challenging to obtain. Exposed fish farming is a relatively new concept, and the people working in the industry have not been eager to share their experience with outsiders, not even students. Despite of this, I was able to complete my thesis in time, mainly because I received great help from very dedicated and talented people.

I would like to thank Safetec Nordic AS, who has been of great help the last year, first with my preparatory project thesis, and now with my master thesis. They provided me with a new and improved version of the COLLIDE model, which has led to more accurate and relevant results for my chosen case. I am also grateful to Håkon Ådnanes and NSK Ship Design for giving me information about Havfarm 1.

Also, a big thank you to my supervisor at the Department of Marine Technology (IMT), Jan Erik Vinnem. This thesis has benefited remarkably from his help and guidance.

Trondheim 06.06-18

Karoline Lunde

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Summary

The Norwegian aquaculture industry has had a large increase in activity over the last years, and the expansion is expected to continue in the years to come. However, a further expansion of traditional fish farming is not feasible right now, due to lack of suitable areas and licences. A favorable solution to this problem is to move the production to more exposed waters further away from the sheltered areas near the coast. This thesis will take a closer look at the challenges that arise when moving the fish farming production to such exposed areas, and elaborate how the risk picture changes. It will focus specifically on collision risk, including both passing and attending vessels. The results mainly consist of calculated collision frequencies by using a new version of the COLLIDE model, provided by Safetec Nordic AS. Some simple calculations of the ability to withstand potential collision impact energies are also included.

Due to lack of developed rules and requirements for exposed fish farming, regulations from the oil and gas industry were collected because the conditions around such facilities are assumed to be similar. Because the dimensions and scope in fish farming have been relatively small up until recently, major accident risk assessments have been omitted. It might therefore be beneficial to use knowledge and experience from the offshore industry in order to map major accident risk in exposed fish farming.

In the beginning of this semester a number of potential hazards were collected from the previous project thesis, and only three were selected to be included in the quantitative assessment. These are passing vessel collision risk, attending vessel collision risk and constructional failure risk. This part of the thesis is based on Havfarm 1 by Nordlaks. Its construction, location and other operational details were used as input in the COLLIDE model in order to obtain the desired results.

The total annual collision frequency for Havfarm 1 was calculated to be 5.51E-04. This was the result when adding the frequencies for attending vessel impact and passing vessel collision, which were 4.49E-04 and 1.02E-04, respectively. Still, for impacts above 14 MJ the total collision frequency is 4.67E-05. Frequencies for impacts above 14 MJ caused by attending and passing vessel collision were 3.44E-05 and 1.23E-05. This means that the frequency for attending vessel collision is generally higher than for passing vessels. This is an acceptable tendency because the expected impacts made by attending vessels are lower than for passing vessels, mainly due to lower speed, size and displacement. Even though the total collision frequency exceeds the limit of 10^{-4}, the severity of impacts below 14 MJ is expected to not lead to loss of main safety functions. For impacts above 14 MJ the frequency is below 10^{-4}, which is an acceptable result since such high impacts are assumed to cause severe consequences and loss of main safety functions.

Three collision scenarios are assumed. The first is where the vessel hits either the bow or stern. The impact limit was here estimated to lie between 190 and 205 MJ. The second and third cases describe scenarios where the colliding vessel hits the middle of a beam and directly on a transverse beam in the midsection of Havfarm 1. These impact limits were calculated to be 81 MJ and 147 MJ, respectively. The impact limit of 14 MJ is considered by some people to be quite conservative and outdated, and the calculations show that the construction might be able to withstand impacts higher than 14 MJ and still avoid severe consequences that could lead to major accidents.

The entire working process has been challenging, interesting, frustrating at times, and highly educational. It has given greater understanding of the situation in the Norwegian fish farming industry and the challenges it faces. The frequencies obtained in this thesis are assumed to be within the risk acceptance criteria, but this does not mean that one could sit back and never think about risk control and mitigation again. Risk is tentative, and for a different location or facility, the results may not be as acceptable as in this case. The risk picture should always be taken into account in order to maintain a safe fish farming industry.

Summary in Norwegian

Akvakulturindustrien i Norge har opplevd en drastisk økning i aktivitet de siste årene, og utviklingen er forventet å øke ytterligere. Det er likevel utfordringer med ekspansjon i industrien, hovedsakelig på grunn av mangel på egnede områder og lisenser. En foreslått løsning er å flytte produksjonen til områder lengre vekk fra de skjermede lokasjonene ved kysten, og til mer eksponerte områder. Denne oppgaven vil gå inn på utfordringer som oppstår når man flytter oppdrettsanleggene til slike eksponerte lokasjoner, og forklare hvordan dette påvirker risikobildet. Den vil fokusere på kollisjonsrisiko, noe som inkluderer både passerende og tilhørende fartøy. Resultatene vil hovedsakelig bestå av kollisjonsfrekvenser, som er beregnet ved å bruke en ny og oppdatert versjon av den veletablerte COLLIDE modellen. Safetec Nordic AS har vært behjelpelig med dette. Noen enkle konstruksjonsberegninger er også gjennomført for å undersøke motstandsevnen og robustheten til det valgte anlegget.

På grunn av manglende regelverk for eksponerte oppdrettsanlegg, har erfaringer fra olje- og gassnæringen blitt brukt. Dette er gjort fordi eksponerte oppdrettsanlegg vil ha flere likheter med dagens plattformer i denne næringen, sammenlignet med tradisjonelle oppdrettsanlegg. Risiko for storulykker har frem til nå blitt utelatt fra risikovurderinger i oppdrettsnæringen, hovedsakelig på grunn av små anlegg og generelt lite potensiale for slike konsekvenser. Det kan absolutt være fordelaktig for operatørene i oppdrettsnæringen å se til olje- og gassnæringen, en næring som har stor erfaring med risiko for storulykker. Dette bør gjøres for å redusere risiko for storulykker på de eksponerte oppdrettsanleggene.

I begynnelsen av arbeidsperioden ble et utvalg av potensielle farer hentet fra en foregående HAZID, som ble gjort i sammenheng med en prosjektoppgave fra forrige semester. Kun tre av disse ble inkludert i den kvantitative risikovurderingen. De utvalgte er risiko for kollisjon med passerende fartøy, risiko for kollisjon med tilhørende fartøy og risiko for konstruksjonssvikt. Denne delen av oppgaven baserer seg på Havfarm 1, en eksponert havfarm fra Nordlaks. Dens konstruksjon, lokasjon og andre operasjonelle detaljer ble brukt som grunnlag i COLLIDE modellen for å oppnå de ønskede resultatene.

Den totale, årlige kollisjonsfrekvensen for Havfarm 1 ble beregnet til å være 5.51E-04. Dette ble resultatet når frekvensene for kollisjon med tilhørende og passerende fartøy ble lagt sammen. Disse frekvensene ble beregnet til henholdsvis 4.49E-04 og 1.02E-04. For kollisjoner med kollisjonsenergi over 14 MJ var de samme frekvensene henholdsvis 3.44E-05 og 1.23E-05. Totalt blir dette en årlig frekvens på 4.67E-05. Dette betyr at frekvensen for kollisjon med tilhørende fartøy er generelt høyere enn for passerende. Dette regnes som et akseptabelt resultat, da de forventede kollisjonsenergiene for tilhørende fartøy er betydelig lavere enn for passerende fartøy. Hovedsakelig skyldes dette lavere fart, størrelse og deplasement. Selv om den totale, årlige kollisjonsfrekvensen overstiger grensen på 10^{-4}, antas konsekvensene for kollisjonsenergier lavere enn 14 MJ å ikke være katastrofale, og heller ikke føre til tap av en eller flere hovedsikkerhetsfunksjoner. For kollisjonsenergier over 14 MJ er frekvensen lavere enn 10^{-4}, noe som anses som akseptabelt da slike støt er antatt å føre til tap av en eller flere hovedsikkerhetsfunksjoner.

Tre scenarioer for kollisjon er antatt. Den første beskriver et tilfelle hvor kolliderende fartøy treffer enten baug eller akter på havfarmen. Her ble motstand for kollisjon estimert til å ligge mellom 190 og 205 MJ. Det andre tilfellet består av kollisjon mellom fartøy og midt på en bjelke i midtpartiet, og motstanden er beregnet til 81 MJ. Det tredje og siste tilfellet beskriver også kollisjon til midtpartiet, men her antas fartøyet å treffe midt på en tverrgående bjelke. Her er motstanden beregnet til 147 MJ. Den tradisjonelle grensen på 14 MJ er av mange ansett som svært konservativ og utdatert. Beregningene gjort i denne oppgaven bygger opp under dette utsagnet, da alle tre verdiene ble betydelig høyere enn denne grensen. Havfarmen kan ifølge beregningene være i stand til å tåle belastninger høyere enn 14 MJ, og fortsatt unngå betydelige konsekvenser med storulykkepotensiale.

Hele arbeidsprosessen har vært utfordrende, interessant, frustrerende til tider, men svært lærerik. Den har gitt økt forståelse for dagens situasjonen i norsk oppdrettsnæring og utfordringene den står overfor. De beregnede frekvensene i denne oppgaven er antatt å ikke overgå akseptkriteriene for risiko. Dette betyr likevel ikke at man kan slå seg til ro med disse resultatene og ikke tenke mer på risikostyring og skadebegrensning. Risiko endrer seg med tiden, og for et annet anlegg kan resultatet ikke være like akseptabelt. Risikobildet burde alltid bli vurdert og kontrollert for å oppnå en sikker og forsvarlig oppdrettsnæring.

Acronyms

ALARP As Low As Reasonably Practicable. ix, 10, 11

BBN Bayesian Belief Network. 20

DOF Directorate of Fisheries. 2, 25, 39, 44, 48

DP Dynamic Positioning. 2, 45, 46

FSA Food Safety Authority. 2

GIS Geographic Information System. 53

HAZID Hazard Identification. ix, 4, 5, 8, 35

NCS Norwegian Continental Shelf. 14, 15, 17

NMI The Norwegian Meteorological Institute. xv, 49, 94

PD Pancreas Disease. 25, 36

PSA Petroleum Safety Authority. 2, 8, 11, 12, 15, 20, 72, 75

RIF Risk Influencing Factor. 20, 27, 78

ROV Remotely Operated Vehicle. 33, 34

RSW Refrigerated Seawater. 33

UWV Underwater Vehicles. 27, 31, 33, 38, 42

WEA Working Environment Act. 2

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Chapter 1

Introduction

This master thesis deals with exposed fish farming, and how the change of location to more exposed areas affects the general risk picture of fish farming. This is a highly relevant topic for Norwegian aquaculture, as there is a lot of potential for further growth in the industry.

1.1 Background

The activity in the Norwegian aquaculture industry has increased largely during the last years. Some scientists believe that there is potential to increase the wealth creation six times by 2050 [26]. The number of employees also shows an expansion trend. The number of workers has increased with 74% from 2000 to 2016. Last year there were 7537 employees in the industry. 6991 of these people work with farming of salmon and rainbow trout, and the number is expected to increase further in the years to come [36].

Figure 1.1: Traditional fish farms

The Atlantic salmon production in Norway has had a uniform increase since the middle of the 1980s. The last five years the expansion has stagnated at around 1,2-1,3 million tons per year [47]. Even though fish farms with other species than salmon exist, it is highly likely that salmon will be the most important species in Norwegian aquaculture in the future. Still, a further expansion of traditional fish farming is not feasible at this time, because of the lack of suitable areas and licences. One solution to this challenge is to move the production to more exposed waters and exploit a larger part of the Norwegian ocean. In order to do so there are some changes that should be taken into account in regard to the fish farm construction, equipment and technology. There are also some new problems regarding fish health and welfare, which should be assessed before expanding.

One potential hazard that needs to be included in the risk assessment is collision. When moving the facilities to more exposed areas with more and heavier ship traffic, the risk of passing vessel collision is expected to increase. The traditional fish farms are usually located in sheltered and hidden areas near the coast due to more suitable growth conditions for the fish, and they are therefore not as exposed to this hazard. The weather conditions in the exposed areas are also expected to be harsher, more challenging and demanding. This raises new demands for attending vessels, their maneuvering and positioning control systems, and the need for Dynamic Positioning (DP) increases. The probabilities of these types of impacts are important to reduce in order to avoid severe consequences for the facility, environment, fish and crew involved.

1.2 Existing rules and requirements

Because exposed fish farming was introduced quite recently in the industry, there is lack of rules and requirements for this concept. The industry has therefore had to base its development on existing sets of requirements for traditional fish farming, as well as create and assume more specified rules adjusted to the change of location, construction and production in general. The existing sets of regulations are legislated by the Government, by using advice from Food Safety Authority (FSA), Directorate of Fisheries (DOF) and the industry itself. Given that the production has typically been placed near the shore, the Working Environment Act (WEA) applies for all employees. Even though parts of the production will be moved to areas further away from shore, this will not change [44].

Due to similarities of the conditions at the new locations and more complex facilities, this thesis collects inspiration, knowledge and experience from the offshore industry. This is done to create a suitable risk picture of the different operations in the exposed areas. For the offshore industry, Petroleum Safety Authority (PSA) is a Norwegian governmental supervisory authority, meaning that they supervise safety, emergency preparedness and the working environment in Norwegian petroleum activities offshore and on land [46]. This is the reason rules from PSA has been used to cover gaps and blanks in regulations for exposed fish farming in this thesis. It should also be mentioned that DNV GL has recently developed a new set of rules for offshore fish farming units and installations[1]. This is however mainly for classification. It is expected that a new and complementary set of requirements will be developed in the years to come, and it will be a cooperation between the industry, DOF and the working authorities (Arbeidstilsynet).

[1] DNVGL-RU-OU-0503

1.3 Objective of the thesis

The main objective of the thesis is to explore the collision risk picture of exposed fish farming. This includes both passing vessels that are not involved in the fish farming production, but also attending vessels such as supply vessels and wellboats. The attending vessels will supply the fish farm with feed and other types of equipment, as well as collect the fish when it is ready for slaughter. Havfarm 1 will be used as a case for the calculations in the quantitative part. This includes dimensions, location, operation schedule and other parameters that might influence the collision risk. The new and improved COLLIDE model by Safetec Nordic AS is used for both collision types. Passing vessel frequency will therefore be calculated by using AIS-data instead of the traditional Gaussian distributed ship traffic model. The attending vessel impact model will include parameters such as vessel type, vessel dimensions and visit frequency. Both models will include wind and weather forecasts for the location during the last twelve months.

In addition to finding the frequencies for both passing and attending vessel collision, a simple constructional analysis will be carried out to predict the consequences of a potential collision. Three different collision scenarios are assumed. The objective is to find the most crucial collision scenarios.

1.4 Limitations and conditions of the thesis question

This thesis will focus on salmon production, because it is the species that has the most growth potential in Norway at the moment. After a qualitative risk assessment of exposed fish farming in general, the scope of the thesis was limited to collision risk and structural failures. In order to do a collision frequency assessment, it is beneficial to chose a specific case to achieve coherent information. The choice fell on Havfarm 1 by NSK Ship Design. Because of the focus on collision risk, this thesis will only include parts of the production cycle which take part inside the fish farm in the ocean. This means that production on land and transportation of the fish between the fish farm and smolt facility or slaughter facility will not be included further. It is assumed that the fish farm will only be serviced by one wellboat and one supply boat.

1.4.1 Challenges

The chosen thesis topic deals with relatively new technology, and it is therefore challenging to do proper and thorough research. The lack of good data has caused frustration at times. Since the technology is new and innovative, the aquaculture industry has not been eager to share information about their exposed fish farming projects. The work process was highly affected by this. It was necessary to make contact early, and sometimes it was challenging to get hold of certain information. There is also lack of requirements and standards developed for offshore fish farms. Because of the relatively new and undeveloped fish farming concepts, it was not always possible for the operators and people working in the industry to give answers, simply because they had not come far enough in the working process. It has been challenging to make suitable assumptions for the cases when the information from the industry has been unavailable.

1.5 Cooperation with Safetec Nordic AS

During the last year guidance have been provided by Safetec Nordic AS. They have been of great help through the entire working process. The thesis would have been harder and much more challenging to complete without this collaboration.

In addition to general guidance with this thesis, Safetec has provided an updated version of the COLLIDE model for collision risk. They have developed a new version of the known model COLLIDE, which this thesis has benefited majorly from. They have also provided suitable software, MapInfo, which is used to plot AIS-data and prepare for the parameter input in the COLLIDE excel sheet.

1.6 Project report and HAZID tables

An initial project report was written last semester as preparatory work for this master thesis. It was based on a general Hazard Identification (HAZID) for exposed fish farming. The HAZID tables are found in the appendix. When exploring the risk picture in exposed fish farming, relevant hazards were collected from these tables, focusing on the most critical ones and especially those that have the most severe accident potential. The professional reviews will also be elaborated further.

1.7 Structure of thesis

Chapter 1

Chapter 1 represents the introduction of this thesis. This includes a general background of the fish farming industry, the objective of the thesis, as well as an explanation of how it was developed and why this topic was chosen. Limitations and conditions are also presented in this chapter, as well as challenges that have affected the working process through the entire semester. The cooperation with Safetec Nordic AS follows, with an explanation of how they have contributed to this thesis. The last section in this chapter deals with the underlying project report that was completed last semester, and how this was included in the master thesis.

Chapter 2

The theoretical background will be presented in chapter 2. The relevant key risk terms will be elaborated, followed by a presentation of the existing risk picture in today's fish farming. Previous studies will also be included here. In addition to this, the topic major accidents in the oil and gas industry will be presented in order to collect experience to bring into fish farming, and thus learn how we can reduce major accident risk in exposed aquaculture. In this chapter the original COLLIDE model will be presented, and how the model approach is. In the end, the difference between the old and updated COLLIDE model will be explained in detail.

Chapter 3

Chapter 3 presents the situation in today's fish farming in Norway, including its challenges and possibilities. Havfarm 1 will be introduced, and how the different operations of the fish farm are planned to be carried out.

Chapter 4

Chapter 4 covers the qualitative risk assessment that was completed before deciding which hazards this thesis will focus on in the quantitative risk assessment. This chapter includes eleven relevant hazards from the HAZID from the underlying project thesis, and how the risk of these hazards can be reduced.

Chapter 5

Chapter 5 presents the case study for Havfarm 1, with description, location, conditions and classification. The different parameters and input will be elaborated here, as well as which collision scenarios that are included. The inputs are weather data, common parameters and parameters by choice. Different input assumptions are also included here. The software used in the working process will be presented further, and how it was used to collect the relevant information. The end of chapter 5 presents the results from the improved COLLIDE model, both attending vessel impact risk and passing vessel collision risk, as well as a simple consequence study of the fish farm and how well it can handle potential impact.

Chapter 6

This chapter will mainly be based on the results obtained in section 5.7, 5.8 and 5.9. The attending vessel risk and passing vessel risk will first be discussed separately, and then they will be compared. How the frequencies from the COLLIDE model and the impact limits from the calculations create the total risk picture will also be discussed here.

Chapter 7

The discussion chapter will deal with the choice of risk model COLLIDE, why it was chosen, the significance of using the improved model instead of the old, and its suitability in this case. Parameter sensitivity and collision energy limits will also be included in this chapter.

Chapter 8 and 9

Chapter 8 and 9 consist of the conclusion and suggestion for further work, respectively. The conclusion will cover the most important results and experiences, with a short explanation. In the chapter for further work, there will be a suggestion on what to do next, and what the natural next step will be to dig deeper into the chosen topic and its challenges.

Chapter 2

Theoretical Background

This chapter represents the theoretical background of general terms in a risk assessment, as well as major accident risk and how this is relevant for exposed fish farming. The principle of the COLLIDE model is also included. Chapter 2 is meant to be a basis for the rest of this master thesis, and give the necessary background for further reading and understanding.

2.1 Relevant key terms

2.1.1 What is risk

Definition of Rausand

In order to explore risk in aquaculture, one needs to define general risk terms. Some harmful events can be foreseen and therefore included in the risk picture, while some events are unexpected because they are so rare that they simply are not considered probable or predictable. In order to identify causes and consequences of harmful events, a risk analysis should be carried out. This way one can decide if the risk related to a system is tolerable [14, p. 4-5]. According to Rausand (2011), risk can be explained by answering three questions;

1. What can go wrong?
2. What is the likelihood of that happening?
3. What are the consequences?

Question 1 describes the identification process of possible hazardous events, which could cause harm to assets one wishes to protect. These assets are often divided into the categories people, environment and material equipment. In question 2 one should consider the likelihood of the hazardous events identified in question 1. Causal analysis is a common method to determine the likelihoods. The last question deals with identifying the potential consequences of the hazardous events found in question 1. The severity of the consequences depends on the barriers and how they function during the hazardous event [14, p. 5].

Risk according to PSA

The risk definition from Rausand is the traditional way of describing risk. According to him, risk is probability times consequence, calculated through various risk values or categories [14]. In the later years, PSA has added the associated uncertainty to the consequences of an activity. This is done to avoid surprises and unexpected events, so that one is prepared in case there are deviations. In order to understand and reduce this uncertainty, quantitative or qualitative analyses associated to it should be completed. The risk must also always be viewed in relation to who is conducting the actual analysis [52].

Hazard identification

The process of identifying and describing all the significant hazards, threats and hazardous events associated with a system is called a Hazard Identification. The objectives are to identify the hazards and hazardous events in the system, and then describe the characteristics of each one, for example when and where in the system one might experience this exact hazard. That way one can find the causes and root causes of the hazardous events, and thus also reduce the probability of them, or limit the consequences if they were to happen [14, p. 213-214].

Hazard log

A hazard log is a log of all relevant hazards that threaten the safety of a system. It should be a dynamic document, which could be a useful tool to provide structure for collating risk information that can be used in risk analyses and in risk management of the system [14, p. 216-217].

Risk management

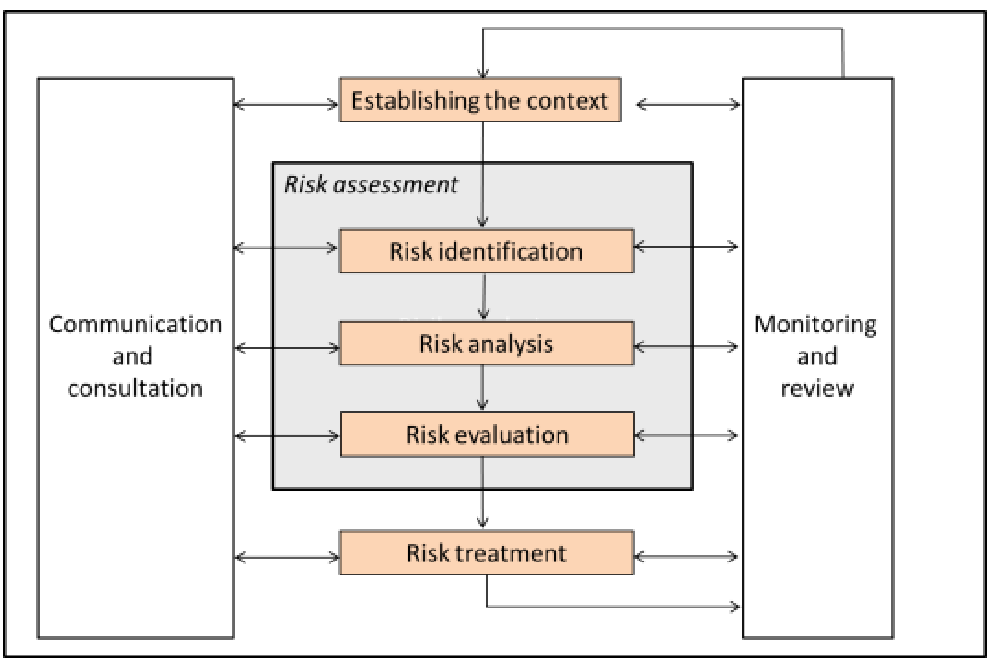


Figure 2.1: Process for risk management in ISO31000

Risk management is a decision support tool based on risk analyses. From figure 2.1 one can see that risk management is made up by establishment of the context, risk assessment and risk treatment. Risk assessment is further divided into three steps; identification, analysis and evaluation of the risks involved. Communication, consultation, monitoring and review are important methods to include during the whole risk management process. The goal of risk analysis is to achieve the best possible overview of the activity or facility, including the identification of knowledge gaps and uncertainty [52]. This is necessary in order to understand the extent of different hazards and how they can arise and develop, so that one can implement the most suitable measures for the actual hazard.

Some assumptions and assessments can be necessary in cases with poor data or information access. In these cases it is favorable with a high degree of experience and knowledge. After receiving the intent results it is important that they are evaluated as well, because the point of retrieving them is to obtain the knowledge needed to control the risk. One process of risk analysis is also to understand the meaning of the risks, so that one can implement risk reducing measures [52].

Risk management strategies

In order to reduce the risk of major accidents, establishment of several layers of safety systems and measures is essential. Because the risk management systems and models are fragmented in the sense that different risks are not subjected to the overall assessment, there is a need for more integrated management models. It is necessary because one wishes to identify potential conflicts between various measures, and find out how to avoid these conflicts [53].

It is important to identify, measure and evaluate risk already in the design phase. This is because any changes or improvements related to risk reduction are easier and less expensive to implement before the construction and operation phase. It is important to understand how the barriers function and how they reduce the risk of major accidents [53].

2.1.2 Barriers and barrier management

According to Rausand, a barrier is a *physical or engineered system or human action (based on specific procedures or administrative controls) that is implemented to prevent, control, or impede energy released from reaching the assets and causing harm* [14, p. 54]. Barriers could both reduce probability of an incident and limit the consequences of the incident given that it has happened. Barriers can be divided into three categories [14]:

1. Barriers that surround and confine the energy source (hazard)
2. Barriers that protect the asset
3. Barriers that separate the hazard and the asset physically, in time or space

Examples of barriers could be fire detection systems, fire walls or evacuation training. The main motivation for proper barrier management is to establish and maintain barriers so the risk at any time can be handled through prevention of undesirable incidents to occur or limit their consequences should the same incidents occur [22].

2.1.3 Risk acceptance criteria

ISO[1] defines risk criteria as *terms of reference against which the significance of a risk is evaluated*. The term is especially useful when trying to answer the question; “How safe is safe enough?” [38]. Risk acceptance criteria are complex and uncertain. It is challenging to determine what is actually safe enough when dealing with human safety. It is not practicable to reduce the risk as much as possible, because of increased costs and effort. In order to not split risk in two simple categories, ”acceptable” and ”unacceptable”, a third risk region is introduced, called ALARP area [38]. Section 2.1.4 explains the term further.

2.1.4 As Low As Reasonably Practicable (ALARP)

ALARP is a risk region between the regions ”acceptable” and ”unacceptable” [38]. The risk in this region should be reduced if *reasonably practicable*, hence the name As Low As Reasonably Practicable.

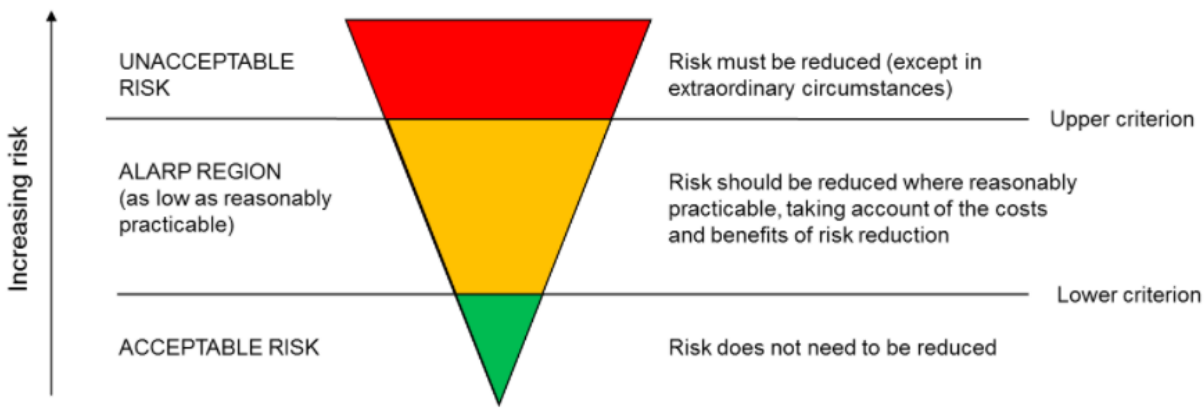


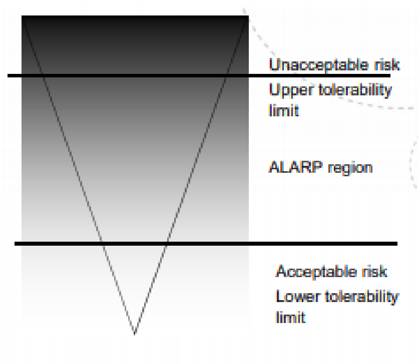
Figure 2.2: ALARP principle

No operation or industrial activity is feasible without a certain level of risk. Risk reducing measures could be avoidance, using alternative approaches or increase in the number and effectiveness of controls.

