Master's thesis

NTNU
Norwegian University of Science and Technology

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Insight Into Fish Welfare At Potential Farming Sites

A Simulation-Based Approach

Master's thesis in Marine Technology
Supervisor: Bjørn Egil Asbjørnslett
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Preface

This thesis is written to complete the master's education to obtain the degree of Master of Science at the Norwegian University of Science and Technology in the spring of 2021.

The thesis has been produced in 20 weeks of the final semester at the Department of Marine Technology and allocates 30 credits in total. The thesis is inspired by and building on the work done in the project thesis, *Use of environmental-based welfare indicators to assess the fish welfare in exposed fish farming*, from the fall of 2020.

My motivation to develop this thesis derives from my interests in the aquaculture industry and how one can use technology to assess the biological challenges the industry is facing towards further growth.

I want to thank my supervisor, Professor Bjørn Egil Asbjørnslett, for guidance and feedback during the semester.

Trondheim, 10.06.2021

Maria Cristina Danielsen

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I would like to thank the following persons for help and support throughout the work with this thesis:

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Jan Tore Fagertun from SINTEF Ocean for valuable input data.

M.C.D

Summary

The objective of this thesis was to study how one can use the available research about the farming of Atlantic Salmon to gain insight into the fish welfare at potential farming sites. Responsible technological development takes place on the premises of biology. This thesis has presented how one can use simulation to gain insight into the welfare of farmed Atlantic salmon with the use of environmental-based welfare indicators.

Stocking density affects the welfare of salmon. Aquasim was used to design three different HDPE fish cages, where the most petite cage had an initial stocking density of 25 kg/m^3. This is the highest allowable stocking density (fiskeridepartementet 2021). The cage's behavior was then simulated for different exposure levels defined by NS9415. It was concluded that none of the cages were suitable for the highest exposure levels. In terms of stocking density, one can use the small and medium cage from *low* to *substantial* exposure levels and still maintain a responsible stocking density that does not compromise welfare.

A model has then been created in Simulink MATLAB to simulate how the welfare of Atlantic salmon is affected by being exposed to a given set of environmental conditions and handling operations during the seawater phase of the farming production. The model was tested through a case study using input data from two potential farming sites referred to as location X and Y. This included current speed, water temperature, and significant wave height. It was not possible to draw any conclusions about one location being better than the other as the historical data used were from a short period.

Validation of the simulation model was performed through a sensitivity analysis. Extreme combinations of the environmental parameters were used as input to see any significant changes in the resulting plots. From the sensitivity analysis, it was clear that periods with either excellent or terrible environmental conditions over time resulted in an accumulation of fish welfare.

It was suggested to implement a maximum value for fish welfare to solve the model's observed weakness with accumulation for further work. One should also include more of the welfare indicators in the model as the fish welfare is affected by several parameters besides the ones included.

Sammendrag

Formålet med denne oppgaven har vært å studere hvordan en kan bruke tilgjengelig forskning om oppdrett av Atlantisk laks for å få økt innsikt i fiskevelferden på potensielle oppdrettslokaliteter. Ansvarlig teknologisk utvikling må skje på biologiens premisser. Denne oppgaven presenterer hvordan en kan bruke simulering for å få innsikt i velferden til atlantisk laks ved bruk av miljøbaserte velferdsindikatorer.

Fisketettheten innad i merden påvirker laksens velferd. Aquasim ble brukt til å designe tre ulike HDPE merder, hvor den minste merden var designet til å ha en fisketetthet på 25 kg/m^3. Dette er den høyeste tillatte fisketettheten (fiskeridepartementet 2021). Merdenes deformasjon ble deretter simulert for ulike eksponeringsnivåer definer av NS9415. Det ble konkludert med at ingen av HDPE merdene var egnet for de høyeste eksponeringsnivåene. Det var derimot mulig å bruke den minste og mellomstore merden fra *lav* til *betydelig* eksponeringsnivå, og fremdeles opprettholde en tetthet som ikke gikk på bekostning av fiskens velferd.

En model ble utviklet i Simulink MATLAB for å simulere hvordan fiskevelferden til atlantisk laks ble påvirket av å bli eksponert for et gitt sett av miljøkondisjoner og håndteringsoperasjoner i sjøvannsfasen av produksjonen. Modellen ble testet gjennom et casestudie hvor en brukte miljødata fra to potensielle oppdrettslokaliteter. Input inkluderte informasjon om strømhastighet, vanntemperatur og signifikant bølgehøyde. Det var derimot en begrenset mengde data, og grunnet dette var det ikke mulig å trekke noe endelig konklusjon angående hvilke lokasjon som var bedre enn den andre med hensyn på fiskevelferd.

En sensitivitetsanalyse ble utført for å validere simuleringsmodellen i Simulink. I perioder med enten veldig gode eller svært dårlige miljøforhold resulterte i en akkumulering av fiskevelferd med ekstreme verdier.

For videre arbeid ble det foreslått å implementere en maksimal verdi for fiskevelferden for å løse modellens observerte svakhet. Videre burde en ta hensyn til flere velferdsindikatorer enn de som allerede er inkludert da fiskevelferd er svært komplekst og påvirkes av mange faktorer.

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Chapter 1

Introduction

1.1. Background

The world needs to produce 70% more food within 2030, and only 2% of the food energy for human consumption comes from the sea (Commission 2017). The animal protein produced from aquaculture uses fewer resources and is more environmentally friendly compared to livestock. Increased aquaculture production is a part of the plan to feed future generations (Bjelland et al. 2015). From modest beginnings in the 1970s, the Atlantic salmon industry in Norway has grown to produce 1,326,216 million metric tons in 2016 (FAO 2018). Most of the growth was between 2000 and 2016. For the last two years, Norwegian production has been growing at a relatively low rate due to regulatory constraints and difficulties with sea lice (Food and Organization 2019).

The high mortality rates in the fish farming industry are alarming, and the consumers are getting more aware of where their food comes from. Seafood consumption in Norway has decreased by 17 percent between 2012 and 2017. The most significant decline is for those under 34, where consumption has fallen by 46 percent since 2012 (NRK 2018a). A larger focus on fish welfare ensures a more efficient production with reduced mortality rates. It is also necessary for the consumers to know that the living creatures are being treated more humanely.

Several environmental concerns are making it hard to increase production further as new farming permissions are restricted for traditional sites as long as key issues with negative environmental impacts are not solved or managed better (Hvas, Folkedal, and Oppedal 2020). In the last couple of years, there has been an increasing interest in ”Offshore aquaculture,” which takes place further at sea compared to today’s regularly used locations. (Bjelland et al. 2015).

Through the scheme with development permits, the government facilitated the development of new aquaculture technology, including technology that is better suited for more exposed locations. However, it is unlikely that fish farming operated further towards the sea will replace the current aquaculture business, but instead come in addition to the current production (Regjeringen 2018). Several authorities regulate aquaculture in Norway, including the Directorate of Fishery, Norwegian Maritime Authority (NMA), Norwegian Labour and Inspection Agency, and Food Safety Authority (Jin et al. 2018).

There are many studies and published reports available regarding fish welfare. With the increasing focus on gathering relevant data about the environment and the salmon's behavior, the industry is going in the right direction. By finding a relatively easy method to analyze and present the information available, one could use this to evaluate how and where it is best to operate a fish farming facility at sea.

1.2. Objectives

This thesis aims to study how one can use the available research and findings regarding the farming of Atlantic Salmon to gain insight into the fish welfare at potential farming sites. The fish farming industry faces many challenges related to high mortality rates, diseases and environment. The purpose of this master thesis is to propose methods to gain insight into the welfare of farmed salmon at different sites. By doing so, the industry can further develop methods and decision-making tools based on maintaining a sufficient level of fish welfare.