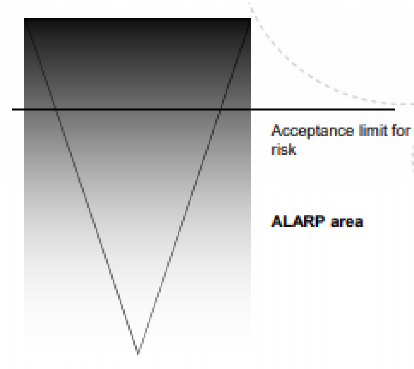
Just because the risk is identified to be in the ALARP area, does not mean that further risk reduction is unnecessary. A general rule is that if the investments of risk reduction become unreasonably disproportionate to the coherent risk reduction, a desired risk level is achieved [62]. It is always desirable to reduce risk as much as possible for the lowest possible cost, because no project or industry has unlimited amounts of resources to spend on risk reduction measures. A qualitative review by competent experts should also be taken into account, instead of trusting that the calculations alone are sufficient.

During the entire operation, it is important to collect feedback in order to improve procedures, manage changes and thus keep the risk within the ALARP level. It is also important to keep in mind that both risk and ALARP are dynamic terms that could change over time. Periodic reviews of the ALARP definition could be favorable.

[1]International Organization for Standardization (2009), “Risk Management - Vocabulary”, Guide 73:2009



(a) ALARP according to UK regulations



(b) Alarp according to Norwegian regulations

Figure 2.3: Difference between ALARP in UK and Norway

Figures 2.3a and 2.3b show the main difference between ALARP according to UK and Norwegian regulations. Both have an upper tolerability limit, which can never be deviated from. The Norwegian ALARP has no lower limit for tolerability and the risk acceptance limit might be deviated from [4].

2.1.5 Risk reducing measures

When looking at risk reducing measures it is hard to avoid barriers and their functions. PSA defines a barrier to be *technical, operational and organizational elements which are intended individually or collectively to reduce possibility for a specific error, hazard or accident to occur, or which limit its harm/disadvantages* [23]. Given that risk is mainly decided by probability and severity, we see that barriers are measures that are meant to reduce the risk. There are two subdivisions of barriers, one is meant to reduce the probability of the accidental event happening and the other one to reduce the severity of the consequences if the accidental event does happen. They are called proactive and reactive barriers, respectively [23].

Figure 2.4 shows the Bow Tie Model. This diagram displays the link between potential hazards, the undesirable (hazardous) event and the potential consequences of this exact event. The blue and red dots in the diagram represents the proactive and reactive barriers, respectively. The barriers on the left side of the diagram show the prevention of the undesirable event while the ones on the right side focus on the recovery of the same event.

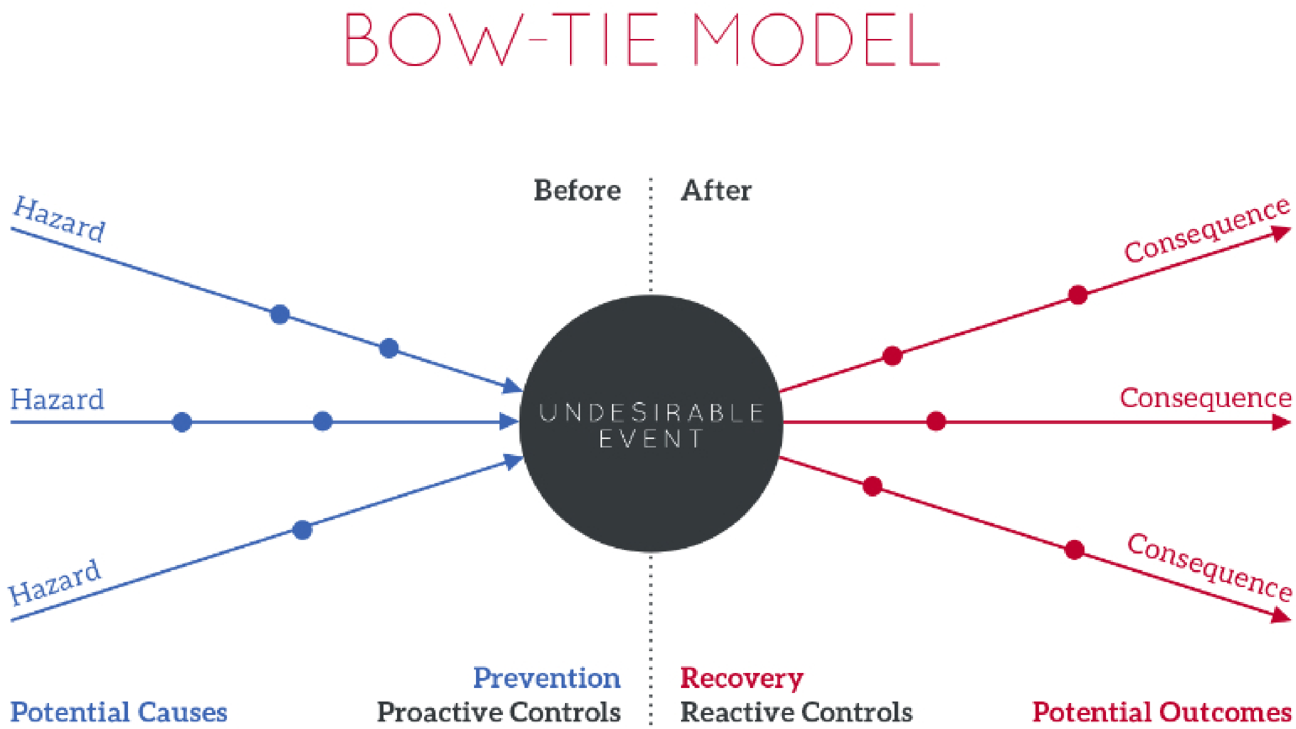


Figure 2.4: Bow Tie Model

2.1.6 Major accident

Definition

The definition of a major accident is *"an acute incident, such as a major discharge/emission or a fire/explosion, which immediately or subsequently causes several serious injuries and/or loss of human life, serious harm to the environment and/or loss of substantial material assets"*, according to PSA Norway [21].

What is a major accident?

The definition above states that there are three different types of assets that one wishes to preserve. They are human safety and health, environment and material assets. Apart from the definition of PSA, there is a number of other definitions used for the term. Common for them all is that the impact should be considerably severe in all three categories. The rapid series of events make it even more challenging to control the major accident risk.

2.2 Risk picture in today's fish farming

Up until recent years there has been a lack of developed rules and regulations for the fish farming industry. This is one of the reasons for the industry being the second most dangerous in Norway today [33]. Still, this situation is expected to change. Because of the change of location to more exposed areas, the demands for improved safety regulations are increasing. The relatively high risks in the industry could therefore be expected to decrease in the years to come.

2.2.1 Previous studies

Because exposed fish farming is relatively undeveloped, there are not many previous studies available, especially regarding safety. One of the leading ongoing projects is SFI Exposed by Sintef Ocean AS, which has a goal to develop knowledge and technology for robust, safe and effective fish farming in exposed areas. Some of their industry partners are Kongsberg (Technology/solution provider), Marine Harvest (End user of technology and solutions) and DNV GL (Certification, classification and advisory) [61].

There are also some earlier master theses that deal with similar topics regarding fish farming, but it has been a challenge to find one that is completely similar. One example is the thesis *"Prinsipper for overføring av fisk mellom brønnbåt og oppdrettsmerder" (Principles for transfer of fish between wellboat and fish farms)*" by Kasper Emil S Ellefsen, written in 2014. His thesis deals with exposed aquaculture, but mainly the operations included and not so much about the risk picture and how it changes. Another thesis is *Development of a Risk Model for Fish Farming Operations* by Helene Nordtvedt (2016), which focuses on exposed fish farming. The number of publications regarding risk and safety in exposed fish farming is expected to increase with the development in the industry.

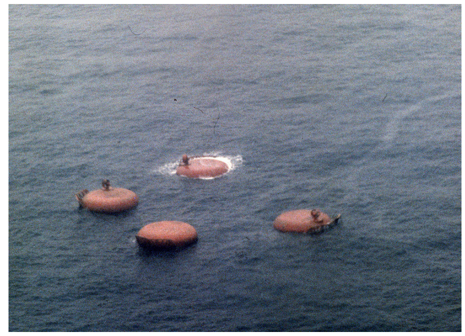
2.3 Major accidents in oil and gas industry

Because the facilities in exposed areas are getting larger and more complex, there are many similarities between them and oil and gas facilities. Because of this it is natural to collect information and experience from this industry, and use it in the expanding fish farming industry. This way it is possible to implement a major risk assessment based on already existing knowledge and technology. The next chapters will therefore deal with major accidents in the oil and gas industry, and how one can learn from them.

Since the beginning of the oil and gas adventure there has been a number of major accidents worldwide. The frequency has generally decreased over the last years, due to the increased focus on safety requirements and regulations. It is still important to maintain risk reducing measures for major accidents, because of the severe consequences they might bring. One of the worst major accidents in the industry and one potential major accident are described further in section 2.3.1 and 2.3.2.

2.3.1 Alexander Kielland

(a) Alexander Kielland platform before the accident



(b) Alexander Kielland platform after capsizing

Figure 2.5: Alexander Kielland

The Alexander Kielland disaster is the accident that has claimed the most lives on the Norwegian Continental Shelf (NCS). It was a floatel based in the Ekofisk area of the North Sea. The rig capsized on the fateful day of March 27th 1980, killing 123 people out of a crew of 212, leaving only 89 survivors [20]. The consequences of Alexander Kielland were especially severe because it was a floatel, and therefore contained many people at all times. The cause of the accident was a weld defect that lead to a fracture in the support structure which caused the loss of one of the five columns of the platform. Because of this a list developed sharply, and the remaining columns and the topside started to take in water. This caused the rig to capsize after only 20 minutes, floating upside down with just the bottom of the columns visible in the sea. On the day of the accident the weather conditions were especially tough, with high waves, strong wind and thick fog.

New safety requirements were introduced after the accident, for example new buoyancy standards for offshore facilities. Also, a number of units had to have additional flotation tanks welded on. Lifeboat measures were improved and new and better survival suits were introduced for offshore use. In the time after the accident, the focus on proper training of offshore crew has increased, especially when it comes to evacuation and procedures during an incident or accident.

2.3.2 Snorre A

The Snorre A incident might not be defined as a major accident, but the series of events on the Statoil-operated facility on November 28th 2004 could have lead to one of the worst accidents on the NCS since Alexander Kielland. 216 people were on board at the time of the incident. During work in well P-31A, it was necessary to pull out a length of tubing so that a sidetrack could be drilled from the main bore [17]. During the evening the situation developed until an uncontrolled blowout took place on the bottom of the ocean with gas under the appliance. 181 people were evacuated, leaving 35 behind to try to regain control. Because of the gas development, supply vessels were unable to reach the platform with extra drilling mud. The remaining crew therefore had to use what they had of available drilling liquids to create mud which could be pumped into the well and stabilize it. This happened the day after, on November 29th. After stabilization and gas outflow prevention, the crew kept working on safety measures to secure the well further [18].

Figure 2.6: Snorre A platform

According to PSA, this is one of the most serious incidents on the NCS, because of the severity of a potential accident. The barriers related to the work in well P-31A had failed to a large degree, and a major accident was avoided only by coincidences. With 216 people on board, there could have been multiple fatalities, and the large amount of hydrocarbons could have created an enormous environmental impact. Not to mention the potential material loss.

2.3.3 Why are Alexander Kielland and Snorre A relevant when discussing major accidents?

The definition in section 2.1.6 states that the incident leading to a major accident is acute, which is the case for both Snorre A and Alexander Kielland. Nobody was able to see them coming, and the time of the series of events was short. The time duration from the initiating incidents to loss of rig was only 20 minutes for Alexander Kielland. The definition further states that major accidents cause several injuries and/or loss of human life, which is definitely the case with Alexander Kielland, where the total number of fatalities were 123, which makes it one of the worst offshore accidents in the history when it comes to number of fatalities. Even though the incident on Snorre A did not cause fatalities or injuries, the accident potential is said to be extremely severe. With 216 people on board, a possible worst-case scenario could have been multiple fatalities the same way as Alexander Kielland. This incident is also remarkable because it happened as late as 2004. Major accidents have become rarer with time, and the general risk has decreased the last decades in the oil and gas industry. The Alexander Kielland accident and Snorre A incident are included in this thesis to increase the understanding of how severe a worst case scenario can be.

2.4 Learning potential from major accidents

By investigating the series of events before, during and after an accidental event, one might learn how to reduce the probability of the same or similar events happening again. This can be done by decreasing the probability of the accident or incident happening in the first place, but also by implementing measures that reduce severity, given that the hazardous event has already happened.

Since exposed fish farming is expected to deal with relatively new technology it might not be feasible to collect information from major accidents in fish farming. Earlier the term major accident has been used to cover large fish escapes and not so much in regard to human safety. It could therefore be an advantage to look at major accidents from the offshore industry because of the similarities between exposed fish farms and offshore facilities. Some might say that there are still some differences, which could lead to unexpected accidental events on the fish farm. It could therefore be beneficial to do a thorough risk assessment specified for fish farming, and not just lean on previous experiences and risk assessments from the oil and gas industry.

2.5 Challenges regarding major accident risk

Major accidents are in general hard to predict. There are also few people left working in the industry that have actually experienced such accidents first hand. This could lead to expectations that major accidents are not likely to happen, which again could cause slack on risk reducing procedures.

It is also difficult to predict the risk of major accidents because the probabilities are relatively low, while the consequences are highly severe. It might therefore be considered unfavorable to implement reactive measures because the accidents are so rare, and the resources invested would be seen as a ”waste” if they remain unused. At the same time it is risky not to have reactive measures because even though the probability is low, it could still happen. A major accident could happen today, next week or 50 years from now, which makes it hard to estimate the optimum amount of resources to invest in reactive risk reducing measures. Such rare events are often called black swans, which are *events or occurrences that deviate beyond what is normally expected of a situation and that would be extremely difficult to predict* [6].

2.6 COLLIDE model

The original COLLIDE model is used to calculate the risk of an impact between vessel and installation. It attempts as far as possible to describe the situation for the responsible navigator on the vessel [24, p. 325]. The first part of the process is advance planning before even leaving port. During this time period the navigator might be or become aware of the facility or not. This planning phase is important for the vessel, because its behaviour during this time period is determined at this stage. From voyage start until the vessel can observe the facility the situation is assumed to be consistent. The distance between vessel and facility at this point is typically around 12 nautical miles. This distance is large, meaning that the vessel can still head directly towards the facility without any real concern.

The situation changes when the vessel has come so close that it is considered unnatural to keep going without changing course [24, p. 325]. The facility will at this point wait for a reaction from the vessel, to avoid collision. The situation on board the vessel might not be as hazardous because they have the ability to manoeuvre away, but the threat increases as the distance between them decreases. When there is only few minutes left before collision, some manoeuvre attempts could still be performed. This is usually last minute evasive actions resulting in glancing blows instead of head-on contact or collision [24, p. 326].

2.6.1 Allision risk

Merriam-Webster dictionary defines allision as *"the running of one ship upon another ship that is stationary —distinguished from collision"* [59]. In this thesis the stationary ship is switched with a fish farm, so that allision in this context will be running of one ship upon a stationary exposed fish farm.

There are some parameters that need to be decided before assessing allision risk. Examples are vessel size and speed, design and structural strength of both vessel and fish farm, and point of impact [40]. Because of the variety of the parameters, there is also a large span in severity of the associated consequences. A small supply boat might hit the stationary facility and sink because of the impact, leaving the facility with only minor damages. On the other hand, if a large shuttle tanker happens to hit the same facility, it could lead to total loss of the fish farm. The impact could be so severe that the facility will be unable to function properly, and the operation might be forced to shut down.

The most common cause of allisions is human error. Up until now there have been no complete collapses of a facility or fatalities of the crew on the NCS, but there have been some incidents that were very close. There are still some facilities offshore that can withstand minor impacts from vessels, but in this case with Havfarm 1 the information about construction and robustness has been unavailable, and it is therefore not possible to assure its relevance to exposed fish farms. An allision between either an attending or passing vessel and the fish farm could potentially cause so large damages that the facility may collapse and its assets might become unable to safeguard [40].

There is however a possibility to increase robustness of the facility, in order for it to be able to withstand collision with passing vessels. Some would still claim that this is an unrealistic move, simply because the dimensions would become unfavorably large.

2.7 Passing vessels

If a collision were to occur, passing vessels will most likely cause more severe consequences than attending vessels. They are expected to have a much higher speed, and the size is likely to be larger than supply vessels. Because they are passing vessels, their focus might not be on the fish farm, unlike attending vessels that mainly operate around this specific facility. Good visibility and ability to move the fish farm might reduce collision risk, but also a suitable choice of location is important to avoid areas with heavy ship traffic. Section 2.7.1, 2.7.2 and 2.7.3 describe typical categories of passing vessels.

2.7.1 Merchant vessels

Merchant vessels could be of significant size, and therefore include large impact energies if a collision were to happen. Other reasons for high collision risk are that they usually travel at high speed and the merchant vessel traffic may be particularly dense in some areas. Also, there is a general unwillingness among them to surrender to limitations during operation. The last challenge has improved the last years due to more traffic restrictions and monitoring systems [24, p. 320], and the occurrences of merchant vessel collision is relatively low.

2.7.2 Naval traffic

Naval vessels are known to have great navigation control. Information and projections of this type of traffic are usually challenging to collect, due to the unwillingness of these vessels to give out information on their position and movements. Naval traffic is normally not included in risk assessments, because they are assumed to not represent a significant risk contribution. This is mainly due to a low number of naval vessels, technical reliability and high manning levels and standards [24, p. 320-321].

2.7.3 Fishing vessels

Fishing vessels are divided into two categories; coastal and ocean-going vessels. Coastal fishing vessels might collide with fish farms because of their location. The excess feed released from the fish farm attracts the fish, which makes the area around it attractive for fishing vessels [24, p. 321]. Especially the coastal fishing vessels are so small that they do not represent any significant risk contribution, but the boats are getting larger and larger every year, and some of the ocean-going vessels might cause a severe impact if a collision were to occur.

2.8 Attending vessels

The attending vessels of the fish farm might not be as large as the passing vessels, but they are still able to make a noticeable impact. The speed and size of the vessel are assumed smaller, but their routes lie much closer to the facility, and they are expected to visit it much more frequently than a passing vessel.

2.8.1 Supply boat

Supply boats can be used for different types of operations. In this case it will mainly be used for fish feed transportation, and perhaps some equipment. It will also be necessary to transport the people working on the fish farm back and forth by boat. The assumption is that one common supply boat will be used to transport feed, equipment, crew and other necessities that show up along the way.

2.8.2 Wellboat

Wellboat is used to transport the fish to the fish farm, and from the fish farm to the slaughter facility after they are fully grown. It is assumed that one wellboat will attend the fish farm alone, and it will go back and forth between the smolt facility and fish farm to transport the smolt, and between the fish farm and slaughter facility when the fish is ready, until all the fish is out of the fish farm. The number of visits is assumed to be 17 times[2] a year.

2.9 COLLIDE approach

There are mainly two causes for collision. The first is drifting, where the vessel has lost its control or propulsion. The second is simply that the vessel is heading towards the fish facility without the crew being aware of it [24, p. 323]. These probabilities add up to the total probability of passing vessel collision, which is presented in equation 2.1. Because the probabilities of collision are usually low values, the probability notation is used in the sense of frequencies due to the lack of real numerical validation [24, p. 324].

$$P_{CP} = P_{CPD} + P_{CPP}, \tag{2.1}$$

where

- P_{CP} = probability of passing vessel collision
- P_{CPD} = probability of collision due to a passing drifting vessel
- P_{CPP} = probability of powered collision

The equation for calculating passing vessel collision frequency for a facility in a specified location is expressed by equation 2.2 below[3].

$$P_{CPP} = \sum_{i=1}^{m} \sum_{j=1}^{6} \sum_{k=1}^{n} N_{ijk} \sum_{l=1}^{4} P_{CC,jkl} P_{FSIR,jkl} P_{FPIR,jkl} \tag{2.2}$$

where

- P_{CPP} = annual frequency of powered passing vessel collision
- N_{ijk} = annual number of vessels in vessel category j in size category k travelling in lane i. The risk contribution from each relevant "lane" is calculated and added together to get the total risk to the fish facility

[2] The assumed wellboat needs to take 17 turns in order to transport all of the fish in Havfarm 1.

[3] The platform facility in the equation explanations is switched with fish farm facility in this case.

- $P_{CC,ijkl}$ = probability that a vessel in vessel category j in size category k in traffic group l travelling in lane i is on a collision course at the point when the vessel can observe the fish facility, visually or on radar. There are six vessel categories:
  - Merchant vessels
  - Fishing vessels
  - Standby boats
  - Supply vessels
  - Shuttle tankers
  - Naval vessels (including submarines)
- $P_{FSIR,jkl}$ = probability that the vessel itself does not initiate some action to avoid a collision with the fish facility (Failure of Ship Initiated Recovery)
- $P_{FPIR,jkl}$ = probability that the fish facility or the standby vessel does not succeed in initiating avoiding action on the vessel, given that the vessel has not initiated such action itself (Failure of Platform Initiated Recovery)

Equation 2.2 is not based on independence of the individual factors, which should be considered as conditional probabilities. The two failure probabilities, $P_{FSIR,jkl}$ and $P_{FPIR,jkl}$, are specific to vessel, size and traffic category, but not dependent on the lane. They deal with the underlying mechanisms when the vessel involved fails to take action in order to avoid collision. For this a reliability analysis is required. N_{ijk} is the most straightforward parameter, with no necessary modelling, only a lot of data are needed. The probability of being on collision course, P_{CC}, is the geometrical factor, and includes all factors related to the composition and position of the traffic flow [24, p. 325].

2.10 Improved COLLIDE model

The PSA has stated that the risk assessments of passing vessels might be too conservative and they request more focus on barriers and risk reduction. This is why a new and improved COLLIDE model has been developed by Safetec Nordic. The new model includes a wider range when using Risk Influencing Factor (RIF)s, and enables a more holistic and detailed analysis of risk factors, barrier elements and dependencies [39]. It is also more transparent and gives a better understanding of the collision risk calculation methods. The new model includes a quantification in terms of a Bayesian Belief Network (BBN). Through this model it is possible to understand which of the barriers that influence the results the most [39].

2.10.1 Collision energy and resistance

In figure 2.7 the black arrows represent collision to the bow/stern, which are evaluated together due to similarities. The green and pink arrows represent collision on the middle of one of the midsection beams and collision directly on one of the transverse beams, respectively.

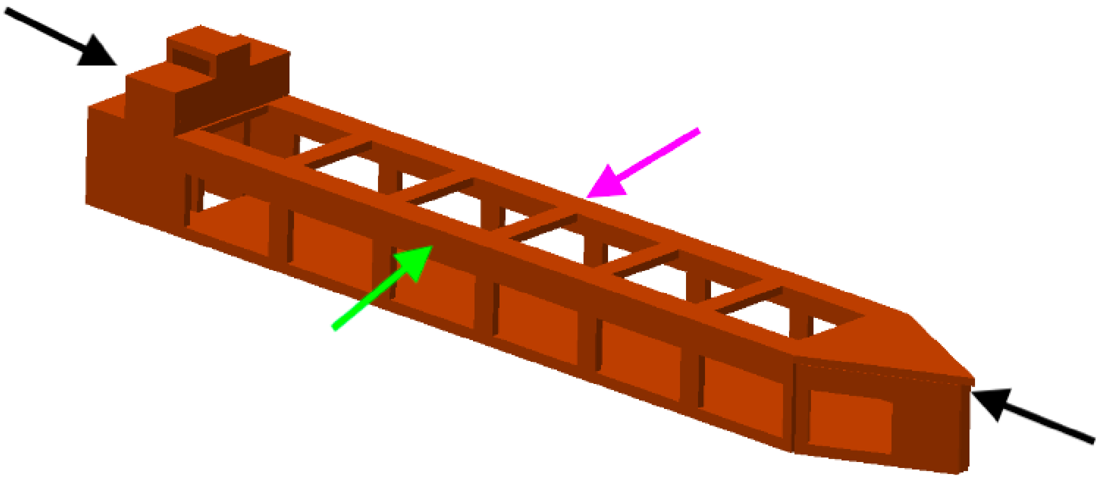


Figure 2.7: Illustration of the three assumed collision scenarios; collision to bow/stern, middle of beam in midsection and on transverse beam

Midsection critical load equations

The following equations 2.3, 2.4 and 2.5 are used when calculating the critical load for a potential collision on the middle of one of the twelve beams around the six fish nets (green arrow). Equation 2.3 calculates the plastic section modulus for the beam cross section, which is illustrated in figure 2.8. Hollow square beams are assumed for both beams, but their dimensions are different. All equations in section 2.10.1 are collected from *Ultimate load analysis of marine structures* [1, p. 2.7-2.19].

$$z = \frac{3}{2}tb^2 \tag{2.3}$$

where

- z = plastic section modulus for square tube
- t = wall thickness
- b = square tube width/height

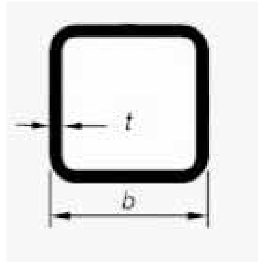


Figure 2.8: Cross section of assumed beam

The value for z is used in equation 2.4, which calculates the plastic moment for the same beam.

$$M_p = \sigma_y z \tag{2.4}$$

where

- M_p = plastic moment
- σ_y= yield strength
- z = plastic section modulus for square tube

The value for M_p is then used in equation 2.5, from which one gets the plastic collapse load in Pa.

$$P_c = \frac{8M_p}{l} \tag{2.5}$$

where

- P_c = plastic collapse load
- M_p = plastic moment
- l = beam length

Transverse buckling equations

When looking at the pink arrow collision scenario, Euler formula for buckling is assumed [1, p. 5.10].

$$P_{cr} = \frac{\pi^2 EI}{l} \tag{2.6}$$

where

- P_{cr} = critical buckling load load
- E = Young's modulus
- l = beam length

Chapter 3

Norwegian fish farming and presentation of Havfarm 1

3.1 Introduction

Chapter 3 deals with Norwegian fish farming in general, how the situation is today and some challenges that need to be taken into account in the future development of the industry. The second part of the chapter will present Havfarm 1, which will be the specific case for the quantitative analysis in chapter 5. This case was chosen because it is one of the most developed projects going on at the moment, and NSK Ship Design has been very helpful when it comes to sharing information. Havfarm 1 was therefore a natural choice for this thesis. The information used in chapter 3 and 5 is collected through the following:

- Nordlaks
- NSK Ship Design
- Articles regarding Havfarm 1
- Assumptions based on guidance from supervisor and Safetec Nordic

3.2 Fish farming

3.2.1 Situation today and possibility for expansion

The growth in Norwegian aquaculture has stagnated the last few years, and further expansion is not feasible due to lack of suitable areas and licences. When moving the fish farms further away from the coast, one can get access to larger areas and larger water volumes for the fish. This way one might increase fish production, and hopefully profitability as well.

The increase of suitable areas could lead to more fish production, more fish farms and the complexity of each fish farm is expected to be higher. This results in a need for more qualified people, which in the long run will improve the wealth creation in Norway. After 2014 there has been an employment decrease in the oil and gas industry, and the aquaculture industry could potentially create more jobs.

Because of the traditional locations being close to land it is not necessary for the fish farm operators to stay on the farm for long periods of time, and the exposure to hazardous events is therefore relatively small. Also, fish farming does not include hydrocarbons the same way as in oil and gas production, so risk of environmental impacts caused by leaks will not be as relevant[1]. Therefore, the term *major accident* in fish farming has earlier been used to describe large fish escapes in fish farming, and not so much in regard to human safety and environmental risk.

3.2.2 Possible incidents

Escape

Fish escaping from the fish farm is one of the main challenges in today‘s fish farming industry. If the fish net ruptures due to careless handling by the operators during an operation, which is the main reason for fish escaping, it is possible for large amounts of fish to escape in a short period of time. The total number of escaped fish is, among other things, decided by the size of the tear damage, amount of fish in the net and the time it takes for the damage to be discovered and repaired. The escaped fish is a threat to the biodiversity in the area around the farm, and not only the wild salmon fish stocks. If the farmed salmon reaches the habitats for wild salmon they could infect them with parasites, viruses or other diseases, but also eat their food or take over their areas for spawning.

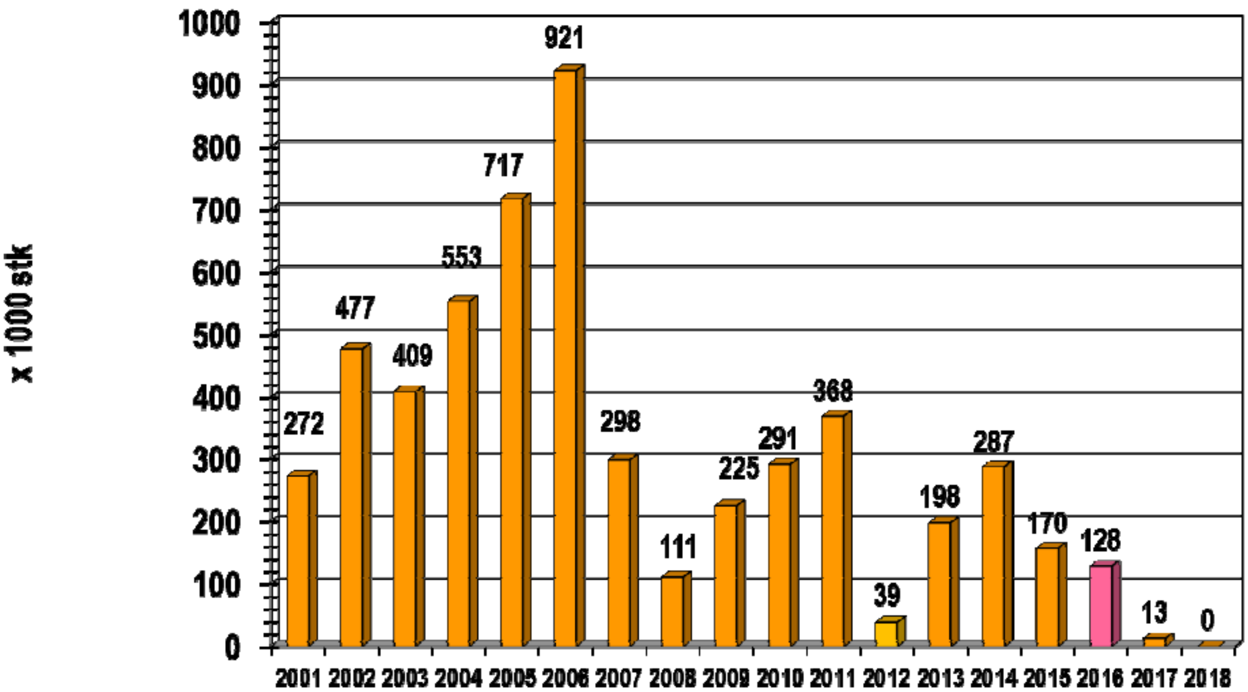


Figure 3.1: Reported number of escaped salmon between 2001 and 2017

[1]There is still some environmental risk due to fish escapes which can have an impact on existing wild salmon stocks.

Figure 3.1 represents the reported number of escaped salmon between 2001 and 2017[2]. The data is collected and presented by the DOF [37]. Based on this figure there is a general decrease of escaped salmon, because of improved robustness and monitoring of the fish nets. This improvement is mainly a consequence of more comprehensive rules and requirements that have been introduced the last years. Some important measures in order to avoid or reduce escapes are proper training and education of operators, improved equipment quality, better use of weather forecasts and learning from previous near-incidents. Surveillance and inspection of the fish net also play an important role.

Even though the main focus should be on the environmental aspects of fish escape, there is also a significant economic consideration that should be taken into account. The economic aspect of fish escape can be a motivating factor for the operators to focus on reducing annual escapes. In the end, the fish is the product that is being sold, and loss of fish leads directly to loss of income. One example is a larger fish escape at one of Salmar‘s facilities at Hitra, which lead to 176 000 escaped salmon and a loss of around 10 million NOK. Around half of this amount was due to loss of fish, and the other half to re-catching and reduction of the consequences [15].

A sizable portion of the loss is connected to production costs and reduced income due to fish loss. There are still some remaining losses that need to be considered. If there is a fish escape, the operator is committed to try to re-catch as much as possible of the escaped fish, which might require use of divers, fishers or technological equipment. These methods are costly, and result in higher expenses. The operators shall also report the number of missing fish, and its average weight. The cause, time and location shall be included in this report as well. This information can be costly and time-consuming to gather. It is also important to include the costs of the repair of the fish net or other parts of the fish farm, if this was the reason for the escape.

Some of these operations might require use of wellboat or supply boat, for example if the remaining fish needs to be moved to an undamaged fish farm nearby [15]. Other consequences might be damage to name or reputation of the company involved, which could cause potential customers to avoid purchasing their products. All in all, it is clear that fish escapes are not just a threat to the environment but also the economy of the companies.

Pancreas Disease (PD)

When expanding fish farming to more exposed areas, the fish could experience higher stress levels and tougher conditions than fish in traditional fish farms. This external strain will generally lower the health of the fish, making it more vulnerable to diseases. PD is one of the most problematic diseases in fish farming today. It is an infection caused by a virus, and its consequences could be decreased growth of salmon and increased mortality. Because of this the profitability will naturally be reduced. A simple eruption of PD might cost a fish farmer 10 million NOK [48].

One of the most common causes of PD infection is the ocean currents. This way the virus could spread from one facility to another, and this should be taken into consideration when choosing location of the fish farm. It is possible to estimate the movement of the currents by looking at temperature and season in order to foresee the spread of PD [48].

[2]Statistics from 2016 and 2017 are still being adjusted and might include some uncertainty.

Salmon lice

Salmon lice is found naturally in all ocean areas on the Northern Hemisphere. It is currently the most challenging and outspreading parasite in salmon production. If the consent ration of salmon lice on salmon gets too high, this might cause harm to the fish [57]. This number should never be above 0,5 salmon lice per salmon [30].

The former definition of major accidents in fish farming covers large amounts of fish escaping, but a high concentration of salmon lice should definitely also be taken into account, because the quality could be reduced considerably by occurrence of salmon lice. Since this thesis is dealing with production of living goods, the profitability is highly dependent on the treatment the fish is exposed to. The biology will in this case be absolutely limiting, one can not farm sick or dead fish. This is a very important aspect regarding offshore fish farms, and the fish health and welfare should be one of the main priorities [35]. Quality loss due to salmon lice could decrease profitability of the production, and therefore have just the same severity as larger fish escapes.

Even though the occurrence of salmon lice has never been lower than today, it is still a serious and severe problem in the fish farming industry. A risk report from the Norwegian fish farming industry, published in 2017 by Havforskningsinstituttet, showed that salmon lice in fish farms is still one of the largest environmental challenges for aquaculture today [47]. The same report also states that there is a clear connection between intensive fish farming and the contagion of salmon lice, both in the fish farm and the wild salmon stock. This is one of the main restrictions on further expansion of salmon farming. Some believe that the salmon lice problem will be reduced in exposed fish farms because of the increase in currents and waves, but also because of increased distances and non-favorable conditions for the lice. This is however not proven, and it could turn out to be a consisting challenge, also in exposed areas.

The salmon lice could, if not taken care of, cause enormous consequences, especially in contact with wild salmon [60]. When the salmon lice release their eggs into the water in the fish farm, they develop into larvae which drift with the current and attach to salmons. The lice feed on the skin cells and the mucus covering it, which is supposed to protect against infection. This could also disturb the growth and salt balance of the fish.

Waste

Fish are living creatures. This means that they excrete faeces and urine, which mainly contains nitrogenous waste such as ammonia. At high concentrations this might become toxic to the environment and the organisms living in it.

The fish is fed every day, and it is highly unlikely that all of the feed is consumed by the fish. A part of it will go undigested through the fish farm and out at the bottom or at the sides. The fish feed contains mainly proteins and lipids, and the excess nutrients might interfere with the natural environment on the sea bottom in the area around the fish farm.

3.2.3 Occupational safety in fish farming

Even though it is expected that the number of autonomous operations is supposed to increase when expanding offshore, there are still some operations that have to be performed manually from the fish farm or boats. Such operations can be daily inspection of floaters, nets or equipment, in order to detect wear or damages. The operations have a tentative risk picture, which could lead to hazardous situations for people involved, but also for fish welfare. The massive volumes and large amount of fish might make it challenging to monitor and discover escape quickly. The large depth of the fish net also contributes to this, as well as dark and cold waters. There is already a need for stronger equipment and machinery in today's industry, mainly cranes and winches. They are usually operated from work vessels moored to the fish farm. This is considered to be an unstable operation because of the unpredictable motions of the vessel. As the lifts get heavier and the operations more complex, manual inspection is expected to be replaced with inspection by Underwater Vehicles (UWV)s. This is also done to reduce risk to human life, and decrease the time needed for inspection as the facilities get larger [41].

The lack of focus on occupational safety in fish farming is the main reason for the relatively high risks in the industry. The operators have been expressing concerns about this, especially when it comes to lifting operations using cranes or winches. One challenge is that there is no common design or measure for fish farming facilities. This results in large differences between fish farms along the Norwegian coast, and it is challenging to develop standards and requirements that applies for all cases. The incident documentation in the industry is poor, and under-reporting is assumed to be a serious issue [41].

The conditions offshore are generally harsher than inshore. The currents, waves and winds will be stronger, and one will experience *more weather*. The design, construction and operational phase must be adapted to handle such conditions. The complex monitoring systems increase the demands when it comes to reliability and safety. More work is transferred from people to automation. The regulation demand increases. Most lifting operations in aquaculture are done by use of cranes, which is one of the most hazardous operations within aquaculture. With heavier weights being lifted the risk increases. In general, exposed areas demand more safety regulations and measures in order to provide a sufficient level of human safety.

3.3 Introduction of major accidents in fish farming

3.3.1 Barriers in exposed aquaculture

In order to reduce the introduction of new risk increasing elements in fish farming there is a need for proper barrier management and RIFs. An example of such new barriers is the use of steel covers around the fish nets. These covers are supposed to protect the fish from strong waves and currents and keep them from getting sea sick, and at the same time avoid predators or other intruders from reaching the fish net. In traditional fish farming this is generally not used, as the fish net alone will work as a barrier between the fish and these hazards. Steel covering is a great example of how one must adjust the production facilities when moving the fish farms to more exposed areas.

3.3.2 Introduction of new risks when expanding offshore

In general, most of the risk contributors within traditional fish farming will be transferred to fish farms in exposed areas. It is expected that the risk will increase in most cases. One likely exception is that the waste concentration on the sea bottom under the fish farm could be reduced because of increased flow and larger available areas.

In traditional fish farming, the term *major accident* has been used to describe severe escape incidents. This event does not occur often nowadays, mostly due to technical improvement [34]. Fatalities or injuries have often not been included in the term, because the number of operators working at the same time on a fish farm has been low and the probability of multiple fatalities has therefore been minimized. Now that the number of people on board the exposed fish farms will increase, there is a higher probability of multiple fatalities, mainly due to the possibility of casualty, both of the wellboat, supply boat and the fish farm itself.

If total loss of the fish farm occurs, not only will the human safety be at risk, but the escape risk increases as well. By expanding offshore, total loss of fish farm is possible to relate to total loss of facility within the oil and gas industry. The safety measures from the oil and gas industry might therefore be possible to transfer into the aquaculture industry, mainly because the offshore fish farm facilities are similar to oil and gas platforms. Since the probability of major accident might increase in exposed areas, it is important to take this into account when assessing the risk picture, and not just neglect the risk. This is to avoid *black swan events*.

3.3.3 Why is it necessary to include major accident risk?

Because of the relatively simple and small facilities in traditional fish farming it has not been necessary to include major accident risk until now. The term has been used to cover large fish escapes earlier. This is about to change when expanding offshore, because of the increased amount of fish and risk to human safety. In order to avoid accidents with the same severity in fish farming, major accident risk needs to be taken into account. This is especially important in the fish farming industry, which has been unregulated compared to other industries. This is considered one of the main reasons for the industry being the second most dangerous in Norway. Proper risk reducing measures are important to keep the risk from increasing further.

3.4 Case study: Nordlaks' Havfarm 1

The rest of this chapter will describe Havfarm 1, including documentation, construction, assets and how the different operations and routines will be implemented.

3.4.1 Case description

Figure 3.2 shows the design of Havfarm 1, which is the first out of three planned fish farms from NSK Ship Design for Nordlaks. The Chinese shipyard CIMC Raffles will be building the stationary fish farm, which is planned to begin in 2018 [51]. Its dimensions can be found in table 3.1[3].

Figure 3.2: Nordlaks' Havfarm 1

Table 3.1: Key Dimensions Nordlaks' Havfarm 1

Total length	385 m
Depth	37.75 m
Width	59.5 m
Total volume	414 000 (69 000 per net) m^3

[3]There are different parameters available for Havfarm 1, depending on where you collect them. The parameters in table 3.1 were chosen early in the process, so the real dimensions might deviate some from these.

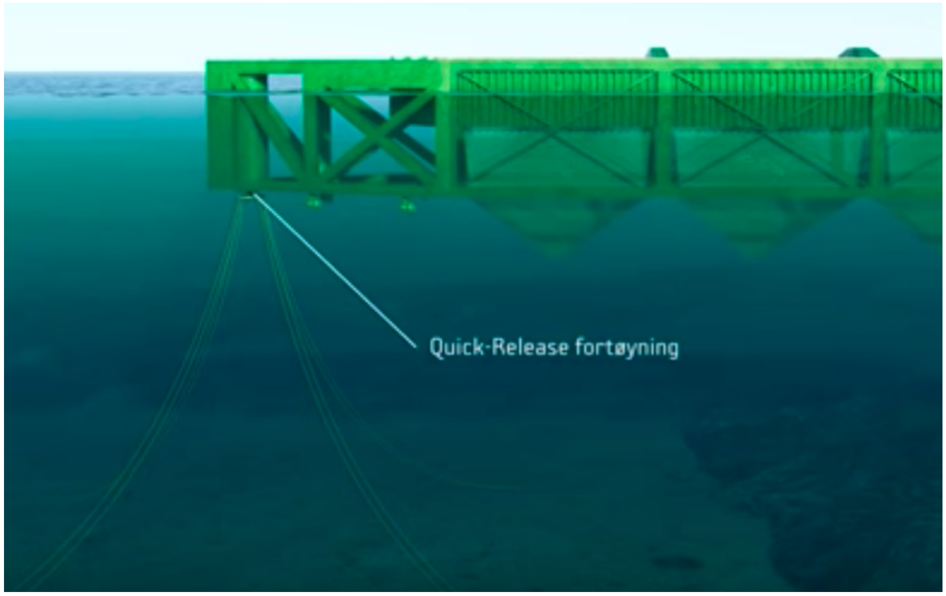


Figure 3.3: Anchoring solution for Havfarm 1

The mooring concept for Havfarm 1 is an anchoring system with a quick-release solution shown in figure 3.3. The figure illustrates the bow which is permanently anchored, meaning that the fish farm will be weather vaining. In smaller time periods with challenging and unfavorable conditions for the fish and crew, the fish farm can release itself from the mooring system, and move to a more suitable area until the original location is back to a more normal state. This movement is possible due to additional propulsion thrusters placed both at the bow and stern. It is important to remember that this is not a part of the normal production, but an exception when the surroundings become too harsh and challenging.

3.4.2 Documentation access

Through the working process of this master thesis it became more and more clear that the access to relevant documentation is generally poor. This is most likely due to a competitive situation in the industry, and the companies involved are trying to keep their progress to themselves. There is however some information on their web pages, as well as articles from newspapers.

In addition to information found online, this thesis has benefited from input from Håkon Ådnanes, who is the project leader of Havfarm 1 by NSK Ship Design. Relevant topic questions were answered by him, which has been of great help. This thesis is also a result of a cooperation with Safetec Nordic, which is already working with exposed fish farming and could give guidance related to this.

3.4.3 Construction

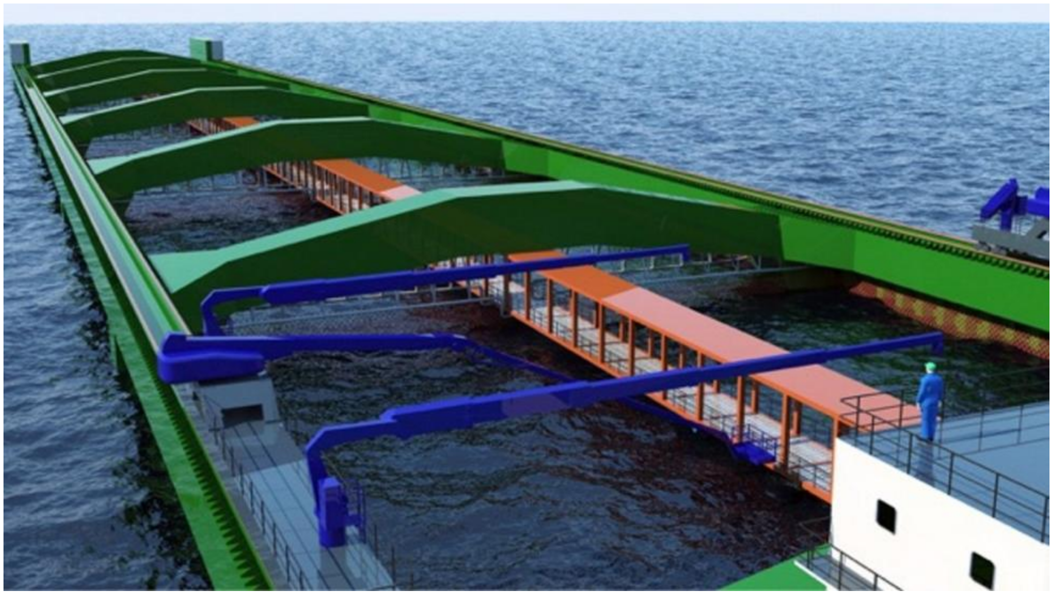


Figure 3.4: Nordlaks' Havfarm 1

The concession application for the stationary Havfarm 1 was approved in December 2016. NSK Ship Design will be doing the design and engineering of the fish farm for Nordlaks. Their application for the dynamic fish farm is also approved, and the engineering part of this project will hopefully begin in the summer of 2018.

Havfarm 1 will be a steel construction that consists of a bow with crew facilities and a simple service station. The fish nets will be placed in the middle section of the fish farm, taking up a large amount of volume. Silage facilities and generator capacity are found at the stern. From figures 3.2 and 3.4 one can see the that the shape of the fish farm reminds highly of a ship. This design is chosen to lower the environmental loads as much as possible, for example waves and currents that will be reduced due to the shape of the bow. The fish farm will have hydrodynamic characteristics similar to a semi-submersible platform.

The fish nets in the midsection will be surrounded by steel covers that go from the surface to 10 meters depth (normal operation). These covers are meant to limit the environmental loads on the fish farm and therefore also the fish. Hopefully, this will reduce the amount of salmon lice and protect from predators and drifting objects. There will also be a movable service facility over the entire section. The fish farm will be able to regulate buoyancy through ballast systems. Other support systems on Havfarm 1 are fish feed storage and feeding systems, treatment and removal of sick and dead fish, silage, thrusters, heading control, UWV, crew facilities and bridge. The bow will be permanently anchored.

3.4.4 Assets

Human safety

Some would say that human safety is the most important asset to safeguard in every operation or industry there is. Because of the change of location from traditional to exposed fish farming, there is a need for the operating crew to be present at all times during the fish farming operation. This increases the exposure to human safety, and the demand for human risk reducing measures is therefore larger.

Environment

One of the main arguments for expansion is the positive changes in environmental challenges that are expected in exposed areas. This is especially relevant for excess waste, chemicals and feed that exit the fish farm regularly. When it comes to the wild salmon stocks the impact risk might increase because of the increase in the amount of farmed salmon. Any escape from the exposed fish farms will most likely have higher risk of damaging the existing salmon stocks.

Fish welfare

One of the main contributors to the profitability is the fish quality, which again is highly dependable on growth conditions for the fish during the production phase, but also slaughter and general processing methods. Rough handling of the fish will result in poor fish quality, which affects the customers impression of the fish and how much they are willing to pay for it. There is also an ethical aspect to consider here, and one wishes to preserve the fish welfare as much as possible.

Reputation and publicity

In local communities along the Norwegian coast there has been opposition against fish farming and the industry in general. This is mainly because people claim the pollution from the fish farms is ruining the environment and the existing fish stocks. This is especially a problem for local fishermen. Because of this there might be a desire in the industry to have a good reputation and create positive publicity, so that this impression could be improved. Newspapers publishing articles about large fish escapes and environmental impacts due to pollution will work against this. Although it might not be necessary to get approval from local communities in order to keep up a profitable production, it makes it a lot easier and more comfortable for the fish farming companies.

3.4.5 Operations and routines

Fish transportation

This section represents both the transportation from the smolt facility to the fish farm, as well as the transportation from the fish farm to the slaughter facility. Both routes involve use of wellboat. The hazards for these transportation routes are assumed to be relatively similar. Exposure to stress is one of the most critical aspects to keep in mind during smolt transportation as it might lead to quality loss and reduced fish welfare. This could be reduced with improved planning and logistics. Proper training and education of the crew involved is expected to decrease risk to human safety, as well as improve conditions for the fish.

One of the differences between the two transportation routes is the distance. The distance between the fish farm and slaughter facility is expected to be much longer than between smolt facility and fish farm. The fish farming company often owns both the smolt facility and the fish farm, meaning that they are able to place the smolt facility relatively close to the granted location of the fish farm, and therefore reduce the distance between them. Slaughter facilities are not as common, and the trend is that they are becoming fewer with larger capacity, meaning that the distance is expected to increase further. Because of the increasing distance, the fish will spend more time in the wellboat. A prolonged retention could arise because of unforeseen events that cause the operation to take longer time than expected. The consequence might be increased stress level of the fish. Especially for transportation of smolt this will be critical, because the smolt is not as robust as a grown fish. Still, after arriving at the fish farm the smolt will have sufficient time to calm down and recover from the stress. If this were to happen with grown fish on its way to be slaughtered, the increased stress level might lead to the slaughtered fish going into rigor mortis much earlier, and one could therefore experience perceptible quality reduction [10, p. 24].

During the transportation itself it is important to keep the conditions for the fish as steady as possible, with sufficient oxygen levels and temperature in the water. The Refrigerated Seawater (RSW) tanks have an inlet and an outlet with water flow from the sea, so that the water inside the tanks is evenly replaced. If this flow system fails or is reduced, the environment inside the tanks could be so damaging to the fish, it may in worst case cause death. All in all, proper planning and improved logistics are important aspects to safeguard during transportation.

Feeding

Because of the increase in size, the feeding in exposed areas is not expected to be done manually. It will be automatic, meaning that the human exposure is reduced, because they do not have to move out of the control room for this operation. The feeding systems are able to spread the feed evenly and adjust the feed to the size and number of fish. This is done to avoid waste pollution, meaning that excess feed is secreted from the fish farm and therefore could disturb the sea bottom environment. Overfeeding is also favorable to avoid, because the fish can get overweight. This is damaging to the fish, but also negative for the economy.

Surveillance, inspection and maintenance

Inspection, surveillance and maintenance have always been important tasks in aquaculture. Earlier these tasks were mostly done manually by operators, but in the later years they have been replaced by Remotely Operated Vehicle (ROV)s or other UWVs. This way the operators are less exposed to the hazardous environment on the fish farm, because the UWVs are doing the job for them. When expanding towards more exposed sites, it is highly likely that the need for monitoring and decision support systems will increase [27]. Cleaning is also an example of an operation where it would be favorable to use UWVs. This is a standard operation after the production cycle is finished and the fish is collected from the fish farm. Proper cleaning is an important tool when it comes to hygiene and disease control.

Figure 3.5: ROV working at fish farm

The launch and recovery of the vehicles today are done using cranes from a service vessel. The expected worsening of weather conditions will most likely cause even more challenges during this operation, and make it dangerous as well as difficult. The weather window for this operation is expected to be small, and it is the single most limiting factor for utilizing ROVs in high wave states [27].

In order to repair a fish net damage in time, it is important that the damage is detected as quickly as possible in order to reduce the time period where it is possible for fish to escape. Most of the fish net is under water and therefore challenging to inspect manually, but the use of underwater vehicles have made it possible to inspect the net and detect damages more often. This was earlier done by use of divers, which is much more hazardous to human safety than use of ROVs.

Delousing

One of the main limitations for further expansion is the prevalence of salmon lice. The allowed number of lice is 0,5 grown lice per fish [16], and measures must be implemented if this limit is exceeded. The main methods for delousing are use of chemicals and delousing by wellboat[4]. The treatment itself might cause harm to the fish. Too much chemicals, insufficient delousing or incorrect use of chemicals might increase the chances of damage and death for the treated fish.

The later years it has become more common with delousing by wellboat, where the fish is pumped into the wellboat. This is done because the lice can not survive in freshwater. However, this treatment might cause mechanical damages to the fish [25]. From 2015 to 2016, there was a reduction in chemical treatment of 41% [34], which has been replaced by wellboat delousing.

[4]Lumpfish is an example of another method, but will not be discussed in this thesis.

Chapter 4

Qualitative risk assessment

Chapter 4 consists of a selection of hazards in fish farming. The chosen hazards are collected from the HAZID from the project paper[1], completed in December 2017. They are considered to be the most relevant hazards, and are therefore included in the risk assessment process. The following list represents the chosen hazards for exposed fish farming, divided into four categories; hazards to fish welfare, hazards to economy and environment, occupational hazards and hazards with major accident potential.

- Hazards to fish welfare
  - Non-optimum growth
  - Lack of usable feed
  - Too much chemicals or insufficient delousing
- Hazards to economy and environment
  - Large fish escapes
  - Net fracture
- Occupational hazards
  - People falling into the water
  - Wellboat casualty
  - Hazardous crane lifts
- Major accident potential
  - Structural failures
  - Collision with passing vessels
  - Attending vessel impact

Only a few of these will be elaborated in chapter 5. The remaining hazards from the HAZID will not be included further in this thesis.

[1]HAZID tables can be found in the appendix

4.1 Hazards to fish welfare

This hazard category covers the main hazards to the fish. All three of them could cause large consequences for the fish welfare if not controlled.

4.1.1 Non-optimum growth

The aquaculture industry has insufficient knowledge about how the fish will thrive in exposed waters. The fish farms will contain larger quantities of water with higher fish density, and the fish could become stressed and therefore not grow optimally. The large amounts of fish will also make monitoring more challenging, both regarding well-being and growth.