1.3. Scope and Limitations

The fish are exposed to several environmental parameters that vary from site to site. Based on the salmon's known tolerance limits for different parameters affecting their welfare, it is possible to use simulation to gain insight into their fish welfare during the seawater phase of the farming production.

The simulation will also take into account standard handling tasks affecting the fish welfare. Delousing, net cleaning and tension of mooring system are complicated operations that are influenced by current speeds and greater wave heights. As these operations are performed regularly and significantly affect the salmon, it is essential to include them in the simulation model.

A basic simulation model was created during the project thesis that only took into account some environmental parameters. For instance, stronger currents gave indications about good welfare due to good swimming training and a higher exchange rate of water, leading to better oxygen conditions. The project thesis did not consider that the circular HDPE cages, which are the most commonly used fish cage today, experience significant deformations when exposed to these types of conditions. A study analyzing the deformation of different sizes of HDPE cages exposed to varying environmental conditions will be included in the master thesis to gain insight into fish welfare based upon stocking density.

The operational simulation model will be tested and further analyzed through a case study using input data from two potential farming locations. The main output will be how the fish welfare varies over a specific period at a given location. Based on these results, one could compare and see if one location is better than the other regarding fish welfare.

The most significant limitation that this master thesis is facing is the lack of relevant data. It is not easy to measure fish welfare, and it is affected by a large number of parameters. The welfare status is based upon the salmon's needs related to resources, environment, health, and behavior. The salmons' tolerance limits for salinity, oxygen, CO_2, and pH are available. These are welfare indicators that should also be included in the simulation model, but the author could not gather these types of data from the chosen locations used in the case study.

Welfare indicators available for the chosen locations were water temperature, current speed, and significant wave height. Information about how the different handling operations affected the welfare was also included. The case study used only data for six months for one specific year, leaving out how the welfare would have been affected for the other half of the year. Therefore, it is not easy to make any conclusions from the results in the case study to decide what location would be more suitable than the other in terms of fish welfare.

1.4. Structure of the Report

The remainder of this paper is organized as follows:
Section 2 contains a literature review. This includes information regarding the fish farming industry, fish welfare, stocking density and HDPE fish cages.
In chapter 3, different methods used to gain insight into fish welfare are presented. The chapter introduces how Aquasim can be used to design and analyze HDPE fish cage deformation. This is used to gain insight into fish welfare related to stocking density. It further goes into the principle of environmental-based welfare indicators, and how one can use this information in Simulink MATLAB to gain insight into fish welfare during the operational seawater phase of fish farming.
Chapter 4 tests the method described in Chapter 3 in a case study. The results from the case study are presented in chapter 5 before they are discussed further in chapter 6.
Concluding remarks and further work are given in section 7.

Chapter 2

Literature review

2.1. Fish Farming Industry

The fish farming industry in Norway is responsible for 29,000 jobs and exports seafood to consumers in more than 130 countries worldwide. In 2018, each job in the core activity of the Norwegian aquaculture industry created two more jobs in other Norwegian businesses or industries. For each krone created in the core activity of Norwegian aquaculture, another area of the Norweigan economy creates 1.48 krone in the value (ISFA 2018).

A commercial license is required to operate a fish farm to regulate the volume produced in Norway to obtain market control. The licensing system is controlled and issued by national authorities. One license has maximum allowable biomass (MAB) of 780 metric tons unless the fish farm location is in Troms and Finnmark, then the MAB is 945 metric tons. A company owns the license to a farm, and it is transferable between different locations, and the company can sell the license further. (MOWI 2019)

2.1.1. Salmon Production cycle

The production cycle for salmon farming takes about three years. The first year consists of fertilized eggs and fish grown to approximately 100 - 150 grams in a controlled freshwater environment. Next up is the seawater phase, where the fish stay until they have grown to around 4-5 kg for 12-24 months. The growth rate of the fish is strongly dependent on the seawater temperatures, which vary throughout the year. Finally, when they reach harvestable size, the fish are transported to processing plants where they are slaughtered and gutted.(MOWI 2019)

In Norway, smolts are usually released into the seawater twice a year. Harvesting happens evenly throughout the year. Most of the harvesting occurs in the last quarter of the year as this is the best growth period. During harvesting, the pattern shifts to a new generation, and consequently, weight dispersion between large and small harvested salmon is more significant at this time than for the rest of the year.

When harvesting is complete for a specific site, the location is fallowed between 2 and 6 months before it receives the next generation (MOWI 2019). Fallowing is important as this method allows the seabed to rest and recover, and it ensures that farmed salmon have a healthy environment in which they can grow and thrive in (SSPO 2020).

See figure 1 for an illustration of the Atlantic salmon life/production cycle.

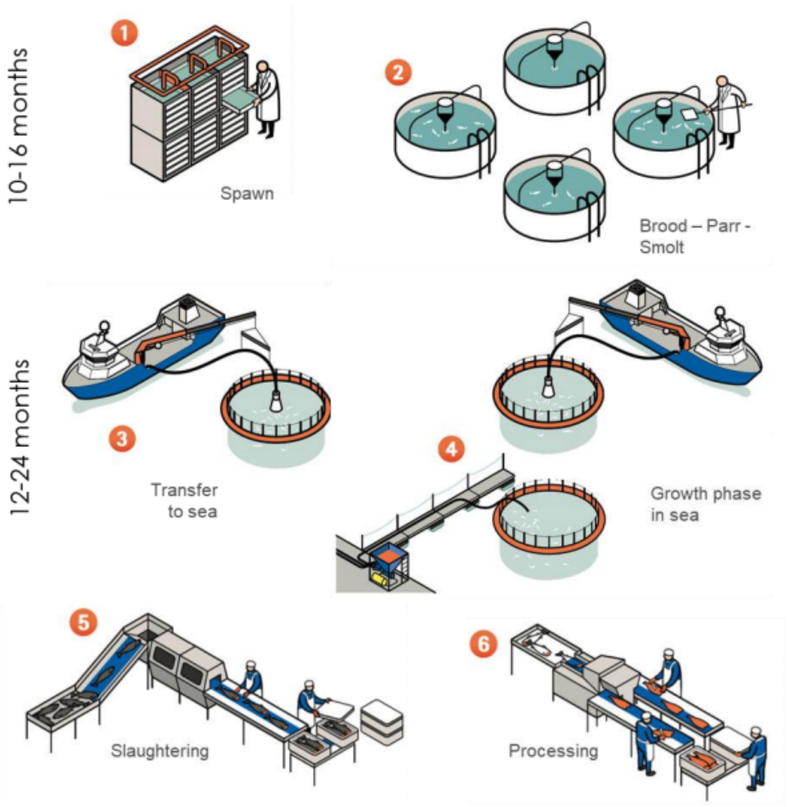


Figure 1.: Atlantic salmon life/production cycle (MOWI 2019)

2.1.2. Site Selection

One of the most crucial factors affecting economic viability is the site selection in any fish farming operation. The choice of the site directly influences the running costs, production, mortality, and overall profitability. Exposed sites have better conditions regarding the environment and fish welfare, but it leads to higher investment costs and risks related to the fish cage and equipment used.

The classification of site exposure between coastal and offshore is heavily debated, and multiple definitions have been proposed so far. In this thesis, one will use the classifications proposed by NS9415 as a standard. NS9415 classifications are basing the degree of exposure on significant wave height (Hs), peak wave period (Tp), and current speed (Vc).