Non-optimum growth might not be perceived as too critical. Human safety and fish escape are not considered relevant here, so it is perhaps easy to neglect or ignore this hazard. It is still important that the growth rate is acceptable in order to have profitable fish farming. Success in fish farming will not only depend on technology, because fish physiological and behavioural limitations are just as important [27, p. 22]. When expanding offshore, water currents and wave strength are main concerns, and the coping ability in farmed salmon is unknown. It is therefore extremely important to include the biological aspect in fish farming, because it will be a limiting factor no matter how good the technology is.

Disease control is one important measure to reduce waste and secure proper growth rate. Infectious diseases, such as PD or salmon lice (see section 3.2.2), could damage the fish so much that the growth is reduced or stopped. Such illnesses could be avoided by vaccination in the smolt phase. In today's fish farming industry it is necessary to implement proper vaccination in order to avoid disease and mortality [5]. Another threat to the fish welfare is mechanical damage due to rough handling or treatment during the smolt, production or slaughter phase. External damage might cause harm and pain to the fish, but also reduce the visual performance, resulting in reduced fish quality and therefore profitability.

Risk reducing measures

Correct temperature, water saturation and feeding are important measures during the smolt phase for the fish. This happens before the fish is placed in saltwater. A good base for growth and well-being is created during this specific phase.

In the salt water production phase, optimization of feeding rate, composition and amount are important aspects for optimum growth. Avoidance of disease, such as PD and salmon lice, along with vaccination and protection from production damages are other examples of risk reducing measures. The vaccination takes part during the smolt phase, and salmon lice control during the salt water phase. In the latter phase, delousing is important to optimize (see section 4.1.3). In all phases, sample testing of the fish could be a solution instead of having to control each and every fish. This is especially relevant for offshore fish farms, mainly because the amount of fish is larger.

4.1.2 Lack of usable feed

Feeding is one of the most critical operations in fish farming, mainly because feed represents 40-50% of the production costs [8]. Also, non-optimum feeding leads to non-optimum growth. Insufficient feeding is therefore important to avoid, and both technical and operational aspects (human error) are relevant. It is also important to reduce the probability of feed contamination and putrefaction.

Risk reducing measures

The expansion offshore demands better implementation of logistics and feed supply. Larger volumes of fish lead to larger amounts of feed needed, and it is important to develop good supply chains in order to make the feed supply as continuous as possible. It is more favorable to be proactive than reactive, so feed control and feeding optimization are important measures to reduce risk of feed contamination. This event is especially important to avoid, because there is already lack of proper feed resources in the aquaculture industry [31]. Further expansion in the Norwegian fish farming industry is expected to increase this potential problem, meaning that feed control and feeding optimization are even more important aspects for exposed fish farming.

4.1.3 Too much chemicals or insufficient delousing

As mentioned in section 3.4.5, there are mainly two delousing methods used in the Norwegian fish farming industry; chemical delousing and mechanical delousing by wellboat. The later years the use of chemical delousing has decreased and wellboat delousing has taken over more and more. This is an important measure when it comes to reducing the risk of too high chemical concentrations inside and around the fish farm. If the amount of chemicals is too large for the volume inside the fish farm, the excess chemicals might exit and spread to areas surrounding it. The high concentration of chemicals might also damage or reduce the quality of the fish, as well as affect the environment on the sea bottom around the fish farm.

One of the biggest sources for biological and economical losses of fish is contagious diseases. In order to safeguard fish welfare in offshore fish farming, it is important to prevent and control these diseases. However, it is limited how many treatments the fish can handle. Every single treatment of the fish, whether it is merging, pumping, delousing or other, will cause a small share of the fish to die [42]. It is therefore important to make sure the delousing is sufficient. If the delousing has to be repeated because of sloppiness the first time, the fish will be exposed to unnecessary stress and the fish stock will be reduced.

Risk reducing measures

The use of chemical delousing is decreasing, which will reduce risk of overusing chemicals, simply because there are no chemicals included in the mechanical delousing. This operation is done by wellboat instead. Exact estimation of the amount of chemicals needed for accurate delousing is another method, because the amount of excess chemicals will be reduced. Still, when less chemicals are used, the probability of insufficient delousing increases. It is therefore important to estimate this as accurate as possible, because both too much chemicals and insufficient delousing are serious hazards to include in a risk assessment.

4.2 Hazards to economy and environment

The two hazards included here are related to each other, since net fractures could lead to large fish escapes. They are still discussed separately, because large fish escapes are not always caused by net fracture, it could for example be structural failures.

4.2.1 Net fracture

The main reason for fish escape is net fracture, often caused by attending vessels coming too close to the fish farm during operation. When expanding offshore, inspection and surveillance of the fish net will likely become even more challenging. This is due to increased depth, colder and darker water as well as more challenging weather conditions such as currents and wave height. Earlier in more simple and traditional fish farms, it was not uncommon to use divers for inspection and maintenance operations. This might not be a good solution because of increased human risk.

Risk reducing measures

Since the main reason for net fracture is damage due to rough handling of the fish net, sufficient education and training of the operators involved might be good measures to reduce probability of tearing. Such damages could even happen during routine operations, which are considered to be easy and low-risk by the operators. When slacking and not taking the safety seriously, the risk of net fracture increases.

If damages were to occur it is desirable to detect and locate them as soon as possible in order to reduce the amount of escaped fish. Frequent and thorough inspection by UWV or simple visual monitoring are examples of such risk reducing measures. The use of Underwater Vehicles (UWV) has increased the last years, and it is expected to take over the human inspection operations, at least under water. With the large dimensions and complex facility systems in exposed areas, the fish farm companies are dependent on UWVs in order to have proper and sufficient monitoring of the fish net.

4.2.2 Large fish escapes

Fish escapes occur through the entire operation from smolt to slaughter. The more operations the fish is exposed to, the higher the probability of escape will be. In general, more handling of the fish leads to increased escape risk [55]. Mesh size of the fish net is one of the important aspects to consider in fish farming. There can be varying sizes in smolt populations, which could lead to the smallest smolt escaping through the net.

There has been opposition towards fish farming since the beginning, and people living close to the traditional fish farms are generally skeptical to the industry, and how it can affect the environment and biological diversity. The most common complaints are disturbance of the wild salmon stocks because of escaped farmed salmon, but also damage to crustaceans and other organisms living under the fish farm. The latter is mainly because of chemical delousing treatment. Some also mean that the fish farms are unaesthetic. The reputation, both for a single fish farming company and the industry itself, is therefore important to prioritize and preserve.

Since the discontent of the fish farming industry is highly related to fish escape, it might be an advantage for the industry to maintain control of the number of annual escapes. The amount of fish escaping from Norwegian fish farms has decreased from 921 000 in the peak year 2006 to as low as 10 000 in 2017 [37], and the general development is looking promising, as one can see in figure 3.1. This is mainly due to improved regulations and technology.

If escapes do occur or suspicions arise, the operators are obligated to report it. All cases are published on the websites of the DOF. Loss of fish is usually covered by insurance companies, but the total profitability for the fish farming companies will most likely be reduced, so this is a challenge the industry wishes to control.

There are large uncertainties connected to the planned expansion offshore, and how this will affect the number of escaped salmon in the future [12]. This will be one of the main concerns for fish farm operators, because more fish in the farms means potential for more escapes, which could increase the impact on the environment. It might be an advantage to have support from the locals, and a high number of escapes could contribute to the general discontent that is already present in some communities because of the local environmental impact.

Risk reducing measures

According to Regulations of Aquaculture (Akvakulturdriftsforskriften) [7], all operators shall implement daily surveillance of fish and facility. Those responsible on the fish farms shall have sufficient knowledge to prevent, discover and limit fish escapes. An updated contingency plan shall be available at all times, and should contain an overview of how escape can be discovered and limited. A risk evaluation is required in order to reduce escape risk [56]. Mesh size of the net shall be adjusted to the size of the fish. This could be a challenge because of varying fish sizes.

In 2015 a new set of regulations was published. It says that there is a common responsibility of the operator to re-catch the escaped fish. This is especially relevant if the amount of escaped fish in rivers reaches too high levels. This participation is mandatory, and is subsidized by the operators. Other important measures are proper training and experience exchange, technology improvement, proper mooring according to the location and learning from incidents and almost-incidents [56].

There have been some attempts to farm triploid, or sterile, salmon. This way the consequences could be reduced if the fish were to escape. Instead of reproducing and affecting the wild salmon stocks, the triploid salmon will eventually die out without any further impact. There is still some uncertainty to how the triploid salmon will grow and thrive in a fish farm and if the quality will be affected. If it succeeds, the fish farming industry will be able to farm fish with reduced escape risk [19]. In order to produce triploid salmon one must expose the salmon roe to high pressure. This way the resulting fish will get two sets of chromosomes from its mother and one pair from its father. This treatment does however make the salmon more sensitive to high temperatures and low oxygen concentration in the water. Use of triploid salmon therefore creates a need for different, more specialized farming conditions for the operators.

4.3 Occupational hazards

Occupational hazards have up until recently not always been controlled in the fish farming industry. This section only presents a few of the potential hazards in this category.

4.3.1 People falling into the water

This hazard covers people falling into the water during wellboat operations as well as during routine or unexpected operations on the fish farm. The possibility of being able to rescue oneself when being alone is an important part of risk and safety management in the fish farming industry. Many of the operations in traditional fish farming are typically done by one person alone, and often when it is dark outside and the weather is harsh. Drowning is not the only hazardous event when falling into the water, hypothermia is also important to include. Especially in Norwegian waters the temperatures are so low that one will not survive for long in the water, especially without survival suits. It is hard to decide how long it takes for a person to die from hypothermia, it depends on the water temperature, clothing and the physique of the person. The possibility of getting up without help is normally smaller than expected [11, p. 72].

Risk reducing measures

When working alone on a boat or on the farm, life jackets and survival suits should always be used to reduce risk of drowning if a person falls into the sea. Even though a person is wearing both, it is just as important to be able to get up from the water while being alone. One could experience unconsciousness, shock or other reasons for being unable to perceive the seriousness in the situation. The fall itself could also cause injuries [11, p. 71]. All of these factors are important to include in the total risk picture.

If a falling incident occurs, it will be necessary for the person to alert and get help. This is especially important if one can not get up from the water alone. A relevant risk reducing measure can be a radio with an integrated alarm that goes off in contact with water. This way people on shore will be alarmed if someone falls into the water, even though that person is unconscious. It is still important that the help will reach the person in the water as quickly as possible, and an alarm system might not be a sufficient measure if the reaction time is too long [11, p. 72-73]. Additional safety measures are proper fastening equipment between people and boat or fish farm, and ladders or other devices to help people climbing up from the water.

4.3.2 Wellboat casualty

Figure 4.1: Seikongen sinking outside the coast of Chile

Figure 4.1 shows the wellboat Seikongen while sinking outside the Chilean coast on October 18th 2017. The crew of 11 was successfully evacuated, but around 200 tons of fish were still on board [43]. Earlier the same year a Norwegian wellboat experienced the same event, when Fisktrans sank outside the coast of Steigen, Nordland. All six crew members were evacuated [45]. Such situations could have a negative impact on the environment if the fish is not collected within a certain time period. If the degradation of the fish gets too far before it is removed from the wellboat, the risk of disease increases, as well as the risk of damage to the sea bottom. This could have huge impact on the local ecosystems. Risk of wellboat casualty is crucial to control in order to reduce probability of injuries or fatalities.

The category wellboat casualty is a particularly wide and general term. A thorough risk assessment for this hazard will be time-demanding and challenging to complete, because of the enormous amount of potential causes that could lead to a casualty. Both grounding and collision with another vessel or facility are common causes for casualty. A wellboat operation is expected to be performed approximately once a year[2], so this hazard can be omitted in large parts of the production cycle.

[2]Confirmed in an e-mail from NSK Ship Design on Feb 7th 2018.

Risk reducing measures

Even though there is a wide selection of potential causes to wellboat casualty, there are some common risk reducing measures for the majority of them. Examples of such measures are proper training and education of the crew. This mainly means learning how to operate and control the vessel in a safe way, but also evacuation procedures and how to use the equipment correctly. A well-developed maintenance strategy will be an effective risk reducing measure. It is important to have sufficient inspection to detect deviations, followed by maintenance operations, as well as proper positioning technology to avoid impact between boat and fish farm.

Another important measure is to pay attention to the weather forecasts and take them seriously. Disturbances could be heavy rain and fog resulting in reduced visibility, but also powerful wind and waves that will increase the demand for manoeuvring and positioning skills. If the wellboat experiences reduced visibility, one solution can be to slow down and pay close attention to the navigation systems and confirm its position. Weather challenges can arise both at dock and mooring, and also during transfer.

4.3.3 Hazardous crane lifts

One of the most dangerous operations is use of crane [32]. Large amounts of fish feed and other types of equipment are necessary for the huge volumes of fish, and safety focus during the crane operations offshore will therefore be even more important than for traditional fish farms. The exposed areas experience more weather, and control of the positioning system is therefore more important than before. Maintaining stability is important to reduce the risk during heavy crane lifts, both in order to avoid impact between boat and fish farm and avoid falling objects or other work accidents. As the lifts are getting heavier and the conditions tougher, the risk of losing control during crane operations is expected to increase. This could cause people being hit by the crane or the item being lifted, or the wire to snap and falling cargo hitting people or equipment, potentially causing fatalities, injuries or material damages.

The launch and recovery of the UWVs today are done using cranes from a service vessel. The expected increase of weather challenges will most likely cause even larger challenges during this operation, and make it dangerous as well as difficult. The weather window for this operation is expected to be small, and it is the single most limiting factor for utilizing ROVs in high wave states [27].

Risk reducing measures

Proper use of the crane is one important measure when it comes to reducing this risk. Training and education of operators are also key elements. Cranes are most often placed on attending vessels, and better positioning and mooring technology are important for maintaining stability and crane control. Paying attention to weather forecasts and taking them seriously is another possible risk reducing measure.

4.4 Major accident potential

The hazards in this section are all related to major accident risk, and is therefore divided into a separate category. These hazards are considered most severe if the hazardous events were to happen.

4.4.1 Structural failures

In contrast to traditional fish farming, offshore fish farms will be more robust, larger and in general more complex. It might therefore be more suitable to collect experience and information from the petroleum industry, since the offshore fish farms remind more of an oil and gas installation than the traditional fish farms. To most people, Nordlaks' Havfarm 1 in figure 3.2 looks more like a ship compared to the traditional fish farms in figure 1.1.

The Alexander Kielland accident described in section 2.3.1 happened because of fatigue in one of the platform legs due to a welding defect. Havfarm 1 will not have legs in the same way, but this does not mean that a risk of fatigue is not present. The facility will lie in exposed waters, with stronger currents and higher waves, meaning that the fatigue risk must be taken seriously. A potential fatigue fracture could in the worst case scenario lead to casualty and total loss of facility, which also means that the fish inside it will be at risk. If the fish is impossible to save after a casualty it will result in enormous economical consequences. What is also important to include is the human safety. Between 5-15 people will be on board at all times, meaning that the exposure increases considerably. Alexander Kielland capsized after only 20 minutes, so if the same type of damage were to occur to an exposed fish farm, evacuation actions must be initiated as quickly as possible.

Risk reducing measures

The Alexander Kielland accident could perhaps have been avoided if some risk reducing measures had been implemented better or more effective. Proper inspection and surveillance routines are examples of measures that failed during this accidental event, and correct maintenance strategies and intervals could have lead to the accident being avoided, or the consequences being limited.

Risk reducing measures for structural failures have been drastically improved the last years, and especially after accidents like Alexander Kielland. In general, one could say that the major accident frequency has decreased. It is important to include structural failure risk already in the design phase, because this is the phase where it is easiest, fastest and of course least expensive to make changes that have an effect on the total risk picture. Some reactive risk reducing measures must be present in case of a structural failure leading to an accidental event with major accident potential. Evacuation training is important, as well as including emergency equipment in the design.

4.4.2 Collision with passing vessels

Because the fish farms are planned to operate in more exposed areas, collision with passing vessels is a hazard that needs to be taken into account. In open locations the ship traffic will be more frequent, especially vessels that are not in the aquaculture industry, but just passing by. The speed of these vessels will also be higher because they are further away from the coast and other obstacles.

According to a risk analysis report from Sintef, there was one fatality connected to collision between 1980 and 2003 [3]. In the same report they have calculated the risk to be in the area for acceptable risk[3] using a risk matrix. The Research Council of Norway states in a report from 2009 that the collision risk with external vessels is low, according to the operators themselves [9]. It is still important to include it in the risk assessment, especially since the risk is expected to increase in more exposed areas.

Even though the risk is found to be relatively low, collision accidents can still happen. In 2016, the DOF received a message that the fish farming company Bjørøya AS had discovered net damage on one of their fish farms at Raudøya in Sør-Trøndelag. The colliding vessel was not a part of the fish farming industry. The net hole was approximately 3,5 meters, and the fish had great possibilities to escape. Because the company is responsible for re-catching the escaped fish they started fishing in the nearby area. Even though the net damage was repaired, the damaged fish farm had to be taken out of production. After counting the fish in the fish farm, they concluded that 10 766 fish had escaped [28]. Considering that in 2017 there were only 10 000 fish escapes reported (see figure 3.1), this could be considered a severe incident.

Risk reducing measures

If the facility is stationary without the ability to move, there are mainly two measures that help reduce the collision risk with passing vessels. The first one is increase of visibility of the facility in the water. The faster a passing ship notices the fish farm, the more time will they have trying to avoid colliding into it. Such visibility measures could for example be elevating the fish farm so that it is located higher in the water line. This is however not an optimum solution because of stability and less volume for the fish to swim in. Another method is the installation of lights or other signals to the passing ship traffic. This is perhaps even more important on fish farms because of their inability to quickly change location. Oil and gas facilities have the same challenge, however most of them are large and at least taller than Havfarm 1, so they are more visible at a long distance. Also, all platforms have radar beacons, which are receiver/transmitter transponder devices used as a navigation aid, identifying landmarks or buoys on a shipboard marine radar display [54]. Radar beacons are useful tools when it comes to collision risk reduction in the oil and gas industry.

[3]Based on a scale of 1-4 the frequency and consequence were estimated to be 1 and 2, respectively.

Visibility increase is a proactive barrier, but it is also important to implement reactive barriers. Robustness is the second main measure in order to decrease the overall collision risk. In figure 2.4, increased visibility will be on the left prevention side while increased robustness will be on the right recovery side. The optimum outcome is of course to avoid the undesirable event collision in the first place, but given that it has happened, reactive barriers are important since the consequences could be limited. This way, if a collision occurs, there might only be small damages to the fish farm, instead of total loss of facility and the fish inside it.

A facility has to fulfill a number of requirements in addition to the design criteria against progressive collapse because of an impact load. The same requirements will often affect the dimensions and design of facility, meaning that the facility might have extensive over-capacity with respect to collision impact if we compare it to minimum design limits. The over-capacity is concept dependent and might vary significantly [24, p. 314].

4.4.3 Attending vessel impact

It is important to include risk assessments for attending vessels and not just passing vessels. Relevant vessels could be wellboat and supply boat. These vessels might not have as high speed as passing vessels, but they work closer to the fish farm, which increases the collision probability. An impact between attending vessel and fish farm might not be as powerful, but both supply vessels and wellboats are increasing in size, meaning that even at low speed the vessels could cause severe damages.

Risk reducing measures

One of the main measures to reduce the probability of wellboat impact is DP. When in the sea, the vessel is exposed to wind, currents, waves as well as forces from the propulsion system. These forces result in different vessel motions that are illustrated in figure 4.2 [58]. The adjustment of the vessel in order to keep a steady position as possible is the main function of the DP system.

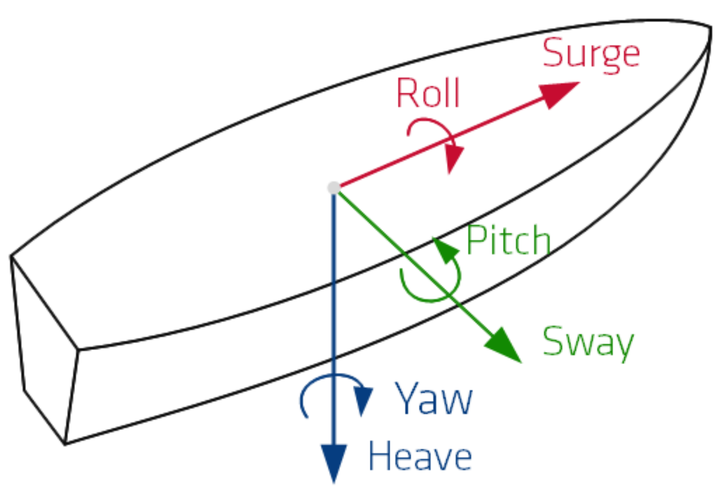


Figure 4.2: Motion model on vessels

The changes in heading, position and speed are taken in by the position-reference systems, gyro compass and vertical reference sensors. Readings from the vertical reference sensors are used to correct reference system readings from roll and pitch. Wind sensors are used to measure speed and direction of the wind. The meaning of DP is to keep the vessel within specified, predetermined position and heading limits, so that wear and tear on propulsion equipment and fuel consumption will be minimized [58]. Choice of DP class, especially DP class 2, is a useful risk reduction measure for loss of position risk.

Net tear due to propellers and other parts of the attending vessel is one of the most common causes of fish escapes. Even though this is a problem in traditional fish farming as well, it is important to keep in mind that this challenge is expected to increase along with the expansion offshore. More and stronger currents, wind and waves result in even more demanding conditions for the fish farm and vessels. Positioning while lying next to the fish farm is therefore important to take into account.

If the weather conditions get extreme the impacts can become quite powerful and cause serious damages on both fish farm and vessel. The major accident risk is therefore absolutely present during the operations that require use of vessel. Because of the large dimensions and amounts of fish, the need for equipment and feed is expected to be larger than the supply need of traditional fish farms near the coast. The development towards more exposed fish farming will also lead to a need of larger supply boats, in order to transport the desired amounts of supplies in a cost-effective way. This size increase, combined with harsh weather conditions and more crane use between vessel and fish farm, are important arguments when discussing the use of DP on the attending vessels, as well as which DP class it is favorable to use.

4.5 Why collision and structural failures?

From this qualitative risk assessment only a few of the hazards will be included further in the quantitative risk assessment in chapter 5. The choice fell on structural failures (section 4.4.1) and collision (section 4.4.2 and 4.4.3). In this assessment, structural failures and damages will be considered a consequence of a potential collision, either by attending or passing vessels.

The change of location to more exposed areas introduces a whole new risk picture when it comes to collision with passing vessels. This risk is therefore considered to be crucial to include in the risk assessment for exposed fish farming, especially compared to traditional fish farming closer to the coast, where the passing vessel traffic is considerably smaller. Attending vessel impact risk is also included due to more challenging weather conditions. Risk of structural failures is included because the consequences of collision are largely decided by constructional variables. The robustness of the facility the vessel collides into will be a large part of limiting the total consequences. Even though this thesis will mainly focus on the proactive side of a collision, meaning the collision frequencies and how they can be controlled, the reactive side is also included. This is to get an overview of how severe the consequences could be for the different collision scenarios, and to see to what extent the fish farm facility will be able to withstand such impacts. Sections 5.7.1, 5.7.2 and 5.8 will cover the frequency calculations from the improved COLLIDE model, and section 5.9 will present the constructional limit calculations.

Chapter 5

Havfarm 1 Case Study

This chapter will present the conditions and information about Havfarm 1, for example its location, classification and the different collision scenarios. The input characteristics will be explained, which includes weather data, common and varying parameters. In the end of this chapter the main results from the COLLIDE modelling and other calculations will be presented.

5.1 Conditions

In this thesis only collision between vessel and the fish farm facility is considered, and collisions including more than one vessel will not be mentioned. Also, the risk assessment will only cover hazardous events and damages to the fish farm, and not the colliding vessels. A safety zone of 500 meters is drawn around the fish farm, which is assumed placed on the real planned location for Havfarm 1. The fish farm is meant to lie at one specific location, and only change position during especially tough weather conditions that might disturb or harm the fish production. During such situations the farm will implement its quick-release system and move using additional thrusters.

5.2 Location

Figure 5.1: Planned location of Havfarm 1

Havfarm 1 is planned to be located on the southwest side of Hadseløya in Nordland. The exact coordinates are N 68°29.9745' E 14°35.139', illustrated in figure 5.1. The shortest distance from shore will be just below 5 km.

5.3 Classification

The DOF has demanded a new development of regulations with a sufficient safety level similar to NS9415[1]. In an e-mail from H. Ådnanes (NSK Ship Design) received on April 12th he says DNV GL has prepared a new set of regulations for them, a so-called regulatory framework. Their design, engineering and construction will follow this. All in all, there are mainly two sets of regulations that are being followed, DNV GL Offshore Rules for the structure, mooring and stability, and DNV GL Ship Rules for all other systems.

Because of the lack of requirements earlier, there has been some confusion in the fish farming industry when it comes to what rules to follow. Even though Havfarm 1 has the shape and structure of a ship, it is important to point out that is not the case, it is an aquaculture facility.

5.4 Collision geometry

Because the fish farm is supposed to be weather vaning, there is a possibility that both passing and attending vessels might collide into all parts of it. In order to simplify, three different collision scenarios are assumed.

5.4.1 Collision into the bow or stern

Collision into the bow and stern are considered to be one collision case here, because their impact energy limits are assumed to be similar. Both of these scenarios are illustrated in figure 2.7, with the two black arrows showing the hitting points. In order to simplify, collision directly into the fish farm with a 90°angle is assumed to cover all cases at all angles.

5.4.2 Collision into the midsection

Figure 2.7 also shows the two different scenarios for midsection collision. The green arrow represents collision to the middle of one of the beams, while the pink arrow covers collision hitting directly on one of the transverse beams across the fish farm. These two scenarios are assumed to cover all midsection collision scenarios because they represent each extremity. A potential collision here is assumed to hit directly into the fish farm at a 90°angle.

[1]Norwegian standard: Marine fish farms; Requirements for design, dimensioning, production, installation and operation

5.5 Input characteristics

5.5.1 Weather data

For the COLLIDE model it was necessary to gather weather data for the planned location of the fish farm. A time period of 365 days was chosen to include all seasons and potential weather. The data for wind speed and direction were provided by the The Norwegian Meteorological Institute (NMI)[2]. There were only data available for Bø i Vesterålen, around 13,5 km north-northwest from the planned location. Due to the locations being very close, their weather registrations are assumed to be similar.

Figure 5.2: Map showing the distance between weather station in Bø i Vesterålen (red circle) and the planned location of Havfarm 1 (red dot) scale 1:277778

5.5.2 Common parameters

The following list consists of common value parameters that were already decided by Safetec Nordic from earlier use of the COLLIDE model. Even though this model is usually used on more traditional offshore operations and the conditions are not completely similar, it is assumed to still be suitable for exposed fish farming operations.

- Failure of own initiated recovery
- Factor for DWT to displacement
- Safety zone
- Standard deviation for supply vessels
- Standard deviation for other vessels
- Probability drift-off (Non-DP vessels)
- Probability drift-off (Supply DP2)
- Mean repair time

[2]Weather data tables can be found in the appendix.

- Effective area factor
- Added mass factor
- Thrust reduction factor
- Reaction time
- Time used for reversing vessel
- Wind speed cut-off
- Wave height cut-off
- Probability of failure of installation initiated recovery
- Probability of failure of ship initiated recovery

5.5.3 Choice of parameters

Section 5.5.3 explains the assumptions and choices when deciding which parameters to use in the COLLIDE model.

Supply boat dimensions and parameters

According to NSK Ship Design, there will be one boat available for fish feed transportation, one service vessel for crew transportation and one wellboat to transfer the fish in the beginning and end of the production[3]. In this thesis this will be simplified. The wellboat will be included in the assessment, as well as one common supply vessel that is assumed to cover fish feed, crew and other equipment. MV "Troms Fjord" was chosen as a suitable supply vessel for Havfarm 1, mainly because of its size and capacity. The dimensions of this vessel are easily collected, as well as engine power, maximum speed and service speed. This vessel also has DP2, which is favorable for a supply vessel in this case. The expected number of visits per year and average length of visit is estimated in cooperation with NSK Ship Design.

The displacement for the supply ship is calculated using equation 5.1. A shape factor of 0,7 is assumed to be suitable for this type of ship.

$$\nabla(tons) = 0,7 * L(m) * B(m) * D(m) * \rho(tons/m^3), \tag{5.1}$$

where L is total length of ship, B is breadth of ship, D is (maximum) draught and ρ is water density.

The feed supply is expected to happen once every two weeks, the same goes with people transportation. There is also a need for equipment supply, so two visits a week will be assumed, meaning 2*52 = 104 times a year.

Wellboat dimensions and parameters

The chosen wellboat parameters for the COLLIDE model are collected from an article from Nordlaks [49]. The missing information is found by using a vessel of comparison, as an approximation. Gåsø Freyja was chosen because of similar length and breadth. The displacement of the wellboat is calculated by using the same displacement equation for supply boat, equation 5.1.

[3] Confirmed in an e-mail April 12th.

The chosen wellboat above will be able to carry around 600 tons live fish at a time. If one assumes 414 000 m^3*25[4]kg salmon/m^3= 10350 tons fish, the wellboat will need to visit the fish farm facility 17 times every time the fish is collected. Because the production cycle will last around 10 months and one should include cleaning and other time-demanding maintenance operations, the wellboat is assumed to operate once per year.

Probability of being on collision course

In this case the probability of being on collision course is set to 1/100 = 0,01. This is a common value for areas without surveillance of traffic. If the chosen area does have surveillance, one can assume a probability of 1/200 = 0,005[5].

Heading angle

Havfarm 1 will be weather vaning while being permanently anchored at the bow. This makes it challenging to decide heading for the fish farm, because this will not be a permanent angle. However, the COLLIDE model is not well suited for varying angles, meaning it was necessary to assume one permanent heading angle at all times. From table 9 in the appendix one can see that the dominating angle range is between 75°and 105°. Almost 19% of the wind came from this range in the given time period, while the other ranges had between 6% and 10% each. The wind rose in figure 5.3 illustrates the typical wind speed and distribution at the location. The wind blows mainly from 90°east. The average wind is therefore assumed to blow from 95°, meaning that this will be the chosen heading of the ship.

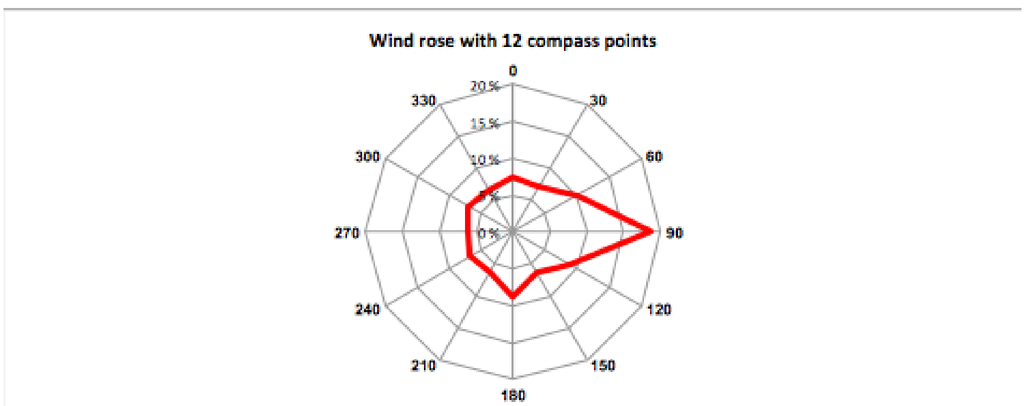


Figure 5.3: Windrose for Bø i Vesterålen with 12 compass points

[4]Limit set by Food Safety Authority.
[5]Parameters confirmed by Safetec Nordic.

Supply ship and wellboat positioning

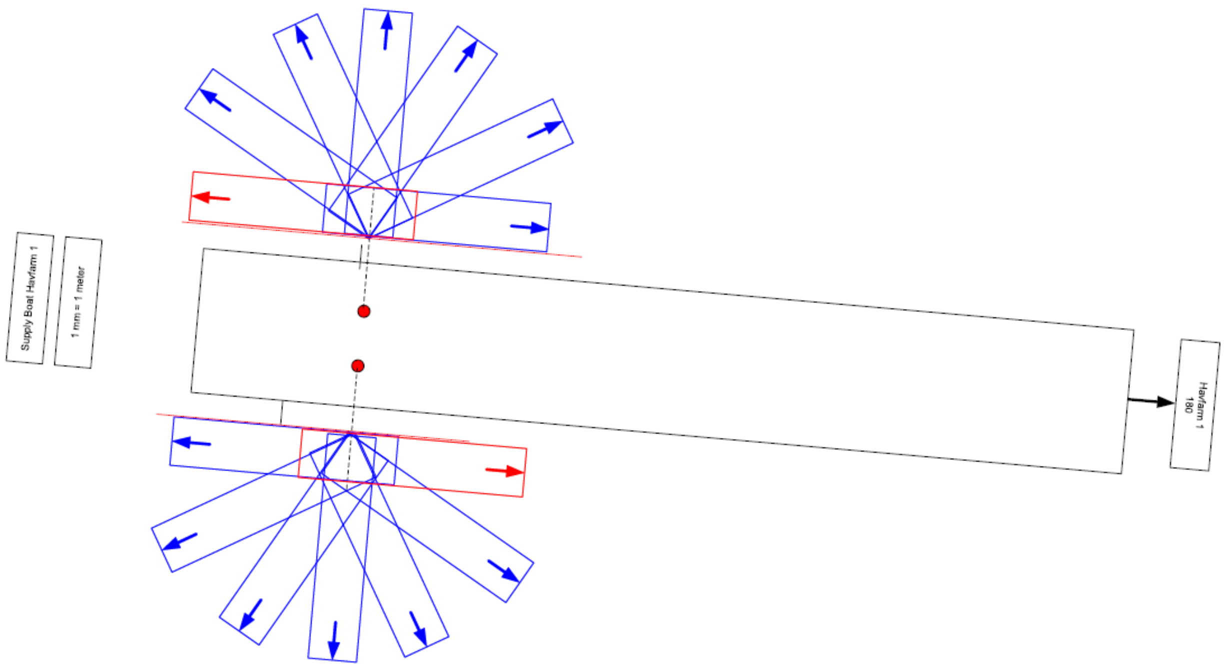


Figure 5.4: Position sketch for supply boat made in Visio

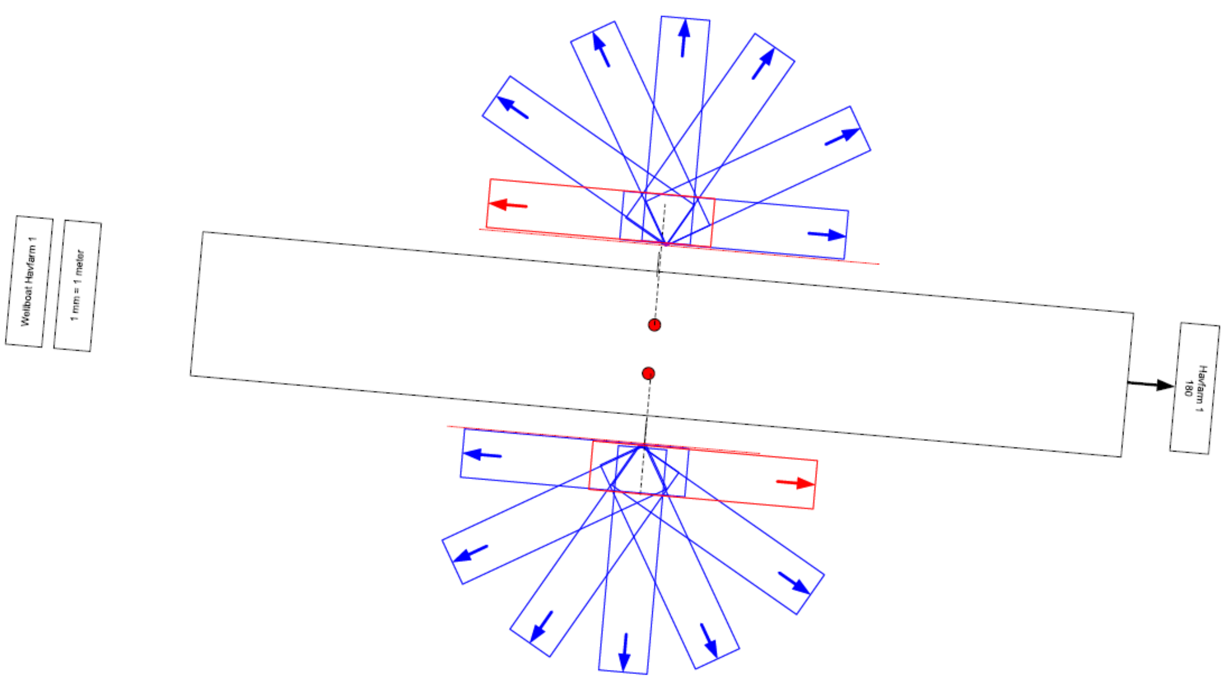


Figure 5.5: Position sketch for wellboat made in Visio

Figures 5.4 and 5.5 represent the different positions the vessels will have during the on- and off-loading operations. The supply vessel is expected to be located at the stern of the fish farm. The wellboat will have varying positions all across the midsection of the fish farm, but to keep it simple it is assumed to be placed only at the middle. These figures were made in Visio, and were used to find the coordinates for the different vessel positions.

5.6 Use of MapInfo

MapInfo Professional is a desktop Geographic Information System (GIS) software product used for mapping and location analysis. In this working prosess it was used to plot the AIS-data in the given area, and give information about the ship traffic and different routes of the planned location of Havfarm 1. Figure 5.6 below shows Hadseløya (up to the right) and the vessel routes in the area around it over a time period of one year. Later the traffic will be divided into five main routes (see figure 5.11). The black dot in the middle of the picture represents Havfarm 1. The two black circles around it define safety zones of 500 and 1000 meters.

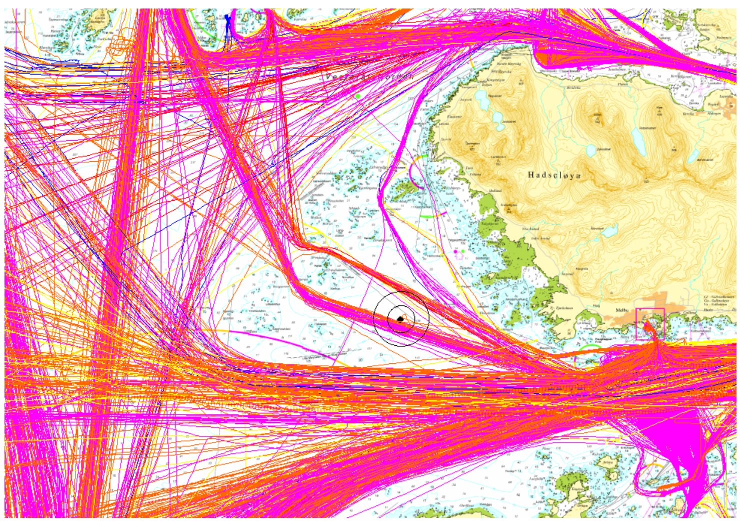


Figure 5.6: Vessel routes during one year drawn in Mapinfo

5.7 Results from COLLIDE model

5.7.1 Attending vessels

Section 5.7.1 will present the results for collision between attending vessels and fish farm. The two chosen vessels are supply boat and wellboat. Due to expected higher transportation frequency of fish feed and crew, the supply boat is assumed to visit the fish farm twice a week, which equals 104 times a year. Since the wellboat Nordlaks will be using for Havfarm 1 can take around 600 tons [49] fish at a time and the fish farm will contain around 10 000 tons fish, it has to visit the fish farm 17 times in order to collect all the fish.

Supply Boat

Supply vessel operations at:	Havfarm1			Impact Energy			
Frequency	[1/yr]	Min <=		14	25	50	100
Results for:	Havfarm1	Max	14	25	50	100 <	
10.05.18 16:04	*Model Revision: Rev37*						
Supply Vessels			**2,83E-04**	**0,00E+00**	**0,00E+00**	**0,00E+00**	**2,59E-05**	**3,09E-04**
-Drive-off			2,87E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,87E-06
--Forward			0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
--Aftward			2,87E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,87E-06
-Drift-off			2,80E-04	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,80E-04
--Forward/Aftward			9,48E-05	0,00E+00	0,00E+00	0,00E+00	0,00E+00	9,48E-05
--Sideways			1,85E-04	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,85E-04
-High speed			0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,59E-05	2,59E-05
-Operational			0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Fishing Vessels			**0,00E+00**	**0,00E+00**	**0,00E+00**	**0,00E+00**	**0,00E+00**	**0,00E+00**
-Transit								0,00E+00
-Fishing								0,00E+00
Passing Vessels			**0,00E+00**	**0,00E+00**	**0,00E+00**	**0,00E+00**	**0,00E+00**	**0,00E+00**
-Head-on incl. move-off								0,00E+00
-Drifting incl. move-off								0,00E+00
-Head-on excl. move-off								0,00E+00
-Drifting excl. move-off								0,00E+00
Total			***2,83E-04***	***0,00E+00***	***0,00E+00***	***0,00E+00***	***2,59E-05***	***3,09E-04***

Figure 5.7: Supply boat impact energy frequencies

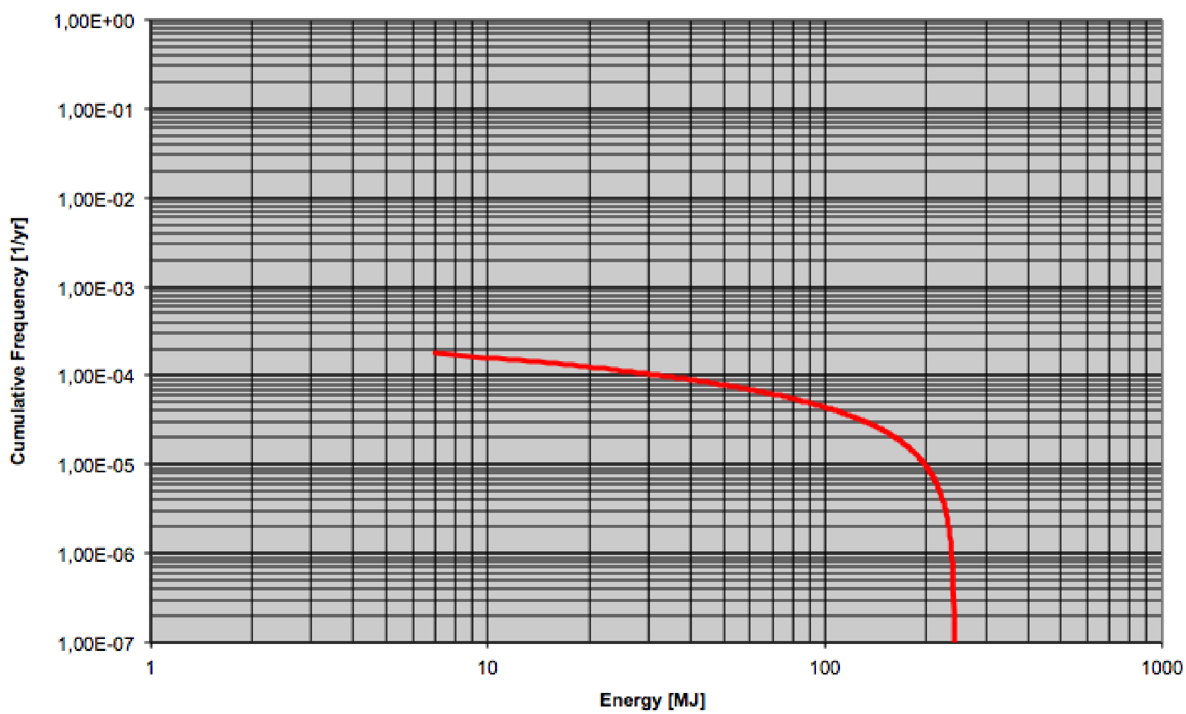


Figure 5.8: Frequency of collision energy during impact between supply boat and fish farm

Wellboat

Supply vessel operations at:	Havfarm1				Impact Energy			
Frequency	[1/yr]	Min <=		14	25	50	100	
Results for:	Havfarm1	Max	14	25	50	100 <		
10.05.18 16:08	*Model Revision: Rev37*							
Supply Vessels			**1,31E-04**	**0,00E+00**	**0,00E+00**	**0,00E+00**	**8,48E-06**	**1,40E-04**
-Drive-off			9,40E-07	0,00E+00	0,00E+00	0,00E+00	0,00E+00	9,40E-07
--Forward			0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
--Aftward			9,40E-07	0,00E+00	0,00E+00	0,00E+00	0,00E+00	9,40E-07
-Drift-off			1,30E-04	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,30E-04
--Forward/Aftward			6,98E-05	0,00E+00	0,00E+00	0,00E+00	0,00E+00	6,98E-05
--Sideways			6,06E-05	0,00E+00	0,00E+00	0,00E+00	0,00E+00	6,06E-05
-High speed			0,00E+00	0,00E+00	0,00E+00	0,00E+00	8,48E-06	8,48E-06
-Operational			0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Fishing Vessels			**0,00E+00**	**0,00E+00**	**0,00E+00**	**0,00E+00**	**0,00E+00**	**0,00E+00**
-Transit								0,00E+00
-Fishing								0,00E+00
Passing Vessels			**0,00E+00**	**0,00E+00**	**0,00E+00**	**0,00E+00**	**0,00E+00**	**0,00E+00**
-Head-on incl. move-off								0,00E+00
-Drifting incl. move-off								0,00E+00
-Head-on excl. move-off								0,00E+00
-Drifting excl. move-off								0,00E+00
Total			***1,31E-04***	***0,00E+00***	***0,00E+00***	***0,00E+00***	***8,48E-06***	***1,40E-04***

Figure 5.9: Wellboat impact energy frequencies

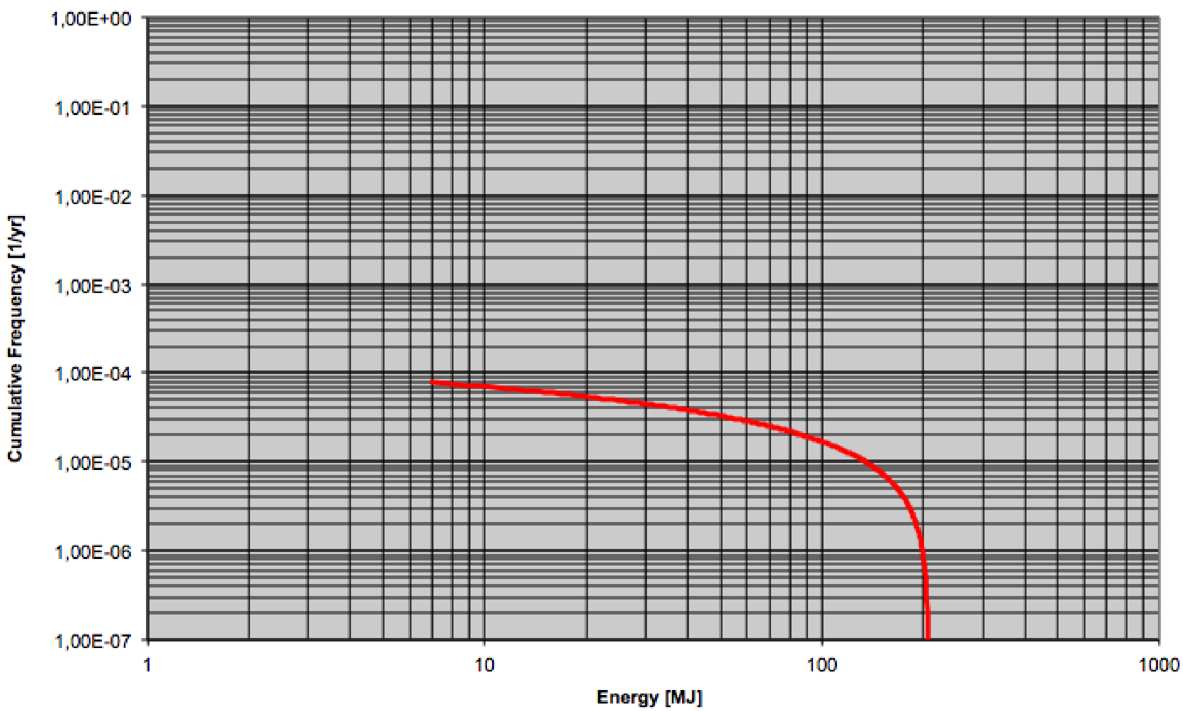


Figure 5.10: Frequency of collision energy during impact between wellboat and fish farm

5.7.2 Passing vessels

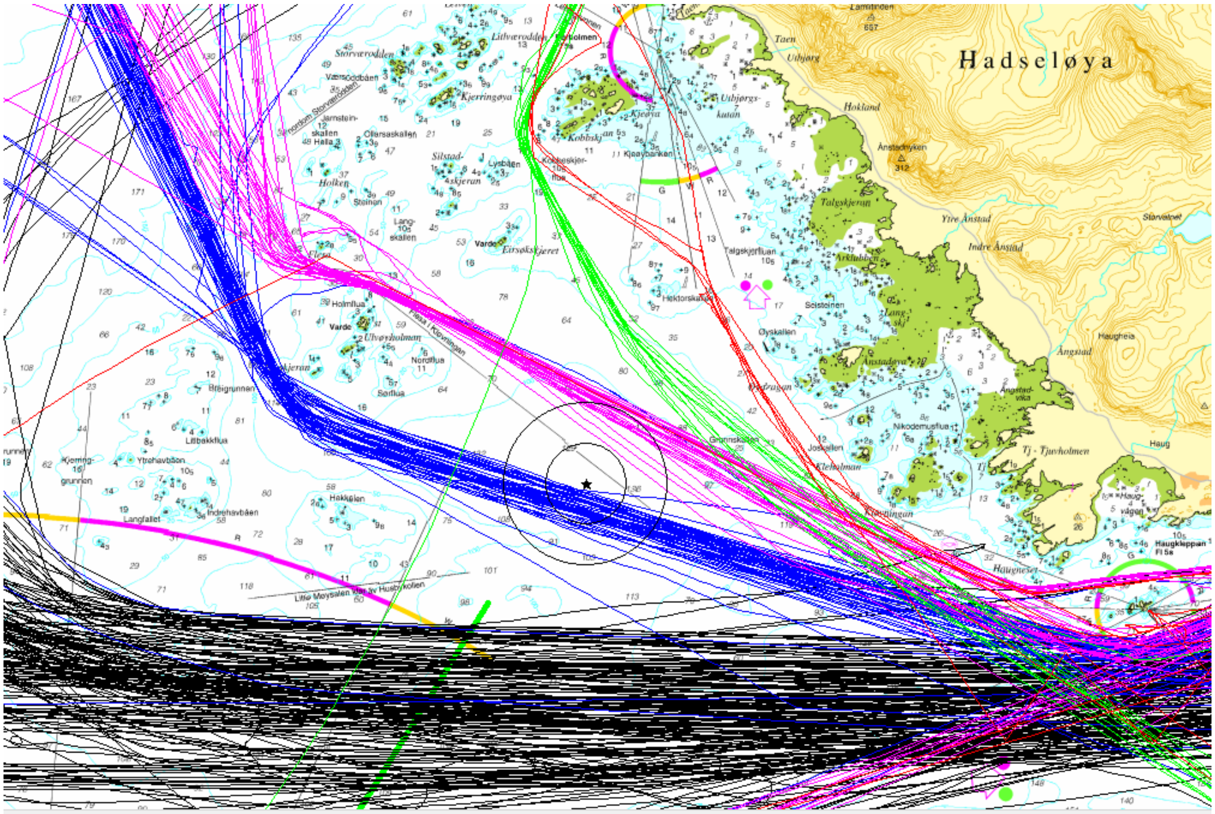


Figure 5.11: Vessel traffic divided into 5 different routes

For simplicity the ship traffic in the area is divided into five different routes illustrated in figure 5.11. Route 1-5 are represented by the colors black, blue, pink, green and red. The black circles in the middle of the figure mark the location of the fish farm and the safety zones around it. Routes that are not representative of the general, annual ship traffic have been excluded. These could be routes of research vessels or seismic ships that only travelled in the area once, or private boats that sail just outside the coast without a specific planned route. These types of vessels are challenging to predict the frequency for, because they have no planned course or path.

Route 1

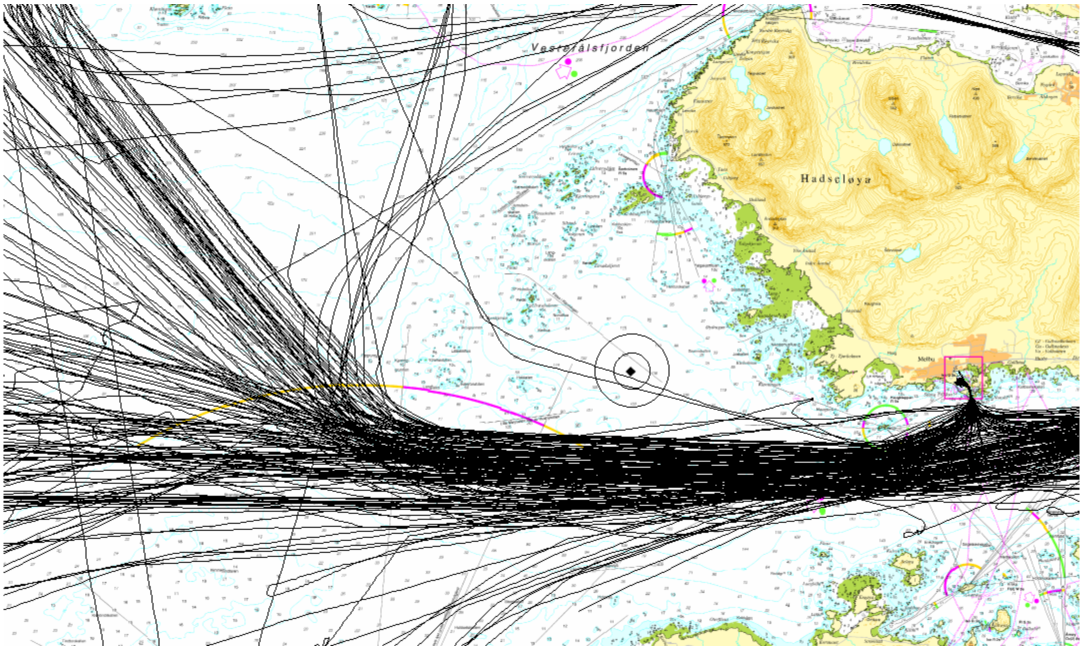


Figure 5.12: Vessel traffic for route 1

Figure 5.12 represents route one in the area where the fish farm is planned to operate. This is the route with the most passings. The vessel categories are fishing vessels, cargo vessels, offshore supply vessels, other work vessels, passenger cruise ships, research vessels and towing/pushing vessels. The largest passing cruise ship, Ship 1A, has a length of 228 meters and a gross tonnage of 47 842. The remaining cruise ships range between 156 and 222 meters, and gross tonnage between 22 496 and 46 052. The dead-weight tonnage of the six vessels range between 3460 and 4870.

Route one is also the only route that includes container ships. 18 of the passings are made by these. However, all of these passings are from the same ship, Container Ship 1B, which is 130 meters long and has a gross tonnage and dead-weight tonnage of 7545 and 8209. 8209 is the largest dead-weight tonnage on this route and therefore on all five routes. Route one is also the only route that includes ships over 100 meters. Eight of the vessels on this route were longer than this.