Site classification (wave classes)	**Wave height (Hs) (m)**	**Peak wave period (Tp) (s)**	**Site exposure level**
A	0.0 - 0.5	0.0 - 2.0	Low
B	0.5 - 1.0	1.6 - 3.2	Moderate
C	1.0 - 2.0	2.5 - 5.1	Substantial
D	2.0 - 3.0	4.0 - 6.7	High
E	>3.0	5.3 - 18.0	Extreme

Table 2.1.: Norwegian site classification based on statistical parameters of waves

Site classification (current classes)	**Current speed (Vc) (m/s)**	**Site exposure level**
A	0.0 - 0.3	Low
B	0.3 - 0.5	Moderate
C	0.5 - 1.0	Substantial
D	1.0 - 1.5	High
E	>1.5	Extreme

Table 2.2.: Norwegian site classification: based on mid-current speed

2.2. Fish Welfare

The production of salmon seems relatively straightforward, as described in section 2.1.1. However, several factors affect the production cycle, fish quality, and ultimately the business as a whole. One of the biggest challenges the fish farm industry is facing is the high mortality rates. The Fish Health Report from 2019 states that the salmon fish farming industry in Norway had a mortality rate of approximately 16% percent (Institute 2019). The media has also shed light on the problem, and from 2018 it was shown that some companies had a mortality rate above 40% while others had a mortality rate below 5% (NRK 2018b). Farmers who improved the fish welfare noticed improved growth rates, reduced fin damage, and improved feed conversion ratios (Stewart et al. 2012). This section will focus on the environmental conditions and the different parameters affecting fish welfare.

2.2.1. 3-way definition

There is no universal definition of animal welfare, but there are several ways of perceiving this. The concept of animal welfare often includes three elements: the animal's normal biological functioning (the animal is well nourished and healthy), its emotional state (no stress or fear), and its ability to express certain normal behaviors (Fraser et al. 1997). However, there is a reason why a universal definition is difficult to establish. An animal's ability to experience stress or fear if there is a natural cause, like the presence of a predator, does not immediately indicate poor welfare but lets the animal express normal behavior.

2.2.2. The Five Freedoms

The Five Freedoms are internationally accepted standards of care that affirm every living being's right to humane treatment. Britain's Farm Animal Welfare Council developed these standards in 1965 (OIE 2020)

We have five freedoms of animal welfare which is freedom from:

- freedom from hunger and thirst
- freedom from discomfort
- freedom from pain, injury, and disease
- freedom to express normal behavior
- freedom from fear and distress

However, there are several drawbacks with the principle of freedom as it reflects a more ethical view than a science-based approach. (Korte, Olivier, and Koolhaas 2007) An argument of why this concept is no longer desirable as a measure for welfare is that with complete freedom of fear, diseases, or injury, the animal would not have the natural defense mechanism helping to protect them against potential threats and dangerous substances.

2.2.3. Stability and capacity with respect to change

Allostasis is stability through change and the capacity to change. Figure 2 shows animal welfare in relation to environmental challenges as shown by the outdated concept based on homeostasis and the new concept based on allostasis. Instead, it is the flexibility to change that is important for good physical and mental health (Korte, Olivier, and Koolhaas 2007).

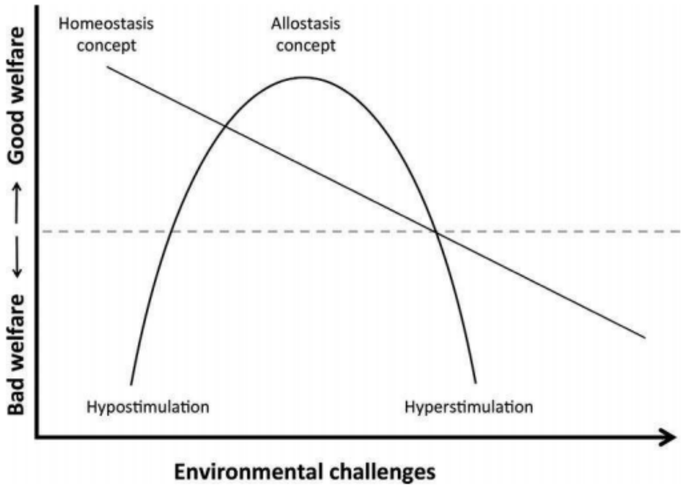


Figure 2.: Allostasis concept

Homeostasis implies that the controlled physiological variables are kept at their *set point*. This definition refers in a way to the balance which exists between the animal and its surroundings. Implicitly it suggests that without environmental challenges, good animal welfare can be guaranteed.

However, this concept does not take into account the absence of environmental challenges that produce hyperstimulation in the animal and, consequently, bad animal welfare. (Korte, Olivier, and Koolhaas 2007)

Following this line of reasoning, overall predictive physiological and behavioral capacity to anticipate environmental challenges characterizes good animal welfare. Thus, good animal welfare is guaranteed when the regulatory range of allostatic mechanisms matches environmental demands.

2.2.4. Factors affecting fish welfare

To achieve good animal welfare the fish needs environmental conditions. Here normal life processes are maintained, and the animal is free from injuries and chronic stress at all stages

(CERMAQ 2018).

Noble et al. 2018, made an overview of the welfare needs of salmon and categorized them into needs directly linked to its available resources, water environment, health, and behavioral freedom. The level of fulfillment of these needs affects their mental state and welfare status of the animals. See appendix A for full overview. The needs are many, and it is not easy to retrieve data and create a model that fulfills them. The following sections give a brief overview of the different categories.

Resources

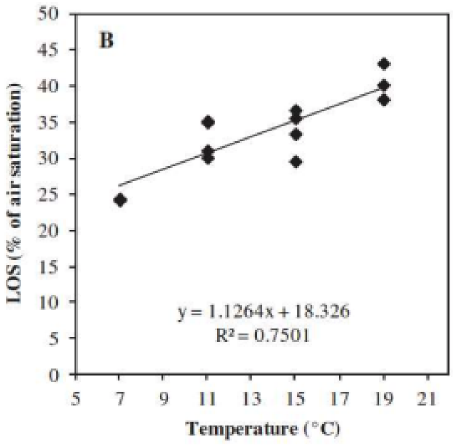
This category covers the fact that the fish should have regular access to nutritious and healthy food to satisfy their hunger.

In the wild, salmon eat small prey from the river before migrating to the sea. In the seawater phase, they consume fish. The salmon needs the right amounts of protein, carbohydrates, fats, vitamins, and minerals. The amount of nutrients varies throughout the life cycle, so the nutrient content on commercial feed must be adapted to how old the fish are. Today, farmed salmon are eating dry pellets. The pellets consist of all the nutrients the salmon requires and have traditionally consisted of 40-60 % fish flour and 20-30% fish oil (Havforskningsinstituttet 2015). Currently, 75% of the content of Norwegian salmon feed is derived from the land, compared to 70% in 2012. The feed primarily consists of plant-based ingredients like soy, wheat, and maize to make it more sustainable. (Aas, Ytrestøyl, and Åsgård 2019).

The feed is distributed to the fish farm from a feed barge that is continuously filled up by vessels transporting it from onshore. Satisfying the welfare needs would be to feed the fish a life stage and species-specific ratio that satisfies its appetite requirements. This is very difficult in practice as the appetite of salmon is fluctuating, and lower feed intake may therefore not be an indicator of poor welfare. There have been several experiments for optimal feeding efficiency by having the fish fast or restricted from food. Food restriction has been giving results that indicate better quality of the salmon, and ultimately increased profitability as the feed-related costs account for 50% of the expenses during the seawater phase (Johnsen 2006). However, underfeeding has also been shown to cause more fighting and injuries as the salmon can be more competitive when hungry (Ellis et al. 2008).

Environment

The industry is always looking for the best location to install fish farms to achieve good animal welfare. Several factors affect fish welfare, and this section will give an overview of how these contribute to a *healthy* cage environment.



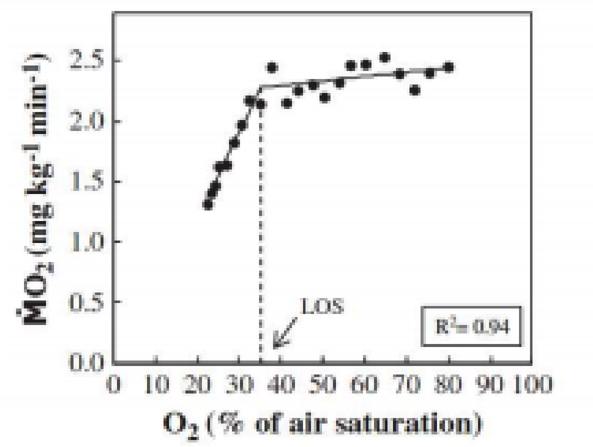


Figure 3.: LOS based on temperature (Remen et al. 2012)

Figure 4.: Metabolic rate based on oxygen saturation (Remen et al. 2012)

To maintain the pH in the body and have aerobic metabolism, the ability to take up oxygen and release carbon dioxide must be present. Without this, a salmon will die within minutes (Noble et al. 2018). *Limiting oxygen saturation*(LOS) is the lowest oxygen saturation that allows metabolism in fed and active fish. Hypoxia is something the body can experience if it does not have adequate amounts of oxygen and can also cause a stress response in salmonids (Remen et al. 2012). A fundamental welfare need for the salmon is efficient respiration and sufficient levels of diluted oxygen. However, only 17% of the behavior can be explained by oxygen level (Oldham et al. 2017). Figure 3 and 7 shows LOS based on temperature and metabolic rate based on oxygen saturation.

Temperature °C	DOmaxFI	LOS
7	42 %	24%
11	53%	33%
15	66%	34%
19	76%	40%

Table 2.3.: Lower limit for oxygen saturation with maximal feed intake (DOmaxFI) and limiting oxygen saturation (LOS) for Atlantic salmon post-smolts of 300-500 g (Remen et al. 2012)

Since salmonids live parts of their life in both freshwater and seawater, they are *anadromous*. In freshwater, the water diffuses in and salt ions out as their bodily fluids have higher salinity than the surrounding water. The opposite happens in seawater, where they are subjected to a constant threat of dehydration through the loss of bodily fluids and increased salt ions inflow.

During the smoltification process, they increase the activity of a gill enzyme (NKA) which is important for salmonids to manage their osmotic balance. Therefore, small salmon that are released too early into the sea suffer from dehydration and die if they are not sufficiently smoltified. (Noble et al. 2018)

Temperature is one of the most dominant environmental factors affecting the salmon. It is also influencing other factors like appetite, critical swimming speed, immunity, and metabolism. Their body temperature is regulated by the ambient water temperature, making them poikilotherms. If salmon experience uncomfortable water temperatures, they can only react by abandoning their territories to seek another location that accommodates their needs, often referred to as an aggregation response (Corey et al. 2019). This response has been observed in sea cages, and it shows that Atlantic salmon are comfortable in temperatures from 6°C to around 17°C and tries to avoid temperatures above 18°C (Oppedal 2020).

Water quality is essential for the production potential and welfare of fish. The Norwegian Food Safety Authority defines the most critical water quality parameters. In practice, the fish farm should be located such that it has good flow conditions to remove and dilute water products (Hvas, Folkedal, and Oppedal 2020).

Health

The welfare situation for farmed fish has in recent years been very poor due to, among other things, the high number of salmon lice treatments. There is still much to be done before the aquaculture industry succeeds in solving the salmon lice problem without influencing the fish welfare in a lousy way (Authority 2020). Harmful pathogens like parasites, bacteria, viruses, and others, can cause many disease conditions. Organisms spread by currents, and the high density of fish inside open fish cages provide the organisms with an excellent opportunity to find new hosts and further spread.

The fish skin is the main barrier again infections, and the safety from danger and protection of their body against injuries is crucial for survival. The fish's skin is usually soft and vulnerable to mechanical damage, and a bite from another fish or predator can be fatal. The ability to move away from danger is an elementary need for all animals, and the fish needs to have the freedom to control their bodily movements (Stien et al. 2013). The fish need to clean their bodies, scratch, and remove parasites. They do this by evolving symbiotic relationships with cleaner fish or taking trips to freshwater rivers (Noble et al. 2018).

Behaviour

When the behavioral control is restricted for an Atlantic Salmon during crowding or handling, one can observe avoidance behavior and increased oxygen consumption. One should minimize this behavior as it is indicating stress and potential fear.

Salmon in sea cages usually swim in a circular schooling structure a few weeks after sea transfer and maintain this group structure the rest of the production time. However, they have not always had this need for social contact, and it varies through the different life stages. When it comes to salmon, they have not been exhibiting schooling behavior during the freshwater phase, but rather the opposite. Here they act somewhat territorial and aggressive before smoltification (Noble et al. 2018).

For salmon being exposed to strong currents, sub-optimal temperatures, or a high degree of delousing treatments, they need to get time for restitution. Even tho the fish are capable of swimming against strong currents for long periods, they need the opportunity to reduce their activity levels as it is vital for their standard body functionality. Salmon under high current velocities has been showing signs of bad welfare in terms of reduced growth and skin and fin damage (Noble et al. 2018). Since fish do not have eyelids, sleeping with shut eyes can not measure how much *rest* the fish is getting. By studying the salmon's inactivity, resting postures, and arousal thresholds, it is possible to get a picture of how much they ”sleep” in terms of fulfilling the behavioral and physiological criteria.

2.3. Stocking density

According to *Forskrift om drift av akvakulturanlegg*, the fish density must be adapted to water quality, the fish's behavioral and physiological needs, health status, operation and feeding technology. The stocking density can however not exceed 25 kg/m^3 (fiskeridepartementet 2021). This rule was established to ensure a sufficient degree of fish welfare.

There are disagreements about whether fish density is a direct cause of decreased fish welfare. There have been numerous studies on stocking density and its effects on fish (Camilla Hosfeld and Fivelstad 2009) (Ellis et al. 2008). Most of the studies suggest that increased fish density harms fish welfare. There have been, among other things, observations of growth reduction, increased feed conversion ratio, and fin erosion. As previously mentioned, there is some disagreement about to which extent the stocking density is the cause of these effects (Ellis et al. 2008).

However, the industry is open to an increase in stocking density in cases where it is beneficial for the economy, and the fish welfare is in place. Large stocking densities reduce the water flow through the cage, which is also why one recommends a relatively *low* fish density. With stronger currents follows a high water exchange rate, ensuring that vital quality parameters, see section 2.2.4, are within acceptable limits. In these cases, it has been shown that it is possible to operate with stocking densities exceeding the current regulations of 25 kg/m^3 (Camilla Hosfeld and Fivelstad 2009).

To drive the industry further with the use of new technological solutions, it must be economically sustainable. It is possible to move the post-smolt phase on land in closed recirculating aquaculture systems (RAS) or too large semi-closed containment systems (S-CCS). However, the overall production costs would be significantly larger. An increased stocking density has been pointed out as a possible contribution to drive the overall costs down, as long as fish welfare and performance are not compromised. Calculations have also shown that an increase of stocking density to 80 kg/m^3 will significantly reduce the coastal area used (Iversen, Frank Asche, and Nystøyl 2020). There are several drivers for increasing the fish density, and there has been a study for determining the stocking density limits for post-smolt Atlantic salmon. This study was a collaboration between several companies within the industry and academia. In this experiment post-smolts ($1150g \pm 13.6$) were stocked at 5 different densities (25, 50, 75, 100 and 125 kg/m^3), and kept at these densities for 8 weeks (Calabrese et al. 2017). The results in the report suggested that it was feasible to rear Atlantic salmon post-smolt in densities up to 75 kg/m^3 at this size and water temperature of around 12°C without the reduction of fish welfare.