It is interesting to point out that there are also many smaller vessels on this route, mainly fishing vessels between 20 and 40 meters. In general one could say that the vessel size on this path is quite evenly distributed, and the route includes smaller vessels with gross tonnage just above 200 and larger passenger cruise ships with gross tonnage of 46 052. Figures 5.13, 5.14, 5.15 and 5.16 represent the results obtained for passing vessels using the COLLIDE model.

Passing vessels						
MIN (MJ)	<=	14	25	50	100	
MAX (MJ)	14	25	50	100	<	TOTAL
Powered vessels	7,88E-06	1,33E-06	2,73E-06	1,40E-06	2,41E-06	1,58E-05
Drifting vessels	4,00E-05	0,00E+00	0,00E+00	0,00E+00	0,00E+00	4,00E-05
TOTAL	4,79E-05	1,33E-06	2,73E-06	1,40E-06	2,41E-06	5,58E-05

Figure 5.13: Total collision frequency for passing vessels in route 1

Passing vessels	Frequency of impacts above 14 MJ	Frequency of impacts above 25 MJ	Frequency of impacts above 50 MJ
Powered vessels	7,87E-06	6,54E-06	3,81E-06
Drifting vessels	0,00E+00	0,00E+00	0,00E+00
TOTAL	**7,87E-06**	**6,54E-06**	**3,81E-06**

Figure 5.14: Total collision frequency for impacts over 14MJ for passing vessels in route 1

Figures 5.13 and 5.14 show the total frequency for passing vessel collision and passing vessel collision frequency distribution above a 14 MJ impact. The total frequency for passing vessel impact is 5.58E-05[6][7]. It is the impact range below 14 MJ that contributes the most to this total frequency with 4.79E-05. From this range and up the frequencies lie between 1.33E-06 and 2.73E-06. In figure 5.14 the frequencies are divided into three ranges above 14 MJ, 25 MJ and 50 MJ. The frequencies are 7.87E-06, 6.54E-06 and 3.81E-06, respectively.

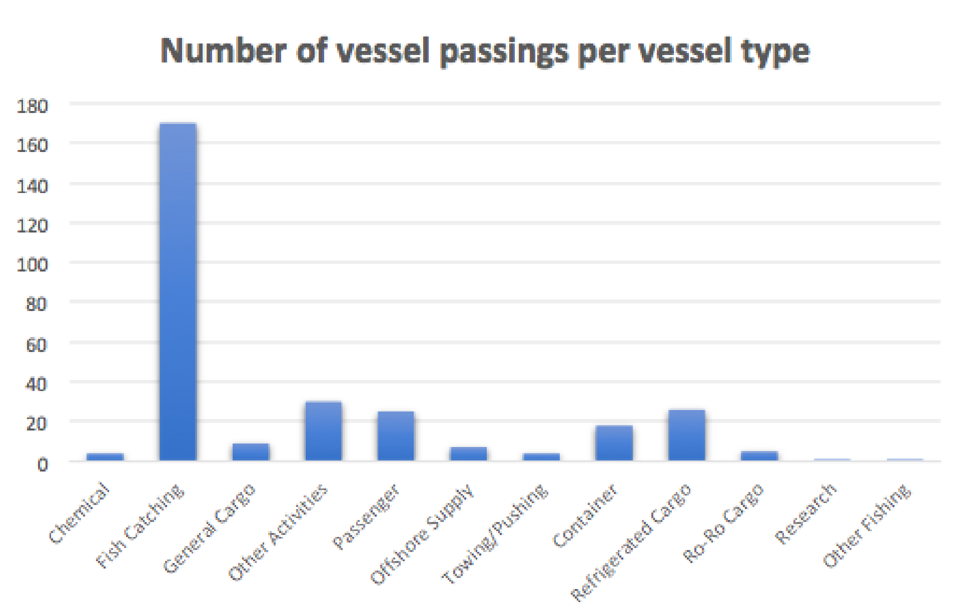


Figure 5.15: Number of vessel passings per vessel type for route 1

[6]The COLLIDE excel sheet is developed in Norway, meaning that they use "," instead of ".". In the text of this thesis, "." will be used.

[7]All frequencies in this thesis apply for a time period of one year.

Figure 5.15 describes the number of vessels that used route one and which vessel categories they belong to. It is clear that fish catching vessels are dominating with 170 vessels, and container ships, refrigerated cargo ships, passenger ships and ships for other activities come in second place with around 20 each.

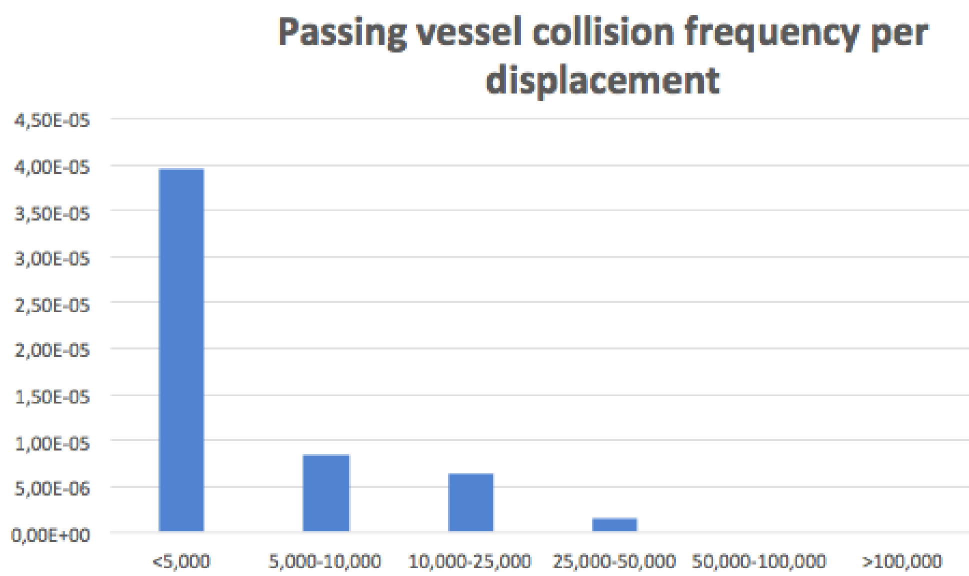


Figure 5.16: Passing vessel collision frequency per displacement for route 1

Figure 5.16 illustrates the passing vessel collision frequency per displacement. The most dominating vessel displacement for route one is below 5,000 with a collision frequency of 3.95E-05. Second largest is vessel displacement between 5,000 and 10,000 with a frequency of 8.48E-06. There are also contributions from displacement range 10,000-25,000 with a frequency of 6.36E-06 and range 25,000-50,000 with a frequency of 1.43-E06.

Route 2

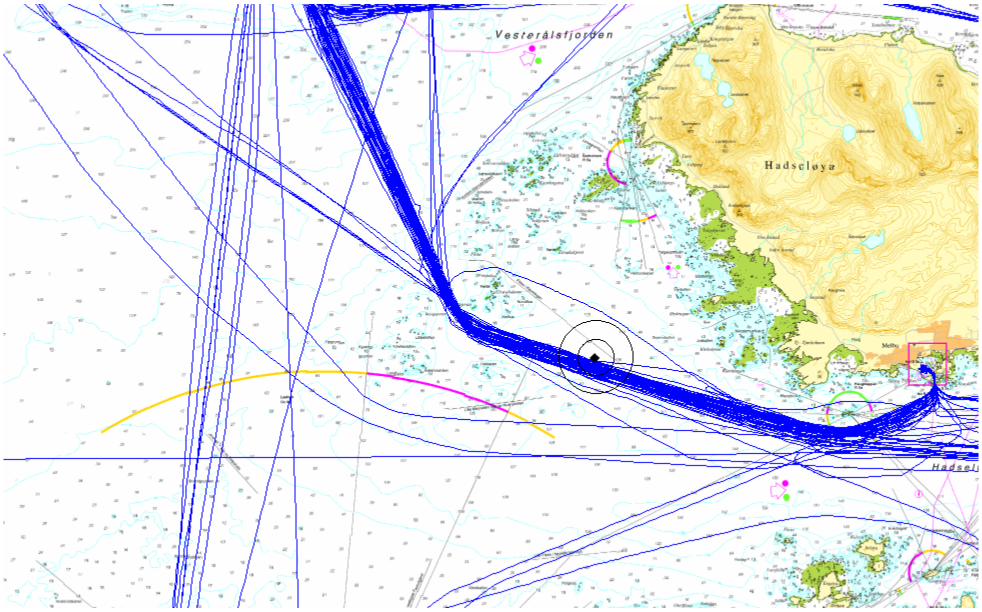


Figure 5.17: Vessel traffic for route 2

Route two includes mainly general cargo and fishing vessels. The largest vessel in this route, Cargo ship 2A, has a length just above 90 meters and gross tonnage and dead-weight tonnage of 1732 and 2665, respectively. Ship 2B and 2C, both refrigerated cargo ships, have the same length of just above 80 meters and gross tonnage of 3538, but a dead-weight tonnage of 2500 and 2532. Another ship, General Cargo Ship 2D, has a length just below 70 meters, and gross tonnage and dead-weight tonnage of 1550 and 2396, which is much lower than ship 2A, 2B and 2C.

Route two is the only route that goes directly through both the 500 and 1000 meter safety zones around the fish farm facility. By looking at figure 5.11, route two will be the most critical with today's traffic distribution. Figures 5.18, 5.19, 5.20 and 5.21 represent the results obtained for passing vessels using the COLLIDE model.

Passing vessels						
MIN (MJ)	**<=**	**14**	**25**	**50**	**100**	
MAX (MJ)	**14**	**25**	**50**	**100**	**<**	**TOTAL**
Powered vessels	7,04E-06	1,76E-06	8,15E-07	2,93E-07	0,00E+00	9,91E-06
Drifting vessels	7,26E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	7,26E-06
TOTAL	**1,43E-05**	**1,76E-06**	**8,15E-07**	**2,93E-07**	**0,00E+00**	**1,72E-05**

Figure 5.18: Total collision frequency for passing vessels in route 2

Passing vessels	Frequency of impacts above 14 MJ	Frequency of impacts above 25 MJ	Frequency of impacts above 50 MJ
Powered vessels	2,87E-06	1,11E-06	2,93E-07
Drifting vessels	0,00E+00	0,00E+00	0,00E+00
TOTAL	**2,87E-06**	**1,11E-06**	**2,93E-07**

Figure 5.19: Total collision frequency for impacts over 14MJ for passing vessels in route 2

Figure 5.18 and 5.19 show the total frequency for passing vessel collision and passing vessel collision frequency distribution above a 14 MJ impact. The total frequency for passing vessel impact is 1.72E-05. The impact range below 14 MJ contributes the most to the total frequency with 1.43E-05. The other frequencies lie between 0 and 1.76E-06, and the frequency in general decreases the higher impact energy range. In figure 5.19 they are divided into three ranges above 14 MJ, 25 MJ and 50 MJ. The frequencies are 2.87E-06, 1.11E-06 and 2.93E-07, respectively.

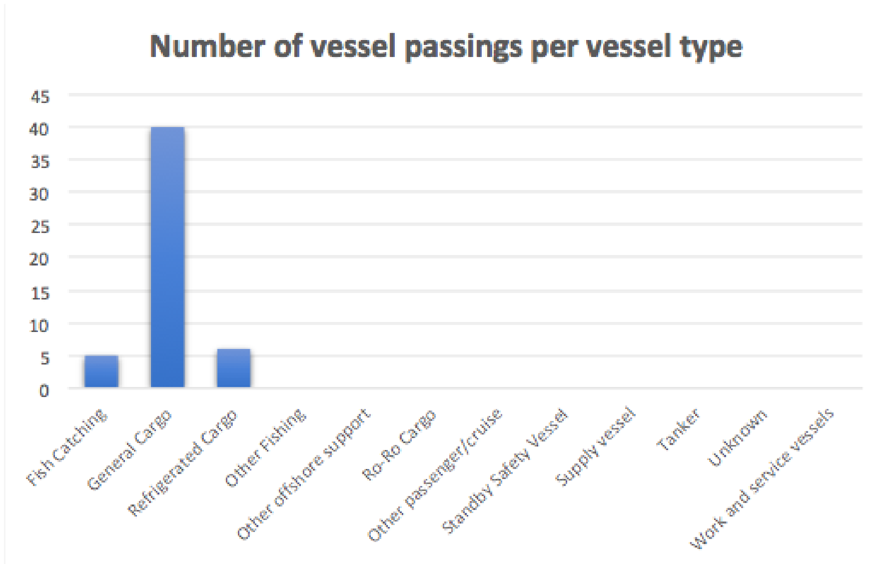


Figure 5.20: Number of vessel passings per vessel type for route 2

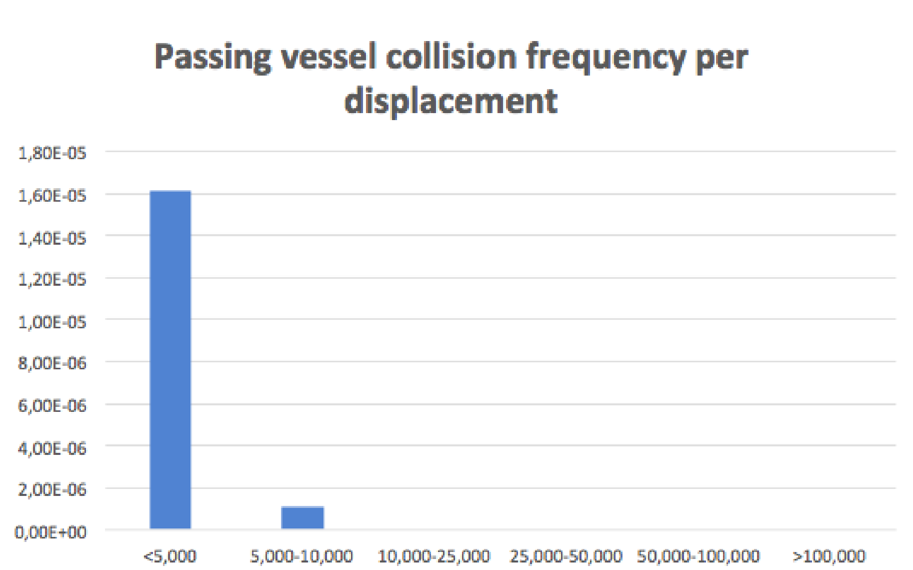


Figure 5.21: Passing vessel collision frequency per displacement for route 2

Figure 5.20 shows that there are three vessel categories for route two. They are fish catching vessels, general cargo vessels and refrigerated cargo vessels. General cargo vessels have the highest number with 40 vessels. Figure 5.21 illustrates the passing vessel collision frequency per displacement. The dominating vessel displacement for route two is below 5,000 with a collision frequency of 1.61E-05.

Route 3

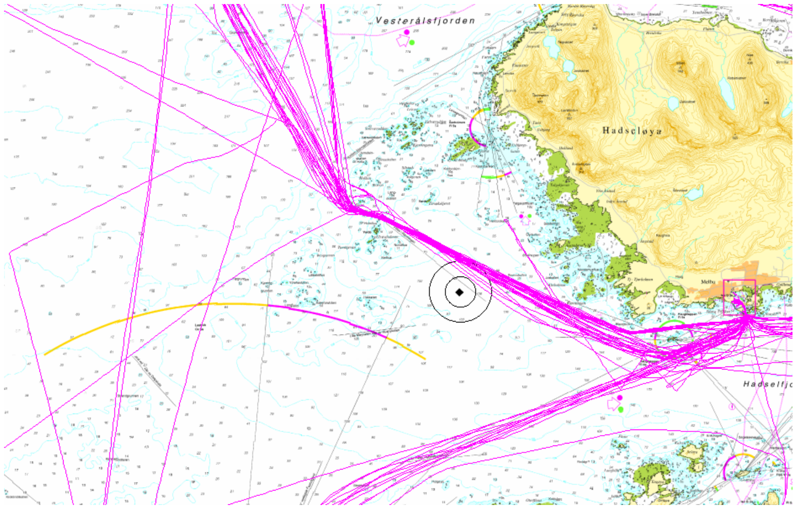


Figure 5.22: Vessel traffic for route 3

Nine of the passings in route three are from Ship 3A. This is a fishing vessel with length just below 30 meters and gross tonnage of 500[8]. The remaining ship traffic is mainly cargo vessels, oil tankers, work vessels and other fishing vessels. One of these passings were made by Ship 3B, which is a 78 meter long refrigerated cargo ship with a gross tonnage and dead-weight tonnage of 2990 and 2713, respectively. Route three is one of the two routes that goes directly through the 1000 meter safety zone around the fish farm facility. Figures 5.23, 5.24, 5.25 and 5.26 represent the results obtained for passing vessels using the COLLIDE model.

Passing vessels						
MIN (MJ)	**<=**	**14**	**25**	**50**	**100**	
MAX (MJ)	**14**	**25**	**50**	**100**	**<**	**TOTAL**
Powered vessels	1,48E-05	5,28E-07	4,11E-07	0,00E+00	0,00E+00	1,57E-05
Drifting vessels	8,12E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	8,12E-06
TOTAL	**2,29E-05**	**5,28E-07**	**4,11E-07**	**0,00E+00**	**0,00E+00**	**2,38E-05**

Figure 5.23: Total collision frequency for passing vessels in route 3

Passing vessels	Frequency of impacts above 14 MJ	Frequency of impacts above 25 MJ	Frequency of impacts above 50 MJ
Powered vessels	9,39E-07	4,11E-07	0,00E+00
Drifting vessels	0,00E+00	0,00E+00	0,00E+00
TOTAL	**9,39E-07**	**4,11E-07**	**0,00E+00**

Figure 5.24: Total collision frequency for impacts over 14MJ for passing vessels in route 3

Figures 5.23 and 5.24 show the total frequency for passing vessel collision and passing vessel collision frequency distribution above a 14 MJ impact. The total frequency is 2.38E-05. The impact range below 14 MJ contributes the most to the total frequency with 2.29E-05. From this range and up the frequency decreases to 4.11E-07 at 25-50 MJ. The frequencies for the three ranges above 14 MJ, 25 MJ and 50 MJ are 9.39E-07, 4.11E-07 and 0, respectively.

[8]Dwt is not given for this vessel.

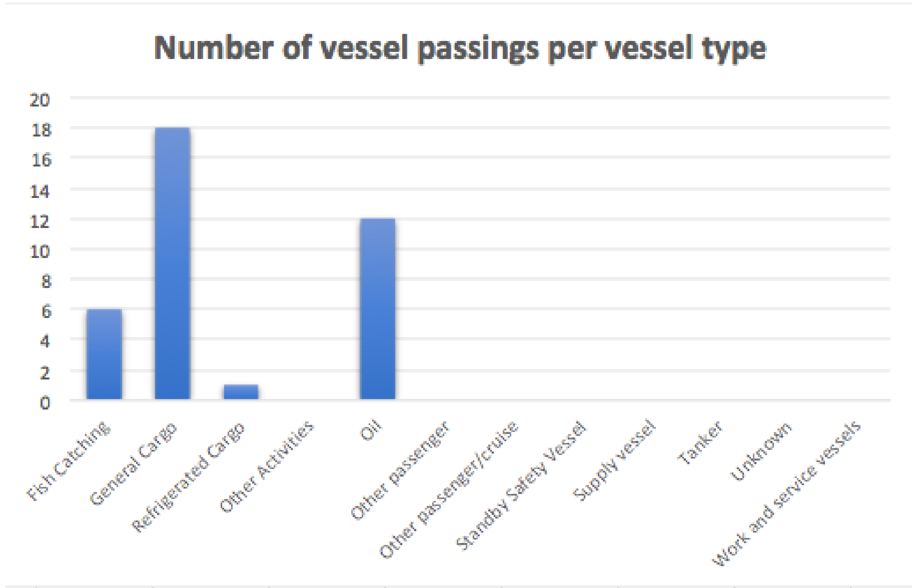


Figure 5.25: Number of vessel passings per vessel type for route 3

From figure 5.25 one can see that general cargo ships and oil ships dominate in route three with 18 and twelve vessel passings. There are also six fish catching vessels and one refrigerated cargo vessel registered.

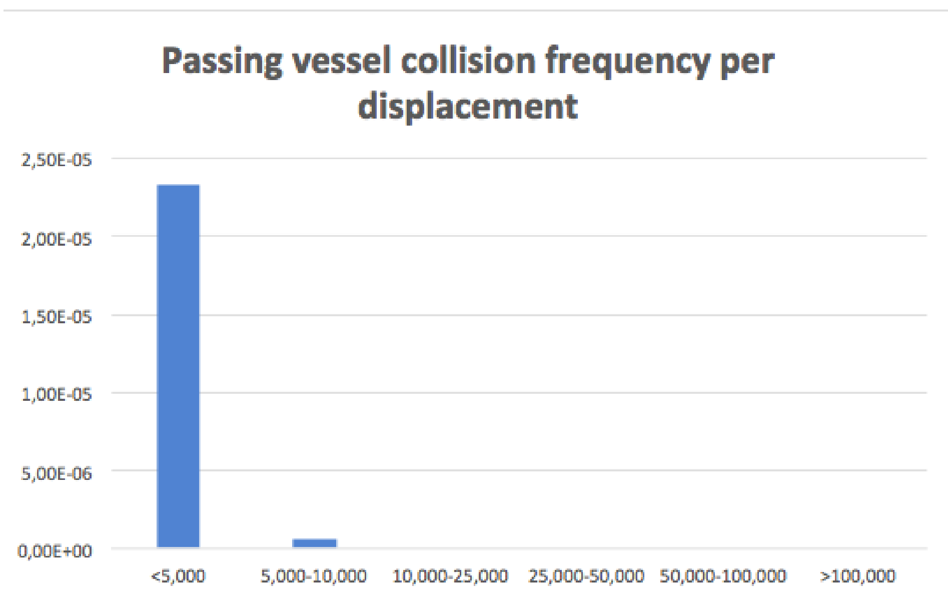


Figure 5.26: Passing vessel collision frequency per displacement for route 3

Figure 5.26 illustrates the passing vessel collision frequency per displacement. The dominating vessel displacement for route three is below 5,000 with a collision frequency of 2.33E-05.

Route 4

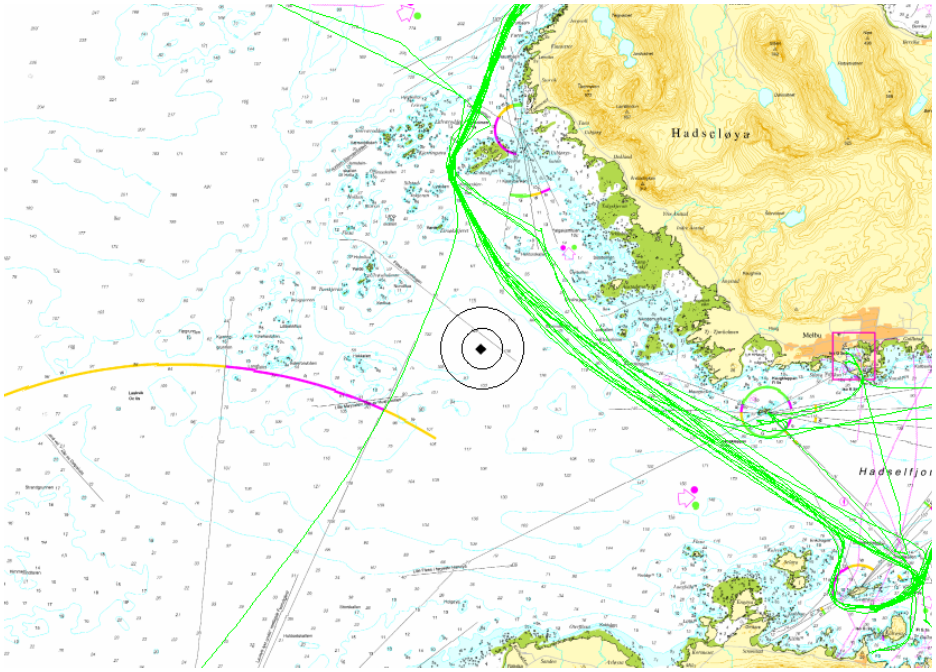


Figure 5.27: Vessel traffic for route 4

The vessel traffic in route four is made up mainly by cargo vessels and work vessels. Eleven of the passings were made by Cargo Ship 4A. This vessel is just below 60 meters with a gross tonnage of 1072 and dead-weight tonnage of 1260. Another vessel, Cargo Ship 4B, only has two passings but has a gross tonnage and dead-weight tonnage of 1679 and 3704, respectively. Figures 5.28, 5.29, 5.30 and 5.31 represent the results obtained for passing vessels using the COLLIDE model.

Passing vessels						
MIN (MJ)	<=	14	25	50	100	
MAX (MJ)	14	25	50	100	<	TOTAL
Powered vessels	6,22E-06	6,00E-07	0,00E+00	0,00E+00	0,00E+00	6,82E-06
Drifting vessels	2,84E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,84E-06
TOTAL	**9,06E-06**	**6,00E-07**	**0,00E+00**	**0,00E+00**	**0,00E+00**	**9,66E-06**

Figure 5.28: Total collision frequency for passing vessels in route 4

Passing vessels	Frequency of impacts above 14 MJ	Frequency of impacts above 25 MJ	Frequency of impacts above 50 MJ
Powered vessels	6,00E-07	0,00E+00	0,00E+00
Drifting vessels	0,00E+00	0,00E+00	0,00E+00
TOTAL	**6,00E-07**	**0,00E+00**	**0,00E+00**

Figure 5.29: Total collision frequency for impacts over 14MJ for passing vessels in route 4

Figures 5.28 and 5.29 show the total frequency for passing vessel collision and passing vessel collision frequency distribution above a 14 MJ impact. The total frequency for passing vessel impact is 9.66E-06. It is the impact range between 0-14 MJ that contributes the most to this total frequency with 9.06E-06. In figure 5.29 the frequencies are divided into three ranges above 14 MJ, 25 MJ and 50 MJ. The frequencies are 6E-07 for impacts above 14 MJ, and 0 for the two other categories.

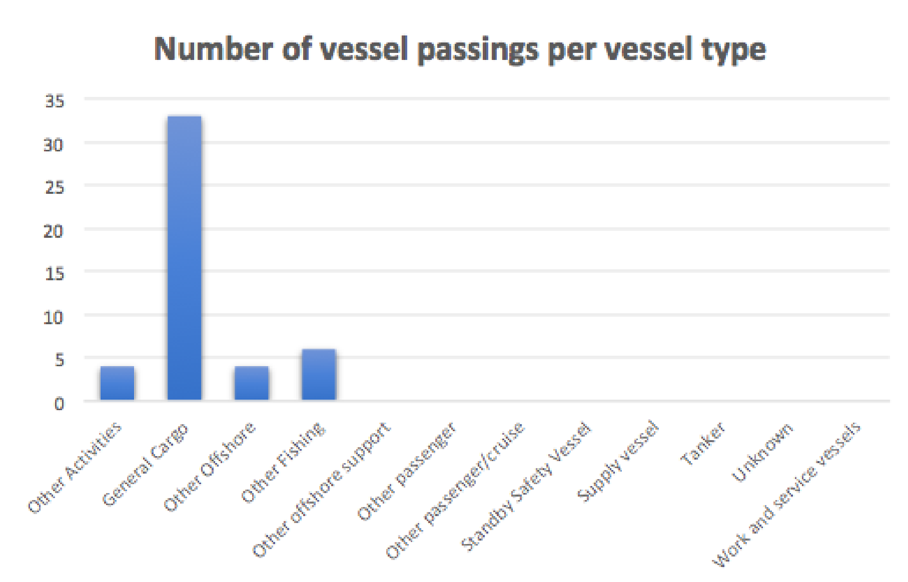


Figure 5.30: Number of vessel passings per vessel type for route 4

General cargo ships dominate in route four with 33 passings. Other offshore ships, and vessels for other fishing and other activities also contribute some to the traffic on this route. Figure 5.31 illustrates the passing vessel collision frequency per displacement. The only vessel displacements registered for route four lie between 0 and 5,000 with a collision frequency of 9.66E-06.