A research paper examined the welfare of Atlantic Salmon in cages on a commercial fish farm subjected to stocking densities going from 9.7 to 34 kg/m^3. The paper suggested that while stocking densities can influence the welfare of salmon in typical production cages, it is only one out of several factors that influence their welfare. Fish density can therefore not be used on its own to predict or control fish welfare. (Turnbull et al. 2005). (Food Business 2019) states that the spatial variability of water quality parameters restricts the space the fish can occupy so that salmon may congregate at densities 1,5 - 20 times higher than the calculated stocking density. A higher fish density inside a sea cage may force more fish into sub-optimal environmental conditions, especially if traditional HDPE (High-density polyethylene) sea cages are used in areas with strong currents that result in large cage deformations. When assessing the bigger welfare picture, it is important to take the stocking density into account.

Maximum stocking density	Details	Reference
22 kg/m^3	<22 kg/m^3 best welfare according to their SWIM model.	(Stien et al. 2013)
26.5 kg/m^3	Above 26.5 kg/m^3, the feed intake, growth and feed utilization declined and there was an increase in cataracts, skin and fin erosions	(Oppedal et al. 2011)
25 kg/m^3	Welfare score lower at stocking densities of 15 and 35 kg/m^3 compared with 25 kg/m^3	(Adams et al. 2007)
7 - 11 kg/m^3 better than 18-27 kg/m^3	18-27 kg/m^3 stocked fish have limited abilities to position themselves at preferred temperatures compared with 7-11 kg/m^3	(Johansson et al. 2009)
22 kg/m^3	Above and below 22 kg/m^3 the welfare decreased. Fin damages increased at density >22 kg/m^3.	(Turnbull et al. 2005)
75 kg/m^3	At specific monitored water temperature and specific fish size	(Calabrese et al. 2017)

Table 2.4.: Summary of scientific research on the effect of stocking densities in the Atlantic salmon welfare

2.4. HDPE fish cages

When the fish density is to be calculated, the volume of the entire fish cage must be taken into account, and it is assumed that salmon are spread uniformly across the sea cage. As previously mentioned in section 2.3, large deformations in traditional HDPE sea cages may force fish into sub-optimal environmental conditions where the densities are 1.5 - 20 times higher than the calculated stocking density. This section will assess the HDPE fish cage looking at its history and development through time and its behavior when exposed to environmental loads such as current, wind, and waves. One can also refer to these cages as gravity cages.

The increasing demand for fish and other sea products has been the primary motivator for the aquaculture industry in developing farming structures in open waters. A wide range of fish cages in different designs, sizes, and materials has been tested and commercially produced in the past decades. The master thesis focuses on deformation in *HDPE floating cages* as the versatility in materials used, the simplicity in operation and relatively low investment costs make these cages very popular in the industry. It is called an HDPE fish cage due to the floating collar ring that consists of a series of HDPE pipes. The floating collar ring is the main structure where one secures the fishnet pen. At the bottom end of the net, one will find a sinker system consisting of weights that maintain the shape and volume of the *gravity cage*.

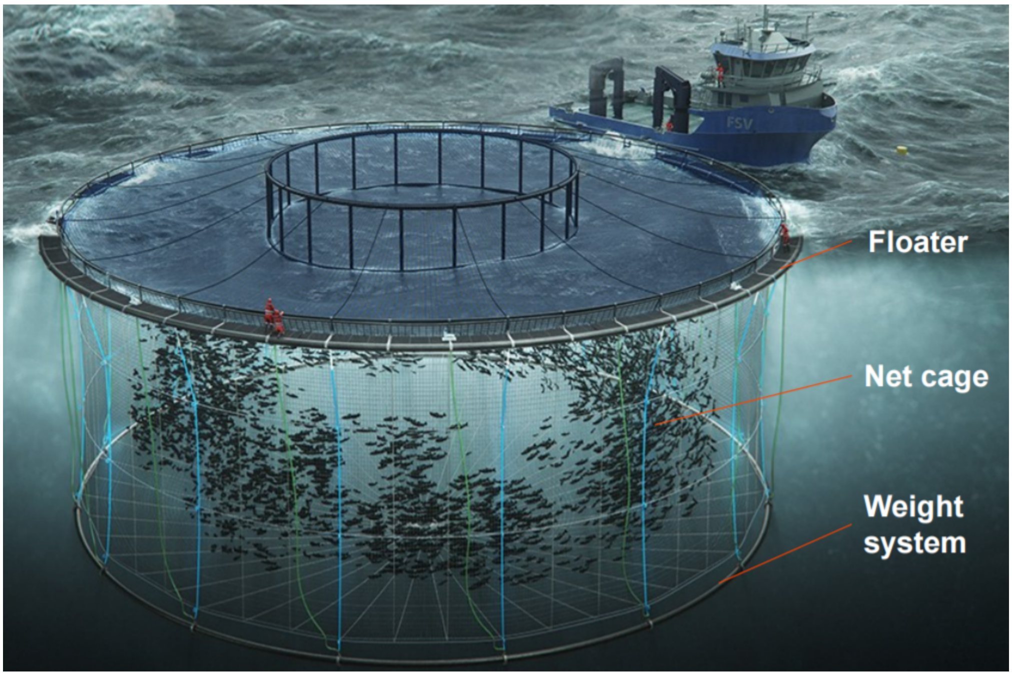


Figure 5.: Typical HDPE fish cage. Source: ScaleAQ

2.4.1. Netting

The most valuable component in any fish cage system is the cage net, as it is the single barrier keeping the fish contained. The loads on the nets from water currents and waves often represent the most significant loads acting on a fish farm, so one must tailor the net to each farm. There has been a shift in the fish farming industry where most of the knotted nets have been replaced with knotless nets in nylon. This is due to knotless nets having up to 50% reduction in weight, lower production costs, and higher abrasion resistance (Net 2020). The netting can be made of a wide range of synthetic fibers, and the most commonly used material is nylon (PA). Nylon has a high elongation and excellent flexibility. However, it has poor resistance to UV light. The nets consisting of this material must avoid being exposed to direct sunlight or include UV stabilization, and one shall add appropriate material during the fiber production process (Food and United Nations 2015).

Square-shaped and hexagon-shaped netting are the two different mesh shapes available for netting used for fish farming. FAO states that there are no apparent advantages in using one instead of the other (Food and United Nations 2015). However, a study performed by Akvagroup (Bollmann 2020) stated that hexagonal mesh netting design distributes the load more evenly and results in a lower maximum load, better elasticity, and are less prone to shrinkage compared to square meshed designs. Shrinkage is a problem limiting the lifetime of nets as it reduces strength and elongation at break. NS9415 suggests a lower strength limit to be 65% of the new netting, and after this point, the net must be replaced.

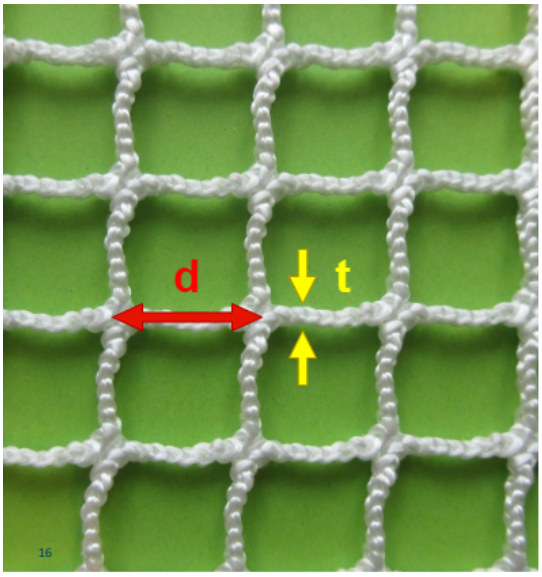


Figure 6.: Unused netting. (SINTEF 2020)

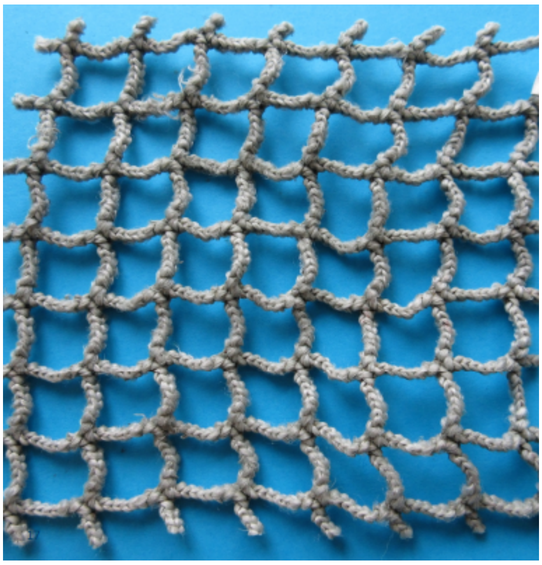


Figure 7.: Used worn netting (SINTEF 2020)

NS9415 has defined solidity (Sn) as *the relationship between projected area and total area of a net panel*, which is the area covered by netting material divided by the area of netting panel (Norge 2009). It has traditionally been estimated based on twine thickness (t) and mesh side (d) for square-shaped mesh, see figure 6.

$$Sn = \frac{2t}{d}$$

To the author's knowledge, there is no official formula to calculate the solidity on the hexagonal mesh.

The number is between 0 (no net) and 1 (closed net) and is usually between 0.20-0.30 for commercial netting. Higher solidity gives larger hydrodynamic loads and affects the exchange of water in the net, and that is the case for hexagonal mesh design compared to square-shaped mesh. Akvagroup specifies that the total loads will be greater, but the analysis to date indicates that a more evenly distributed total load will offset this (Bollmann 2020). However, the hexagonal mesh design is more expensive than the square-shaped mesh, making it less competitive on the market today.

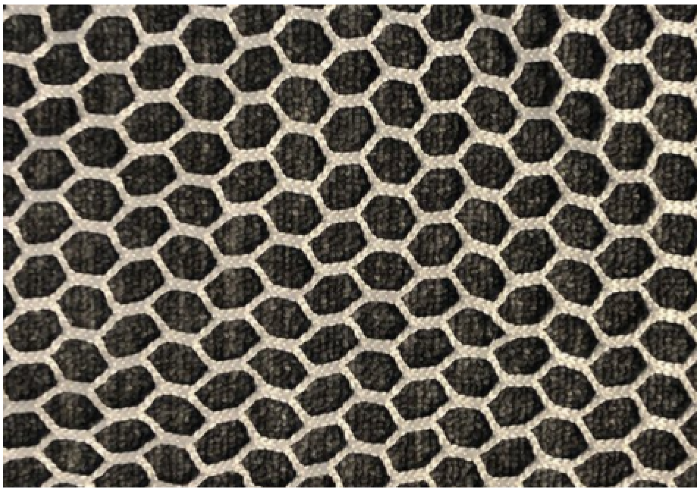


Figure 8.: Hexagon-shaped netting (Bollmann 2020)

2.4.2. Weight System

The volume of the cage is maintained through the connected sinker system. A sinker system can consist of several weight elements (sinkers) or using a single sinker tube. The different configurations and combinations are presented in figure 9.

The sinkers' weight depends on the net dimensions, mesh size, and environmental conditions at the chosen location. A heavier weight system will obtain the volume better and is therefore used on sites with stronger currents and larger waves. The sinkers are usually made of concrete, but the weight of these drops more than 50% when submerged in water (Food and United Nations 2015). A cheaper version of the sinkers consists of mesh bags filled with pebbles and sand, but there is a more considerable risk for these bags to tear and lose their ballast. Chains are also commonly used due to their high density.

The way the weights are integrated into the cage configuration is critical. A hole in the net is one of the most common escape causes, and the weight system was responsible for 47% of the total escaped fish from 2010 - 2018 (SINTEF 2020). To avoid abrasion, it is crucial that the sinkers are not hung directly from the nets but should instead be carried by the cage collar. To avoid interaction between sinkers and the net base, one should be aware of the *down-current* and make sure that the sinker ropes are long enough or cover the weights with spare netting.

An experimental study looking into the interaction between the net and the weight system

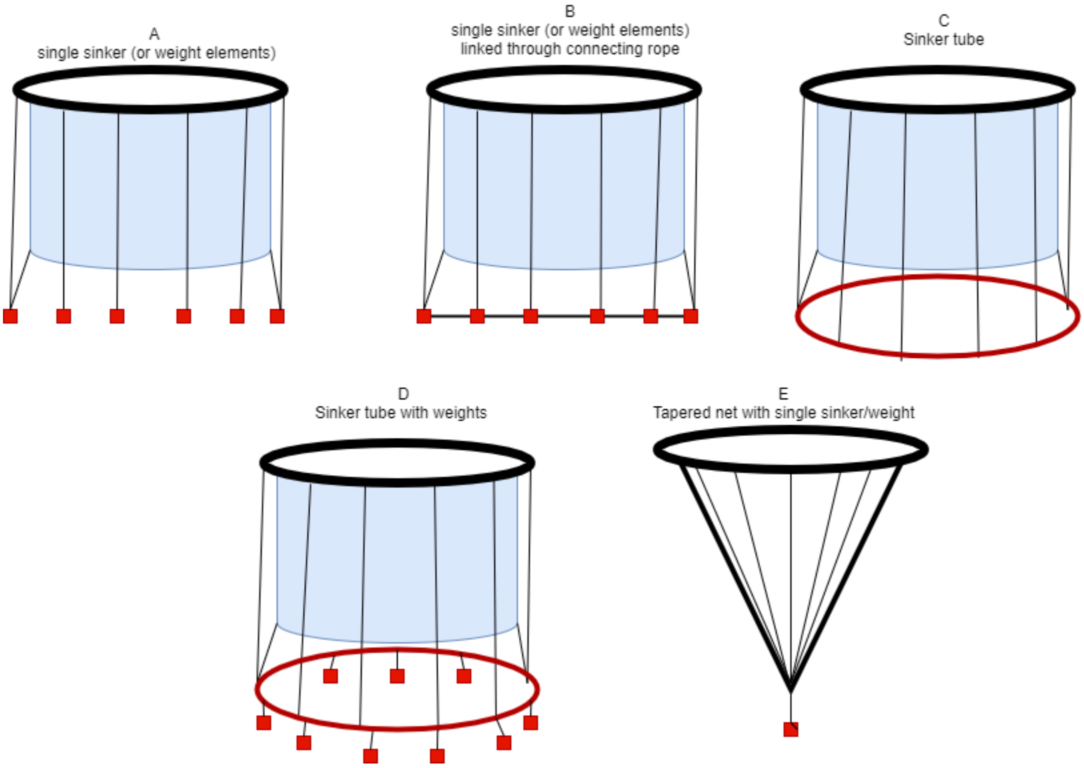


Figure 9.: Different sinker systems

for a gravity-type fish farm, (Lader et al. 2013), found that abrasion will occur at moderate current levels independent of net geometry and weight system. It was shown that cylindrical nets experience abrasion at lower currents over larger areas compared to a conical shape. Finally, they also found that a sinker tube would give less probability of abrasion than single weights. Although the sinker tube is more expensive than sinkers, the more rigid structure behaves better when subjected to current and will better maintain the shape of the net base and the cage volume.

2.4.3. Mooring System

Grid mooring systems are used to keep circular plastic cages in place as they are held on the sea bed with an array of mooring lines. The system is dynamic, meaning that all the components are designed to keep the structures moored to the sea bed while dampening the forces generated by the wave motion. A layout of a typical grid mooring system and its corresponding components can be found in figure 10 and 11.