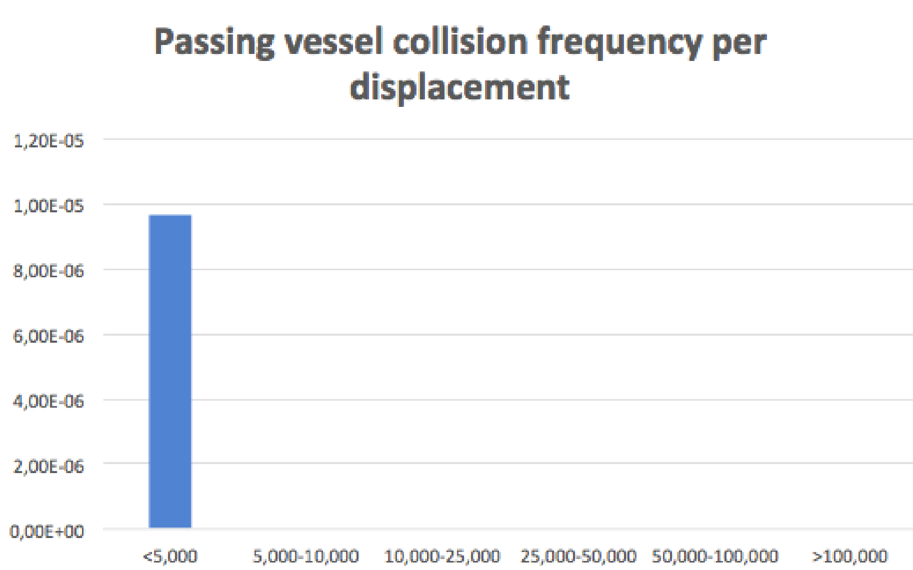


Figure 5.31: Passing vessel collision frequency per displacement for route 4

Route 5

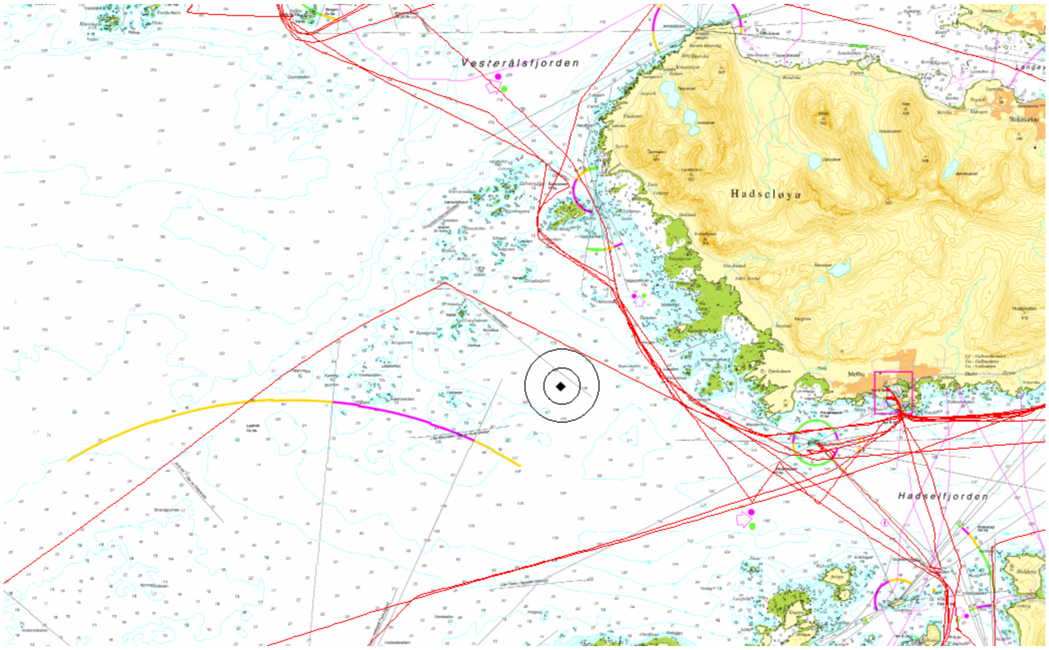


Figure 5.32: Vessel traffic for route 5

Route five in figure 5.32 is the route with the least ship traffic. The vessels involved are mainly work vessels for passenger transport, fishing and other activities. Three of the vessels are between 30 and 35 meters. None of them had gross tonnage or dead-weight tonnage above 500. Figures 5.33, 5.34, 5.35 and 5.36 represent the results obtained for passing vessels using the COLLIDE model.

Passing vessels						
MIN (MJ)	<=	14	25	50	100	
MAX (MJ)	14	25	50	100	<	TOTAL
Powered vessels	3,30E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	3,30E-06
Drifting vessels	1,97E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,97E-06
TOTAL	5,27E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	5,27E-06

Figure 5.33: Total collision frequency for passing vessels in route 5

Passing vessels	Frequency of impacts above 14 MJ	Frequency of impacts above 25 MJ	Frequency of impacts above 50 MJ
Powered vessels	0,00E+00	0,00E+00	0,00E+00
Drifting vessels	0,00E+00	0,00E+00	0,00E+00
TOTAL	0,00E+00	0,00E+00	0,00E+00

Figure 5.34: Total collision frequency for impacts over 14MJ for passing vessels in route 5

Figures 5.33 and 5.34 above show the total frequency for passing vessel collision and passing vessel collision frequency distribution above a 14 MJ impact. The total frequency for passing vessel impact is 5.27E-06. It is only the impact range between 0-14 MJ that contributes to this total frequency. In figure 5.34 the frequencies are divided into three ranges above 14 MJ, 25 MJ and 50 MJ. The frequencies are 0 for all three categories.

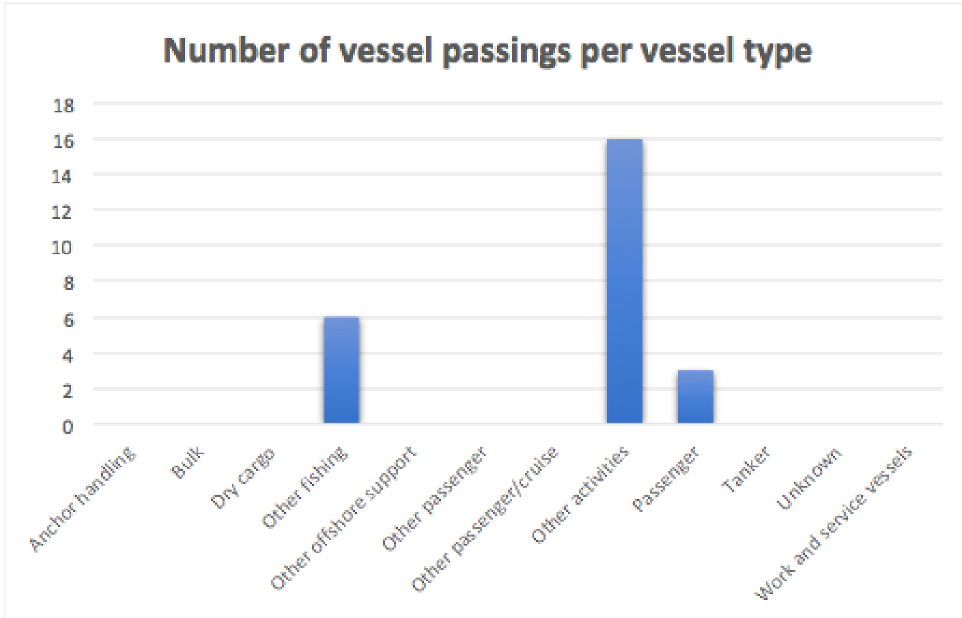


Figure 5.35: Number of vessel passings per vessel type for route 5

Vessels for other activities dominate in route five, with 16 passings during this time period. Other fishing vessels and passenger vessels are also represented.

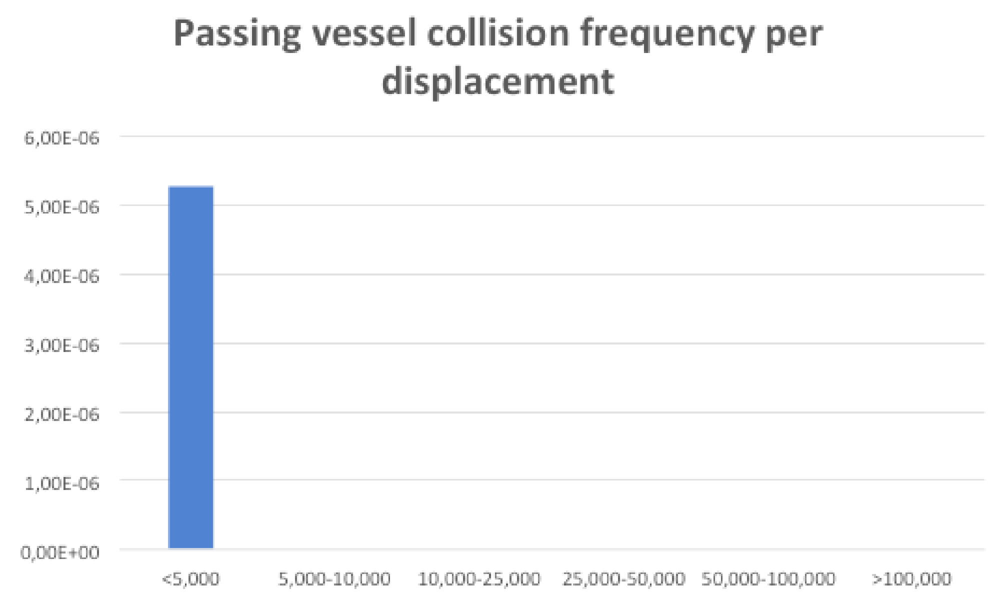


Figure 5.36: Passing vessel collision frequency per displacement for route 5

Figure 5.36 illustrates the passing vessel collision frequency per displacement. The only vessel displacements registered for route five lie between 0 and 5,000 with a collision frequency of 5.27E-06.

5.8 Total collision frequency

Table 5.1: Total frequency for attending vessel impact

Supply vessel impact frequency	3.09E-04
Supply vessel impact frequency over 14MJ	2.59E-05
Wellboat impact frequency	1.40E-04
Wellboat impact frequency over 14MJ	8.48E-06
Total attending vessel impact frequency	4.49E-04
Total attending vessel impact frequency for impacts over 14MJ	3.44E-05

From table 5.1 one can see that the total attending vessel frequency is 4.49E-04, but for impacts above 14 MJ the total frequency is only 3.44E-05.

Table 5.2: Total frequency for passing vessel collision

Passing vessel collision frequency for route one	5.58E-05
Passing vessel collision frequency for impacts above 14 MJ for route one	7.87E-06
Passing vessel collision frequency for route two	1.72E-05
Passing vessel collision frequency for impacts above 14 MJ for route two	2.87E-06
Passing vessel collision frequency for route three	1.40E-05
Passing vessel collision frequency for impacts above 14 MJ for route three	9.39E-07
Passing vessel collision frequency for route four	9.66E-06
Passing vessel collision frequency for impacts above 14 MJ for route four	6.00E-07
Passing vessel collision frequency for route five	5.27E-06
Passing vessel collision frequency for impacts above 14 MJ for route five	0
Total passing vessel collision frequency	1.02E-04
Total passing vessel collision frequency for impacts over 14 MJ	1.23E-05

From table 5.2 one can see that the total passing vessel frequency is 1.02E-04, but for impacts above 14 MJ the total frequency is only 1.23E-05.

Table 5.3: Total collision frequency

Total collision frequency	5.51E-04
Total collision frequency for impacts over 14MJ	4.67E-05

Table 5.3 shows the total collision frequency for both passing and attending vessels. The total frequency for impact energies above 14 MJ is presented in the same table.

5.9 Consequences and collapse loads

Table 5.4 below shows the assumed properties for the steel beams of the fish farm. The same type of steel is assumed used for the entire construction.

Table 5.4: Steel properties

Yield strength	250 MPa
Young's modulus	200 GPa

5.9.1 Collision to middle of beam

Table 5.5: Beam properties

Width	3000 mm
Wall thickness	300 mm

When putting the parameters from table 5.5 in the equations from section 2.10.1, one gets a plastic collapse load of 162 000 000 Pa = 162 MPa. In order to change this into work, the force must be multiplied with the distance. If one further assumes a critical movement of the beam of 0,5 meters, the total energy limit becomes 81 MJ.

5.9.2 Collision to transverse beam

Table 5.6: Beam properties for transverse beam

Width	1500 mm
Wall thickness	150 mm
Moment of inertia	3.74E11 mm^4

The transverse beams in the fish farm are assumed to be smaller than the other beams. When putting the parameters from table 5.6 in the equations from section 2.10.1, one achieves a critical buckling load of 294 MPa. If one further assumes a critical movement of the beam of 0,5 meters, the total energy limit becomes 147 MJ.

5.9.3 Collision to bow and stern

Due to the shape of the bow and stern, it is challenging to estimate these collision load limits. They are however assumed to be higher than the loads for midsection collision[9], and are therefore not calculated as thoroughly as the more critical collision cases. After a total assessment, the impact limits for both bow and stern were estimated to lie between 30% and 40% higher than collision to a transverse beam. This gives a collision energy range of approximately 190 and 205 MJ.

[9] Confirmed in a conversation with Jørgen Amdahl May 9th 2018.

5.10 General observations

The fishing vessels observed in the area in the one year time period generally belong in the category for smaller vessels. There are also more small vessels than large ones. Cargo ships, both refrigerated and general cargo, as well as passenger cruise ships are the main types of large vessels in the area. Route one contains the most passings during the time period, and it also includes the largest vessels. Route two has the second most passings and largest vessels, and the size of the vessels are generally found to be smaller on route three, four and five. Vessels using these routes also need more precision and maneuvering in order to avoid collision and grounding.

Route two and three are the only ones that cross the safety zone. The second route includes more ship traffic and larger vessels than route three, as well as being closer to the planned location of the fish farm, making it the most critical one out of the two. Route two, three, four and five demand high maneuvering skills due to islands and islets, compared to route one, which is more straight forward.

The collision energy resistance of the fish farm is the lowest on the middle of the beam on the fish farm's midsection. If the vessel collides directly into the transverse beam the energy limit is nearly doubled, meaning that the first collision scenario is much more critical than the latter due to the larger bending moment. Collision to the bow or stern is less critical than both of the first scenarios, and is at first sight not considered crucial.

It is important to keep in mind that in the passing vessel collision calculations, not all passing ships contributed to the tables. If a vessel had no registered value for dead-weight tonnage in the AIS data, it was only included in some of the tables and diagrams. The obtained results are therefore expected to deviate some from the results.

Chapter 6

Risk evaluation

6.1 Attending vessel risk

This chapter will first discuss attending vessel risk and passing vessel risk separately, and then compare them to see which one is the most critical, and where one should invest in risk reducing measures to achieve the largest risk reduction.

6.1.1 Comparison between supply boat and wellboat

The total impact frequencies for supply boat and wellboat are 3.09E-04 and 1.40E-04, respectively (see section 5.8). This means that the probability of supply boat impact is more than twice as high as for wellboat. The two chosen vessels for each category are relatively similar when it comes to size, displacement and engine power. The main difference between them is the visit frequency to the fish farm facility. While the supply vessel operates twice every week the wellboat only visits the fish farm once a year. It will then go back and forth between the fish farm and slaughter facility until all the fish is collected. Calculations show that this will be 17 times.

The different positions of the supply and wellboat could also lead to differences in impact frequency. Figures 5.4 and 5.5 show the planned position for both vessels. However, the distance between the positions is relatively small and is not expected to have that much of an impact on the total frequency in the COLLIDE model.

6.1.2 What can be done to reduce the risk?

Based on what has been presented in sections 5.8 and 6.1.1, the most appropriate frequency to reduce is supply boat impact frequency. One obvious solution is to reduce visits to the fish farm and hours spent lying next to it, meaning supply chain improvement. There is also a possibility to use weather forecasts actively in order to predict a suitable weather window for supply. Certain weather conditions may favour to postpone or expedite the planned operation, meaning that proper planning will be the key to a reduced supply vessel impact frequency.

The use of weather forecasting may have a larger impact on wellboat impacts, because they are only operating once a year. This operation is normally planned in good advance before start-up, and is thus more flexible to move due to harsh weather conditions. A well-planned operation makes it easier to make changes based on the weather forecast. There is of course a question about economy, how long can the operators actually wait before the costs of having a wellboat ready get too high? It is also important to keep in mind that a more quiet sea will lead to calmer conditions on board for the fish, and fish quality is expected to be better, increasing the total profit. This means that the most favorable time to start operation should be optimized according to weather forecast and available vessels and crew.

6.1.3 Attending vessel positioning

In figures 5.4 and 5.5 the assumed positions for supply vessel and wellboat during operation are shown. From the results (see section 5.9) it is clear that midsection collision is more critical than bow and stern collision, based on these calculations alone. Because of the positioning, it is expected that bow collision is not that relevant for attending vessels. The wellboat is assumed to lie along the midsection, close to the critical hitting point on the middle of a beam.

Based on the calculations in section 5.9, the impact limit is 81 MJ. From figure 5.9 it is observed that there is a higher frequency of an impact energy below 14 MJ with 1.31E-04, which contributes the most to the total wellboat impact frequency of 1.40E-04. In the same figure there is a small frequency contribution of 8.48E-06 for impact energies above 100 MJ. Such an impact between the wellboat and fish farm is considered to be severe, because the energy exceeds the limit of 81 MJ. If the wellboat hits directly on a transverse beam, the limit will be 147 MJ. Based on this, the fish farm will be able to withstand the impact if it is lower than this limit. Even though a potential impact on the middle of the beam could cause crucial damages, the frequency is considered so low that the risk will not exceed the risk acceptance criteria (see section 2.1.3).

According to PSA, facilities must be designed for a collision with an annual probability of 10^{-4} per year [13]. There is also a common rule for mobile facilities to be designed to withstand a collision energy of 14 MJ[1]. The total frequencies for wellboat and supply vessel collision do however exceed this limit of 10^{-4} per year. Still, these frequencies are for impact energies below 14 MJ, which are assumed to only lead to minor and local damages, and not have major accident potential. The conclusion is therefore that the calculated attending vessel impact frequencies are within the risk acceptance criteria.

Another important consideration to make is where a potential hit would be most crucial for the fish, given that the collision itself does not lead to total loss of fish farm facilities. If the impact energy only causes small damages, it will most likely be more beneficial with an impact to bow or stern, rather than the midsection. This is because the six fish nets are planned to lie in this section, and a smaller collision could here cause net damage and rupture. This way there could be a large amount of fish escaping, without necessarily losing the entire fish farm facility. Therefore, if the impact energy is low enough for the fish farm to stay afloat, but high enough to cause local damages, it could be an advantage to reduce the number of midsection activities and operations.

[1] 14 MJ is also a guiding criterion in NORSOK for production facilities.

For both wellboat and supply vessel impacts the dominating impact energy range is below 14 MJ. Impacts under this limit are not traditionally considered to cause severe consequences such as total loss of facility. Since the wellboat is assumed to lie next to the midsection during its operations, a suitable risk reducing measure could be to find another position for these operations. If the wellboat could be placed closer to the bow or stern and still execute its functions properly, the risk of hitting vulnerable parts of the fish farm could be reduced. There is of course a challenge here regarding pumping and moving the fish effectively. The wellboats are placed there for a reason, the closer they are to the fish nets the easier and faster the fish movement will be completed. The COLLIDE model does not take the impact limits of the different parts of the fish farm into account, so this assessment was mainly done qualitatively.

6.2 Passing vessel risk

6.2.1 Explanation of existing routes

It is not coincidental that there are mainly five routes in the area around the planned location of the fish farm. When studying the map in figure 5.11 one can see the distributions of islands and shears on the west side of Hadseløya. They are a natural explanation to the sudden turns in the plotted routes, and why the vessels are unable to travel closer to Hadseløya to reduce distance and therefore save time.

The fact that the smallest vessels are found in the category for route five is not surprising either, given that this route is the closest to shore and have the narrowest path and shallowest waters. It is still important to remember that there are small vessels in both route one and two, they are not reserved for the large vessels.

6.2.2 Major accidents caused by passing vessel collision

Figures 5.16, 5.21 and 5.26 show that the passing vessel collision frequencies for displacements below 5,000 are 3.95E-05, 1.61E-05 and 2.33E-05 for route one, two and three, respectively. Vessels with large displacements are more capable of causing higher impact energies, and thus higher probability of a major accident with associated consequences. Since all three frequencies for such displacements are lower than 10^{-4}, and their associated displacements are lower than 5,000, one could say that they do not exceed the risk acceptance criteria.

For route one the collision frequency for displacement between 5,000 and 10,000 is 8.48E-06, which is even lower than for displacements below 5,000 for the same route. A displacement between 5,000 and 10,000 could cause more severe damages related to major accidents, but the frequency is assumed to be so low that the risk is still within the risk acceptance criteria. The frequency of displacements between 10,000 and 25,000 is 6.36E-06. The potential impact would have been even larger than 5,000-10,000, but the frequency is even lower and does not exceed the limit of 10^{-4}. The frequency of collision with displacements between 50,000-100,000 is so low that it is not included further.

Route four and five include only vessels with displacement below 5,000, with collision frequencies of 9.66E-06 and 5.27E-06, respectively. This is well below the known limit of 10^{-4}, and the displacement is also so low that the total risk will fall within the acceptable limits. Even with higher displacements the total risk picture could have been acceptable.

6.3 Comparison between attending and passing vessel risk

Equation 6.1 calculates the kinetic energy for collisions. For a long time, an impact energy limit of 11 MJ for head-on collisions and 14 MJ for sideways collisions have been a rule of thumb for Norwegian offshore structures according to DNV GL [24, p. 342-343].

$$E = \frac{1}{2}(m + a_m)v^2 \tag{6.1}$$

where

- m = mass of vessel
- a_m = hydrodynamic added mass
- v = impact velocity

Assuming a vessel of 1000 tons, added mass of 10% and a velocity of 5 m/s in equation 6.1, the collision energy becomes E=0,5(1000*1,1)*5^2 = 13,75MJ. This is just below the limit of 14 MJ. 1000 tons equal to a small vessel, which indicates that the facility might be able to withstand an impact from this type of vessel. However, the limit of 14 MJ is considered to be very conservative, and calculations for over-capacity related to collision and reserve strength implied by the design rules have earlier shown that facilities might be able to tolerate considerably higher impact energies. For semi-submersibles, energy absorption capacities in the range of 60 MJ have been found and for large concrete platforms the impact resistance is likely to be considerably higher. Still, for smaller and less robust facilities, the capacity may be close to the design criterion. The conclusion of this is that the smallest vessels pose no critical threat to larger platform facilities, even at full speed. Smaller and less robust facilities might however be more vulnerable to such impacts[2] [24, p. 343].

From the results obtained in section 5.7.1 and 5.7.2, one can see that the annual frequencies for attending vessel collision are higher than for passing vessel collision. Based on the paragraph above this is considered to be a acceptable result, because the supply vessels and wellboats are considered to belong to the category of smaller vessels. Even though the probability of attending vessel collision is higher, the consequences could therefore be assumed to not be as critical as consequences for passing vessel collision, mainly due to the much larger vessels with higher speed in this category.

[2]It is important to keep in mind that semi-submersibles are normally placed on the sea bottom, unlike Havfarm 1 that will be weather vaining. This might result in different conditions when it comes to robustness and resistance.

6.4 Total collision risk

NORSOK Z-013[3] defines 10^{-4} as a frequency limit for events that will lead to loss of a main safety function[4]. The same standard defines main safety functions as *safety functions that need to be intact in order to ensure that pollution is controlled and personnel that are not directly and immediately exposed, may reach a place of safety in an organized manner, either on the installation or through controlled evacuation.* It is still important to point out that main safety functions are to be defined for each facility individually [2]. PSA Norway also uses a limit of 10^{-4}, which is a common frequency limit for offshore operations. They also state that an impact energy limit of 14 MJ has traditionally been used as a guiding criterion in NORSOK for production facilities, meaning that they should be able to withstand such an impact without losing a main safety function [13].

Based on the paragraph above, one could say that the frequency limit of 10^{-4} applies for impact energies above 14 MJ, because impacts under this limit are assumed not to cause severe damages and loss of main safety functions. The annual total collision frequency for Havfarm 1 was calculated to be 5.51E-04. This is more than five times as high as the frequency limit. Still, the total frequency for impacts above 14 MJ turned out to be 4.67E-05, which is within this acceptance criterion. Because the limit only applies for events that will cause loss of main safety functions, and collisions with energy impact below 14 MJ are not included, one could say that the total collision frequency is lower than the criteria from NORSOK and PSA. For exposed fish farming facilities, it is assumed acceptable to collect acceptance criteria from the oil and gas industry, due to the similarities of the constructions.

Three collision scenarios are assumed. The first is where the vessel hits either the bow or stern. The impact limit was here estimated to lie between 190 and 205 MJ. The second and third cases describe scenarios where the colliding vessel hits the middle of a beam in the midsection and directly on a transverse beam. These impact limits were calculated to be 81 MJ and 147 MJ, respectively. The impact limit of 14 MJ is considered by some people to be quite conservative and outdated, and the calculations show that the construction might be able to withstand impacts higher than 14 MJ and still avoid severe consequences with major accident potential. Since the calculated energy limits are higher than the traditional 14 MJ, one could say that the frequency results are absolutely lower than the impact energy limits. Some would perhaps state that the calculations are too simple or that a potential collision scenario will be completely different than the three cases. Still, due to the lack of constructional information the conditions are assumed to be suitable. A more specific and detailed risk assessment should however be implemented if possible.

[3]The NORSOK standards are developed by the Norwegian petroleum industry to ensure adequate safety, value adding and cost effectiveness for petroleum industry developments and operations [50].

[4]Main safety functions are traditionally used in the offshore industry, but due to assumed similarities it is expected to be suitable for exposed fish farming facilities.

Chapter 7

Discussion

Chapter 7 will discuss the choice of the risk model COLLIDE, and how this choice has affected the results.

7.1 Choice of risk model

Early in the working process the choice of model fell on COLLIDE. This model assesses the probability of collision with offshore installations by using shipping lane information. The term *allision* is not a common expression, and some risk models use the term *collision* instead of it. COLLIDE is one of these models, and it might therefore also be used when dealing with allision. This model also has a primary function of predicting the probability of an impact between passing vessel and offshore installations, not ship-ship collision [40]. There might be some arguments that there are differences between offshore installations and fish farms. The model could also be challenging to adjust to the different concepts for exposed fish farming that are being developed at this time, since they are much more varying, for example in size, shape and robustness. The model is still assumed to be suitable for Havfarm 1, because the shape of it is similar to a ship or FPSO. COLLIDE has earlier been used to cover both of these types of facilities.

The old COLLIDE model could be able to adapt by manually processing the AIS traffic study that is used as input for the model. Some would say that this could be an advantage in this case where the routes are expected to change when the new installation is introduced in the area. This is a method that has already been used occasionally, to predict traffic patterns several years into the future based on expert judgment [29].

7.1.1 Suitability of COLLIDE in this case

The fish farm is supposed to be located in an area with many islands and islets, meaning that it is difficult to assume straight paths and Gaussian traffic distributions. This is clear by looking at figure 5.11, where the five routes are winding in order to avoid grounding. This zigzag motion would have been challenging to model with Gaussian distribution, meaning that the results will match the real life situation better with the new model.

7.1.2 Significance of using new COLLIDE model

The new and improved COLLIDE model by Safetec takes the actual routes of the area into account. This means that the obtained results match the chosen area better than if the old method had been used. One could therefore say that they are more accurate.

In addition to AIS-data, the new model also includes more RIFs compared to the old one. Among other parameters, both average wave and wind data for the last 12 months are included in the new model, as well as parameters such as thrust reduction factor, reaction time and added mass factor. Some would perhaps state that the registered weather the last year only describes the past, and it says nothing about how the weather will be in the future. Despite of this, it would have been quite challenging to collect weather forecasts for the next 12 months, as it is not feasible to predict how the weather will be like in detail a year from now. The uncertainty would have been too large, at least if one compares it to using previous weather data. The weather data from the last 12 months is therefore assumed to suit the next year to come. It might still be beneficial to collect new weather reports annually, to see if the weather changes noticeably over for example five years.

7.1.3 Attending vessel parameter sensitivity

The first round of results for attending vessel risk led to impact frequencies of 1.32E-03 and 3.31E-03 for wellboat impact and supply vessel impact, respectively. Since the impact related to the frequencies were below 14 MJ, this could have been an acceptable result, assuming that 14 MJ would only have caused minor damages. It was still favorable to reduce this risk, and another calculation with different parameters was completed, resulting in frequencies of 1.40E-04 and 3.09E-04. The main parameters that were changed are general dimensions and engine power of the supply vessel, as well as the total number of visits per year. By removing half of the annual visits to the fish farm, the risk got, not surprising, half of the previous value. This was expected because if you double the exposure time, the total risk will double as well. Given that so many parameters had to be changed to reduce the risk to such a level, the sensitivity of each parameter of the model is assumed low. Due to the high number of different parameters that contributes to the frequency calculations, this is not surprising.

Some would say that it could be challenging to find a suitable supply vessel and wellboat that fit these assumptions. This case is assumed especially challenging because the planned vessels are not built yet. Also, unexpected events might arise, leading to increased need of attending vessels. It could therefore be insufficient to estimate a visit of twice a week, since it in reality could be more.

7.1.4 Passing vessel parameter sensitivity

The method for passing vessel calculations takes in fewer parameters than the method for attending vessel calculations. According to Hassel (2017), the three factors that influence the results the most are ”Vessel on collision course”, ”Passing distance” and ”Navigator action”. This did not come as a surprise, because a potential impact requires a ship to have a heading that intersects with an obstacle, and a lack of operator intervention or some form of operator error [40, p. 56].

The time it takes for the vessel to potentially hit the target is mainly decided by the distance between them, which explains why ”Passing distance” affects the probability to a high degree. When using the passing vessel collision sheet, changes in most of the parameters did not cause a large change of the results, but the three parameters mentioned gave a larger variation than other parameters.

7.1.5 Main safety functions

In general, the main safety function loss frequencies for all routes are low. It is however important to remember that the COLLIDE model is mainly used for offshore operations. The assumptions here when it comes to safety are quite different from the expected conditions on board Havfarm 1, both because it is a different facility, but also because of location and type of production. The COLLIDE model assumes that these safety functions are present, which is most likely not the case on a fish farm facility. This could be evacuation methods, reaction times or requirements of redundancy. One might therefore question if the definition of the main safety functions is the same for fish farming as in the oil and gas industry.

7.1.6 Use of safety zone

In the COLLIDE model a safety zone of 500 meters is assumed around the fish farm. An entry past this line will be seen as a hazardous event, and should be avoided as far as possible. Two of the five routes intersects with the safety zones directly. Even though one assumes that the future routes change so that they do not intersect with the safety zones, it could be stated that a ship could still cause a hazardous situation due to irresponsible behaviour [29]. These cases are hard to predict, and could lead to very threatening situations for the installation. The vessel could for example not respect the safety zones at all and pass the fish farm at an insufficient distance, which increases the probability of collision. Such irresponsible vessels lead to a level of uncertainty in the risk assessments, and one could therefore ask if the calculations could be trusted at all. These vessels are still assumed to be such a small part of the total vessel traffic, so the risk assessments should be sufficient if one takes the uncertainties into account.

7.1.7 Possible changes after placement of Havfarm 1

The existing routes will most likely not stay constant after Havfarm 1 is placed at its location [29]. It is assumed that the ship traffic will avoid sailing right into the fish farm, and that the crew on board these vessels are capable of steering away from both the facility and its safety zone. From figure 5.11 it is clear that it is mainly route two and three that will be affected by this. It is therefore expected that the traffic will change here. This makes it challenging to perform sufficient risk assessments as the traffic pattern changes. Still, it could be argued that the risk assessments might become overly conservative if one ignores the introduction of a new installation [29]. It is also important to point out that the water depth south-west of the fish farm, between route one and two, are shallow. For larger ships this might introduce higher grounding risk, and it should therefore be avoided. One solution for these large vessels is to follow route one around the islands and shallow waters. It will take longer time, but collision and grounding risk will likely be lower.

There might also be some challenges using AIS-data. It describes the ship traffic of the past, which is not necessarily suitable to use to describe the ship traffic of the future. Still, it is challenging to estimate the ship traffic patterns of the future, especially since it is expected to change after Havfarm 1 is placed in the ocean. Especially during the months before an installation is installed, there might be a lot of field-related traffic in the area, which could influence the traffic pattern of the location [29]. Because of this, it might be preferable to use datasets from the past, before the installation started. The goal is to find the "real" traffic pattern, meaning that the data should be collected now and not during installation. Even though there is a physical object blocking the previous route, it is not always given that the ship traffic will go around with sufficient distance. Most ships will try to reach their destination as soon as possible, meaning that they could pass the fish farm much closer than what is recommended.

7.1.8 Collision risk reduction for Havfarm 1

There are some collision risk reducing measures available for the fish farm. Even though it is stationary it does not mean that the operators should hope for the best and that other vessels will steer away from the location. The facility itself could be made more visible by use of lights and signage, or a lighthouse could for example be placed on one of the closest islets and islands. They could also invest in external traffic surveillance for the area around the location, or other alarming systems that contact the vessels that are on collision course. These measures are mostly relevant for passing vessel risk. Havfarm 1 will also be equipped with thrusters in order to change location, but it is not certain that this will be a quick enough solution to avoid a potential collision.

7.2 Collision energy limits

In order to simplify the many different collision scenarios, it was chosen to only look at collision to the bow or stern, collision on the middle of a midsection beam and collision directly on a transverse beam. There are of course more potential scenarios than these three, but they are assumed to represent the most critical cases. The beams are assumed hollow, and their dimensions were estimated based on looking at the figures and pictures of the fish farm because of the lack of proper drawings and accurate models. Some would say that the results might have large uncertainties due to this. Still, because of lack of other documentation these values are assumed to be suitable for such a case, especially because the parameters are estimated using drawings from NSK Ship Design. It is important to point out that the energy limit calculations have only been a small part of this thesis, the main focus has been on frequency calculations for passing and attending vessels.

The calculated impact energy limit for bow and stern collision is much higher than for midsection collision, meaning that midsection collision risk should be much more critical. However, by looking at the collision routes in figure 5.11 and knowing that the fish farm will have an average heading of 95 °, it is not unthinkable that a vessel has a higher probability of hitting the bow or stern than the midsection in a potential collision scenario. The COLLIDE model for passing vessel collision does not separate the different collision angles and hitting scenarios, but the heading of the fish farm is expected to mostly be pointed nearly parallel to the nearest routes. There is of course still a possibility of drift-off and drive-off from the other routes, so midsection collision is still a relevant hazard.

Chapter 8

Conclusion

The growth in the Norwegian aquaculture industry has stagnated the last few years, and further expansion is not feasible due to lack of suitable areas and licences. The lack of focus on occupational safety in fish farming is the main reason for the relatively high risks in the industry. Up until the last years there has been lack of suitable rules and regulations for exposed fish farming. It is expected that a new set of requirements will be developed in the years to come, in order to fill the gap of missing regulations. Experience could be collected from the oil and gas industry and introduced to fish farming. One of the main differences is the fish welfare consideration that needs to be taken. It is extremely important to include the biological aspect in fish farming, because it will be a limiting factor no matter how good the technology is.

The total annual collision frequency for Havfarm 1 is calculated to be 5.51E-04. The frequencies for attending vessel impact and passing vessel impact were 4.49E-04 and 1.02E-04, respectively. For impacts above 14 MJ the total collision frequency is 4.67E-05. Frequencies for impacts over 14 MJ caused by attending and passing vessel collision were 3.44E-05 and 1.23E-05. This means that the frequency for attending vessel collision is generally higher than for passing vessels, which is acceptable because the expected impacts made by attending vessels are lower than for passing vessels. It will not be feasible to dimension the facilities for passing vessel collision, because the expected impact energies will be too high. The focus should be on reducing the probability of passing vessel collision.

Even though the total collision frequency exceeds the limit of 10^{-4}, the impacts below 14 MJ are not expected to lead to loss of main safety functions. For impacts above 14 MJ the frequency is below 10^{-4}, which is acceptable since such high impacts are assumed to cause severe consequences and loss of main safety functions.

Three collision scenarios were assumed. The first is where the vessel hits either the bow or stern. The impact limit was here estimated to lie between 190 and 205 MJ. The second and third cases describe scenarios where the colliding vessel hits the middle of a midsection beam and directly on a transverse beam. These impact limits were calculated to be 81 MJ and 147 MJ, respectively. The impact limit of 14 MJ is considered by some people to be quite conservative and outdated, and the calculations show that the construction might be able to withstand impacts higher than 14 MJ and still avoid severe consequences that could lead to major accidents.

The entire working process has been challenging, interesting, frustrating at times, and highly educational. It has given a greater understanding of the situation in the Norwegian fish farming industry and the challenges it faces. The frequencies obtained in this thesis are assumed to be within the risk acceptance criteria. The ones that exceed this criteria are not assumed to lead to severe consequences with major accident potential. Even though the risk is acceptable, it does not mean that one could sit back and never think about risk control and mitigation again. Risk is tentative, and for a different location or facility, the results might not be as acceptable as in this case. The risk picture should always be taken into account in order to maintain a safe fish farming industry.

Chapter 9

Further work

A more specific and detailed risk assessment for Havfarm 1 could be favorable. Efforts should be made to obtain more details regarding construction, dimensions, operations, logistics and choice of attending vessels, so that the results are as accurate as possible for the case. More research of the consequences of a potential collision should be done, because this thesis mainly covers the proactive part of the risk assessment. Drawings and other details for Havfarm 1 could make the energy impact calculations more accurate.

It will be necessary to develop a new and updated set of requirements for exposed fish farms. It could be challenging due to the different types and shapes of facilities, so it should be general in order to cover as many concepts as possible. A part of this process is to sort out the information that is transferable from the oil and gas industry, and which that should be left out. The missing gaps and blanks could be filled with assumptions from traditional fish farming.

Appendices

HAZID diagrams

Table 1: HAZID - Movement of fish from smolt facility to wellboat

No.	*Hazard description*	*Operation*	*Where*	*Hazardous Event*	*Consequence*	*Mitigation*
1	Net Fracture	Elevation of fish net	Smolt facility	Lifting operation causes the net to hook or get stuck on equipment and tear	Fish escape	Double fish net
2	Damage to hose/ detachment of hose	Pumping	Wellboat	Hose is unable to function properly	Fish escape/ Damaged fish/ Low oxygen access for fish	Proper attachment of pump
3	Contamination	Transportation	Wellboat	Contagious diseases spread from wellboat to fish	Fish die	Proper cleaning of wellboat after use, especially delousing
4	People falling into sea	Crane Operation/Positioning	Smolt facility	People falling into cold water	Drowning/Hypothermia	Life vests, proper positioning and safety measures
5	Work accident	Crane Operation	Smolt facility	Exposure to chemicals, hypothermia, fall overboard, equipment injury, loss of limbs, cuts, lacerations, fire, burns,crushing, drowning	Injury or fatality	Proper training, safety equipment, following regulations
6	Fish damage	Pumping	Pump	Fish get stuck in hose/ Low oxygen access	Fish die/Stress/ might reduce appetite	Proper attachment and use of pump, limit operation time
7	Crane damage	Crane operation	Crane	Net drops from crane during lifting	Harm or stress to fish, crane damage	Inspection, maintenance and correct use of crane
8	Prolonged retention in wellboat	Pumping	wellboat	Unforeseen events cause the operation to take longer time than expected	Fish exposed to stress	Improve planning and logistics

Table 2: HAZID - Transportation from smolt facility to fish farm and from fish farm to slaughter facility by wellboat

No.	*Hazard description*	*Operation*	*Where*	*Hazardous Event*	*Consequence*	*Mitigation*
9	Stress	Transportation	Wellboat	Exposure to high fish density causes the fish to stress	Fish get stressed and die	Improve planning and logistics
10	Impact of wellboat into fish farm	Positioning	Wellboat	Wellboat slams into fish farm	Wellboat damage	Better control and operation of the positioning system
11	Positioning failure during delivery	Positioning	Fish farm	Impact of wellboat into fish farm during delivery	Wellboat damage	Better control and operation of the positioning system
12	People falling into the sea from wellboat	Transportation	Wellboat	People falling into the cold water	Drowning, Hypothermia, fall injury, crushing between supply boat and fish farm	Life vests, proper positioning and safety measures
13	Damage to hose/ detachment of hose	Pumping	Wellboat	Hose is unable to function properly	Fish escape/ Damaged fish/ Low oxygen access for fish	Proper attachment of pump
14	Fish damaged on its way out of wellboat	Pumping	Pump	Fish get stuck in hose/ Low oxygen access	Fish die	Proper attachment and use of pump
15	Prolonged retention in wellboat	Transportation	Wellboat	Unforeseen events cause the operation to take longer time than expected	Fish exposed to stress	Improve planning and logistics
16	Wellboat casualty	Transportation	Route between fish farm and slaughter facility	Fire, extreme weather, stability loss, stranding	Loss of well boat, fish die if not recovered	Implement safety systems on board, proper training of captain and crew
17	Impact of wellboat into slaughter facility	Positioning	Slaughter facility	Wellboat slams into facility	Wellboat damage	Better control and operation of the positioning system
18	Damage to hose/ detachment of hose	Pumping from well boat to slaughter facility	Wellboat	Hose is unable to function properly	Fish escape/ Damaged fish/ Low oxygen access for fish	Proper attachment of pump

Table 3: HAZID - Supply

No.	*Hazard description*	*Operation*	*Where*	*Hazardous Event*	*Consequence*	*Mitigation*
19	Impact into fish farm by supply boat	Positioning	Fish farm	Supply boat slams into fish farm	Supply boat damage	Better control and operation of the positioning system
20	Impact into fish farm by supply boat	Positioning	Fish farm	Supply boat slams into fish farm	Fish farm damage	Better control and operation of the positioning system and robustness of fish farm
21	Net Fracture	Positioning	Fish net	Fracture of net causing a hole big enough for fish escape	Fish escape	Double fish net
22	Work accident	Positioning	Fish farm	Exposure to chemicals, hypothermia, fall overboard, equipment injury, loss of limbs, cuts, lacerations, fire, burns,crushing, drowning	Injury or fatality	Proper training, safety equipment, following regulations
23	Falling object	Crane lifting	Crane	Object falling and hitting people	Injury or fatality	Proper safety equipment, following regulations and improve evacuation
24	Falling object	Crane lifting	Crane	Object falling causing harm to fish farm/net	Injury or fatality	Identify areas on the fish farm that may be subjected to impact loads, and ensure integrity towards dimensioning loads
25	People falling from supply boat	Transfer of people	Supply boat	People falling into cold water	Drowning, Hypothermia, fall injury, crushing between supply boat and fish farm	Life vests, proper positioning and safety measures
26	People falling from supply boat	Transfer of equipment	Supply boat	People falling into cold water	Drowning, Hypothermia, fall injury, crushing between supply boat and fish farm	Life vests, proper positioning and safety measures

Table 4: HAZID - Feeding

No.	*Hazard description*	*Operation*	*Where*	*Hazardous Event*	*Consequence*	*Mitigation*
27	Incorrect feeding, technical	Feeding	Fish farm	Fish receive wrong composition of amount of feed	Non optimal growth	Proper inspection and maintenance
28	Incorrect feeding, human error	Feeding	Fish farm	Fish receive wrong composition of amount of feed	Non optimal growth	Proper training of operators
29	Overfeeding	Feeding	Fish farm	Fish eat too much/ Feed leaves fish farm without being digested	Overweight fish increased costs	Accurate feeding evenly distributed in fish farm
30	Feed contamination	Normal operation	Fish farm	Disease is transferred from feed to fish	Fish catch disease and die	Feed quality control
31	Lack of usable feed	Normal operation	Fish farm	Fish does not get enough feed	Starving/ weight loss	Optimize use of feed to given amount of fish/Improve logistics and planning
32	Pollution to sea bottom and sea	Feeding	Sea bottom	Excess feed secreted from fish farm to sea bottom	Feed attracts other species and could change the environment on the sea bottom	Optimize use of feed to given amount of fish

Table 5: HAZID - Inspection, surveillance and maintenance

No.	*Hazard description*	*Operation*	*Where*	*Hazardous Event*	*Consequence*	*Mitigation*
33	Mooring line fracture	Inspection by underwater vehicles	Mooring lines	Damage leading to mooring line fracture caused by underwater vehicles	Loss of mooring traits leading to drifting	Correct use of underwater vehicles, multiple anchor lines
34	Net Fracture	Inspection by underwater vehicles	Fish net	Fracture of net causing a hole big enough for fish escape	Fish escape	Double fish net/ better UWV manoeuvrability
35	Fuel, oil or chemical emission	Inspection	Fish farm	High concentrations in water because of uncontrolled emissions	Fish get sick and die	Sufficient detection and removal traits
36	Insufficient cleaning	Cleaning	Fish farm	Fouling	Wear damage to net causing fracture	Proper cleaning and inspection after cleaning
37	Loss of camera or instruments	Inspection/Surveillance	Fish farm	Environmental conditions leading to loss of camera or other types of monitoring instruments	Loss of monitoring traits, increased costs	Proper fastening of equipment, especially during harsh environmental conditions
38	Incorrect output from measuring instruments	Inspection/Surveillance	Control room	Uncertainties or incorrect use of measuring instruments leading to inaccurate results	Incorrect results from instruments	Correct use of measuring instruments and take uncertainties into account
39	Loss of UWV	Inspection/Surveillance	Fish farm	UWV loses contact with facility on deck, unable to recover from mission	Loss of UWV	Correct use of UWV, sufficient recovery actions, avoid harsh weather
40	Insufficient removal of dead fish	Dead fish removal	Inside fish net	Dead fish lying in the fish farm over a long period of time without being collected	Dead fish might spread disease or attract predators	Detect and collect fish evenly
41	Icing	Ice removal	Fish farm deck	People slipping and falling on slippery deck	Falling injury, fall into water, drowning	Evenly ice removal
42	Fish net fracture not detected	Inspection	Fish net	UWV unable to detect deviations leading to further escalation of the fish net damage	Fish escape	Maintenance and quality control

Table 6: HAZID - Delousing

No.	*Hazard description*	*Operation*	*Where*	*Hazardous Event*	*Consequence*	*Mitigation*
43	Too much chemicals	Delousing by chemicals	Fish farm	Chemical concentration in fish gets too high	Fish die/ quality loss	Accurate use of chemicals evenly distributed in fish farm
44	Too much chemicals	Delousing by chemicals	Fish farm	Chemical emissions secreted from fish farm	Damage to environment on sea bottom	Accurate use of chemicals evenly distributed in fish farm
45	Insufficient delousing by chemicals	Delousing by chemicals	Fish farm	Insufficient removal might leave some lice alive	Lice stock increases again	Make sure delousing is done properly
46	Insufficient delousing by wellboat	Delousing by wellboat	Tanks in wellboat	Insufficient removal might leave some lice alive	Lice stock increases again	Make sure delousing is done properly
47	Fish damage during transfer between fish farm and wellboat	Pumping into wellboat/ retention in wellboat	Pump/wellboat	Hose is unable to function properly when pumping	Fish escape/Fish damaged or stuck/Stress	Proper attachment of pump, limit operation time
48	Stress caused by chemical delousing	Delousing by chemicals	Fish farm	Merging, especially over a long period, causing stress	Fish die	Gentle handling over a limited time period
49	Stress caused by wellboat delousing	Delousing by wellboat	Wellboat	Merging, especially over a long period, causing stress	Fish die	Gentle handling over a limited time period
50	Contamination from wellboat	Delousing by wellboat	Wellboat	Contagious diseases spread from wellboat to fish	Fish die	Proper cleaning of wellboat after use, especially delousing
51	Damage to hose/ detachment of hose	Pumping	Wellboat	Hose is unable to function properly	Fish escape/ Damaged fish/ Low oxygen access for fish	Proper attachment of pump
52	Net fracture	Net elevation before delousing	Fish farm	Lifting operation causes the net to hook or get stuck on equipment and tear	Fish escape	Double fish net

Table 7: HAZID - Normal operation

No.	*Hazard description*	*Operation*	*Where*	*Hazardous Event*	*Consequence*	*Mitigation*
53	Bacteria, virus, fungus or parasites	Normal operation	Fish farm	Fish is infected with disease and not detected and removed	Disease spread and infect more fish, fish die	Vaccination, antibiotics, good hygiene and detection of sick fish
54	Antibiotics resistance	Normal operation	Fish farm	Fish get sick from bacteria that are resistant to antibiotics	Unable to treat infection/fish die	Preventive actions such as vaccination instead of treating disease with antibiotics
55	Too high faeces concentration	Normal operation	Sea bottom under fish farm	Too much faeces is secreted from fish farm and ends up on sea bottom	Too high concentrations of faeces might disturb the natural environment on the sea bottom	Proper sea bottom surveillance and removal of faeces at too high concentrations
56	Chafing on fish net	Normal operation	Fish net	Predators are attracted to fish in fish farm and starts chafing on fish net	Might cause net fracture and escape	Remove dead fish from fish farm to avoid attraction of predators/ Proper cleaning and inspection
57	Collision	Normal operation	Fish farm	Vessel colliding into fish farm	Structural damage to fish farm	Design for collision loads, reconsider position of fish farm
58	Drifting object	Normal operation	Fish farm	Objects drifting in the sea into the fish farm	Structural damage to fish farm	Reconsider position of fish farm/ Identify areas on the fish farm that may be subjected to impact loads, and ensure integrity towards dimensioning loads of fish farm
59	Extreme weather	Normal operation	Fish farm	Fish farm is exposed to loads exceeding allowed limits	Structural damage of farm leading to casualty	Design for given weather forecast, reconsider position of fish farm
60	Work accident	Normal operation	Fish farm	Exposure to chemicals, hypothermia, fall overboard, equipment injury, loss of limbs, cuts, lacerations, fire, burns,crushing, drowning	Injury or fatality	Proper training, safety equipment, following regulations
61	Fire	Normal operation	Control and machine room	Fire eruption in control or machine room	Injury or fatality	Fire safety measures
62	Fire	Normal operation	Control and machine room	Fire eruption in control or machine room	Damage to equipment	Fire safety measures
63	Birds	Normal operation	Deck on fish farm	Birds flying over fish farm because they are attracted to the fish excrete faeces	Bird faeces on deck	Proper detection and cleaning
64	Predators	Normal operation	Fish net	Predators chafing on net trying to reach the fish in the fish farm	Net fracture and fish escape	Inspection, remove dead fish and avoid overfeeding dead
65	Strong currents	Normal operation	Fish farm	Fish net not being able to withstand the external impact because of currents	Fish getting seasick, loads on net might exceed aloud load limit causing rupture	Reconsider position of fish farm, improve net strength
66	Loss of electrical force	Normal operation	Fish farm	Fish farm loses all electrical power	Unable to implement operations that depend on electrical power	Redundancy, back up power
67	Non-optimal growth rate	Normal operation	Fish farm	Fish is unable to grow optimally	Non-optimal growth rate might cause malformations, general quality loss of the fish and therefore profit reduction	Improve feeding routines, disease control, avoid stress

Table 8: HAZID - Movement of fish from fish farm to wellboat

No.	*Hazard description*	*Operation*	*Where*	*Hazardous Event*	*Consequence*	*Mitigation*
68	Damage to hose/ detachment of hose	Pumping	Wellboat	Hose is unable to function properly	Fish escape/ Damaged fish/ Low oxygen access for fish	Proper attachment of pump
69	Net Fracture	Elevation of fish net	Fish farm	Lifting operation causes the net to hook or get stuck on equipment and tear	Fish escape	Double fish net
70	Contamination	Transportation	Wellboat	Contagious diseases spread from wellboat to fish	Fish die	Proper cleaning of wellboat after use, especially delousing
71	People falling into the sea from wellboat	Pumping	Wellboat	People falling into the cold water	Drowning, Hypothermia, fall injury, crushing between supply boat and fish farm	Life vests, proper positioning and safety measures
72	People falling into the sea from fish farm	Pumping	Fish farm	People falling into the cold water	Drowning, Hypothermia, fall injury, crushing between supply boat and fish farm	Life vests, proper positioning and safety measures
73	Work accident	Crane operation	Fish farm/ wellboat	Exposure to chemicals, hypothermia, fall overboard, equipment injury, loss of limbs, cuts, lacerations, fire, burns,crushing, drowning	Injury or fatality	Proper training, safety equipment, following regulations
74	Fish damage	Pumping	Pump	Fish get stuck in hose/ Low oxygen access	Fish die/Stress might reduce appetite	Proper attachment and use of pump, limit operation time
75	Crane damage	Crane operation and positioning	Crane	Net drops from crane during lifting	Harm or stress to fish, crane damage	Inspection, maintenance and correct use of crane
76	Stress	Merging/Pumping	Fish farm/ wellboat	Merging and pumping, especially over a long time period cause the fish to stress	Fish get stressed and die	Gentle handling over a limitied time period
77	Impact into fish farm from wellboat	Positioning	Fish farm	Wellboat slams into fish farm	Damage to fish farm	Identify areas on the fish farm that may be subjected to impact loads, and ensure integrity towards dimensioning loads

Weather Data from NMI

Table 9: Wind direction and speed from NMI (hours)

Wind direction Wind speed	345 15	15 45	45 75	75 105	105 135	135 165	165 195	195 225	225 255	255 285	285 315	315 345
<= 1.9	92	118	133	93	81	56	35	28	67	61	74	55
2.0- 3.9	163	272	374	606	228	138	90	70	90	86	156	135
4.0- 5.9	172	157	265	554	187	134	143	108	88	75	111	135
6.0- 7.9	124	53	91	254	145	98	151	149	101	68	69	118
8.0- 9.9	53	12	6	68	66	83	124	108	58	62	58	66
10.0- 11.9	31	1	1	34	27	34	101	42	69	71	54	33
12.0- 13.9	7			10	15	3	64	23	65	50	30	18
14.0- 15.9	4			6	10		29	10	31	29	33	11
16.0- 17.9				1	3		15	3	5	15	14	3
18.0- 19.9							12	3	3	3	4	1
>=20.0							3			3	4	

Table 10: Wave periods and height from Eklima

Wave period [s]	Min (>=) Max (<)	0 2	2 3	3 4	4 5	5 6	6 7	7 8	8 9	9 10	10 11	11 12	12 >
Wave height [m]		Probability for observation within each interval											
Min (>=)	Max (<)												
0	1	0,0000	0,0000	0,0000	0,0000	0,3551	3,5511	0,8523	0,2131	0,0000	0,0000	0,0000	0,0000
1	2	0,0000	0,0000	0,0000	0,0000	0,4972	14,9148	12,8551	4,8295	0,7102	0,0000	0,0000	0,0710
2	3	0,0000	0,0000	0,0000	0,0000	0,0000	4,6875	10,2273	5,9659	1,4915	0,2131	0,2131	0,0000
3	4	0,0000	0,0000	0,0000	0,0000	0,0000	0,1420	7,3864	6,6051	1,7045	0,4972	0,0710	0,0000
4	5	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	2,2727	6,0369	2,1307	0,5682	0,0000	0,0000
5	6	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,1420	3,4801	1,9886	0,3551	0,0000	0,0000
6	7	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	1,0653	2,2017	0,2841	0,0000	0,0000
7	8	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,9943	0,1420	0,0000	0,0000
8	9	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,1420	0,0710	0,0000	0,0000
9	10	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0710	0,0000	0,0000
10	11	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
11	12	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
12	13	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
13	14	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
14	>	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000

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