Today's modules commonly used on fish farms consist of 6, 8, or 12 cages installed in two parallel columns. One can also use larger systems which consist of up to 36 cages, but there are some concerns regarding sufficient oxygen levels and the loads on the mooring lines. In

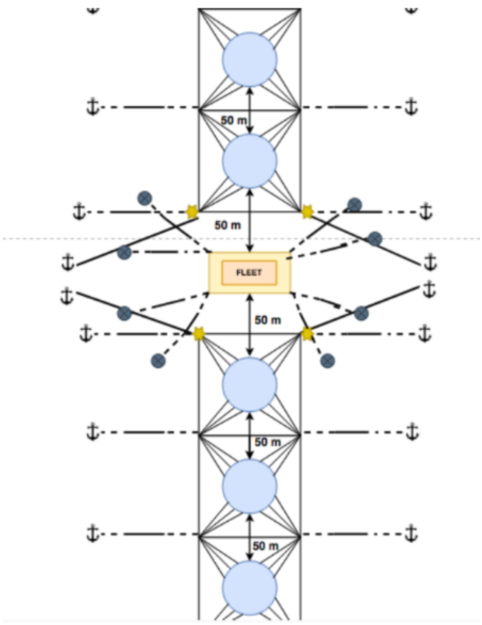


Figure 10.: A simplified drawing of a regular mooring system

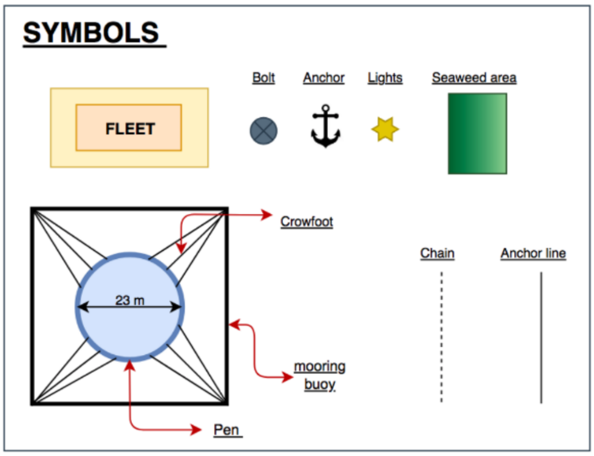


Figure 11.: Description of symbols used in mooring layout seen in figure 10

exposed sites with strong currents and waves, one wishes to hold the number of cages lower than for a sheltered site as a module consisting of few cages will have a relatively high number of mooring lines per cage. See figure 12.

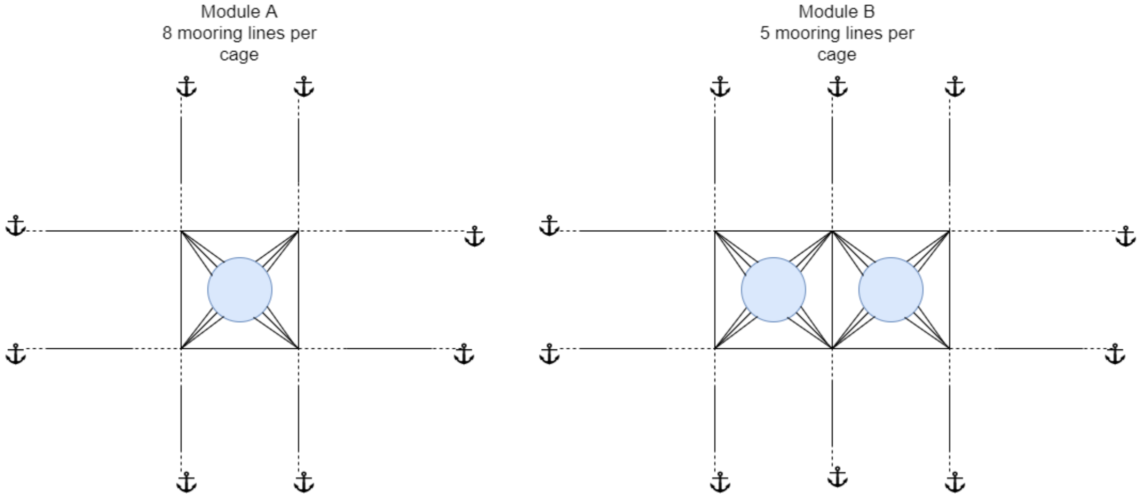


Figure 12.: 2 modules showing how an increase in fish cages reduce the number of mooring lines *per* cage

NYTEK are the Norwegian regulations on the technical requirements to floating aquaculture structures (LOVDATA 2012). It is founded on the Norwegian Aquaculture Act, where its objective is to prevent fish escapes from Norwegian fish farms. NYTEK includes mooring analysis and deployment requirements, including that the mooring analysis shall be performed by an inspection body accredited to carry out mooring analyses. However, the analysis shall not be carried out until there is a site survey, and the analysis shall contain an assessment that shows that the mooring complies with the Norwegian Standard NS9415 (Norge 2009).

NS9415 requires mooring to keep the cage at the correct position, and it shall be designed to specific environmental conditions and according to its use. It also specifies that it shall be designed based on information about additional loads from the net (Norge 2009).

2.4.4. Net cage design and dimensions

The specific cage designs are based on site characteristics, production plans, and operators' experience. One can choose to have circular or square circumference with vertical or inclined sides. A coned bottom is also convenient to collect dead fish in the center. See figure 13 for an overview of different net cage designs.

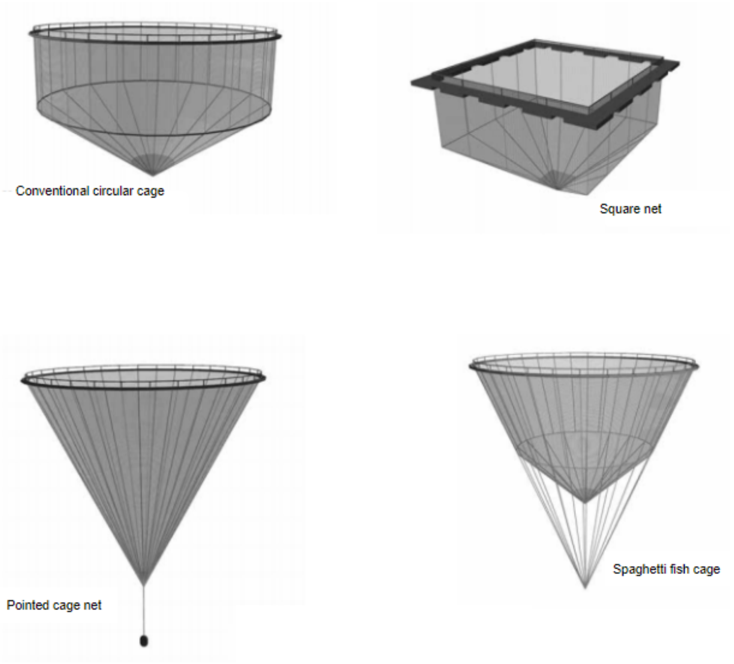


Figure 13.: Different cage designs (Selstad 2020)

When it comes to net cage dimensions, one must follow the dimension grade requirements from NS9415. Based on depth and cage circumference, going from shallow and narrow to deep and broad, the table designates cage classifications from grade I to VII. Grade I-VII includes tables with specific requirements for cases where the significant wave height H_s is less than 2.5 m, and the current velocity is less than 0.75 m/s.

In some cases, the fish cages are exceptionally deep or broad and should be analyzed further as it holds critical aspects. Cages that stand out are graded to dimension class 0. See table 2.5.

Depth of net pen m	**Circumference m**							
	<49	50 - 69	70 - 89	90 - 109	110 - 129	130 - 149	150 - 169	170<
0 - 15	I	II	III	IV	V	V	VI	0
15.1 - 30	II	II	IV	IV	V	VI	VII	0
30.1 - 40	III	III	IV	V	V	VI	VII	0
40 <	0	0	0	0	0	0	0	0

Table 2.5.: Dimension grades for net pens - NS9415

The different dimension grades have also specified requirements for the key structural parameters of the cage net, for instance, the number of ropes and their corresponding minimum breaking load (MBL). See table 2.6.

	Dimension classes							
	I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**0**
Max. distance between vertical ropes (m)	7.5	7.5	6.5	6.5	5	5	5	n/a
Min. vertical ropes (no.)	4	8	8	16	16	24	32	n/a
Min. base cross ropes (no.)	0	0	2	4	6	10	14	n/a
MBL for ropes (kg)	1 900	1 900	2 800	3 400	4 100	4 100	5 000	n/a

Table 2.6.: Dimension grade requirements regarding ropes - NS9415

2.4.5. Environmental loads and behaviour of HDPE fish cages

From total forces acting on a cage farm, 70 - 75% is a result of current speed and directly influences the cage in terms of water exchange, feed dispersion, sinker system, and net shape (Food and United Nations 2015). Strong drag forces are generated due to the large area of the net, especially if it is heavily fouled. This increases the load on the mooring system, and can in the worst case exceed its weight-bearing limit. If the mooring buoys are too small, the buoyancy will be less than the downward force that has been generated by the effects of loads on the bridle and mooring line. In strong current conditions, there is a risk of submerging both the buoy and the cage collar. See figure 14.

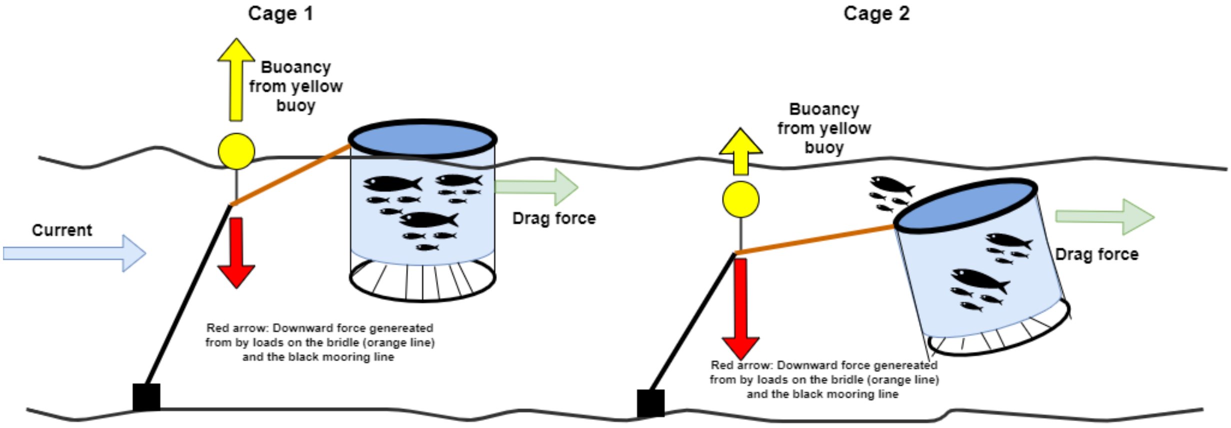


Figure 14.: Case where strong current drag can submerge sea cage

The wind accounts for approximately 5-10 % of the total forces on a cage mooring system. Direct impacts like disturbing the vessels moving around the farm to indirect impacts in terms of wind-driven current and waves make the wind an essential environmental parameter that should be accounted for when selecting a site. Moving sea cages towards more exposed locations includes tougher environmental loads in terms of larger waves. Out of the total forces affecting the mooring system of a sea farm, the waves account for approximately 20 - 25%. (Food and United Nations 2015).

When calculating the forces acting on the net structure, it is possible to split the net into several cylinders, as shown in figure 31 to simplify the drag calculations. The drag force acting on a smooth cylinder can be found by using a part of Morisons equation 2.1, where ρ is the water density, C_D is the drag coefficient, A is the area of the cylinder and U is the current velocity.

$$F_D = \frac{1}{2}\rho C_D A U^2 \tag{2.1}$$

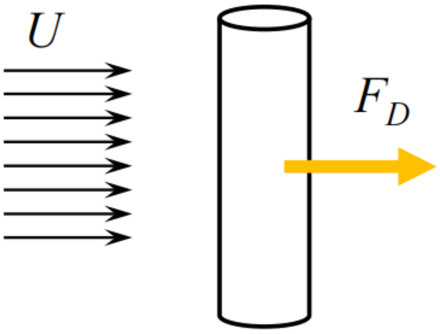


Figure 15.: Force on a smooth cylinder

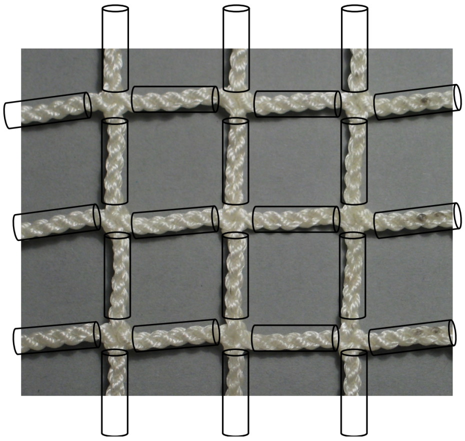


Figure 16.: Net represented as cylinders

However, when conducting drag measurements on a net structure, one can see that the simplified calculations using equation 2.1 as a starting point give only similar drag values up to a specific current speed, see figure 17. This is because the cage deformation decreases the total drag forces. When implementing deformation into the drag calculations, the results are more representative towards the measured values, see figure 17. The net deformation *help* decrease the drag forces, reducing the loads on the mooring system. Too much deformation will however increase the stocking density, as previously mentioned and could potentially lead to issues related to fish welfare.

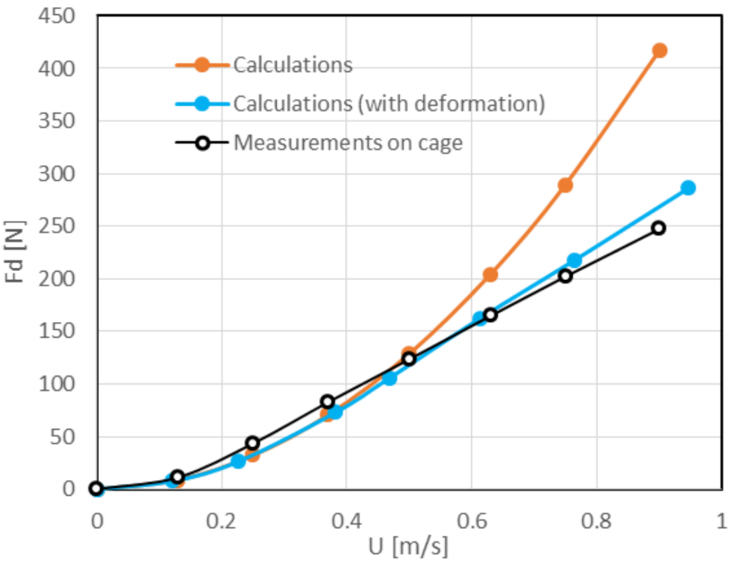


Figure 17.: Drag forces on cage using formulas with and without deformation compared to real measurements. Source: TMR4140 NTNU

Chapter 3

Methodology

This chapter presents the method used to gain insight into the fish welfare of farmed salmon. The method will consist of three parts. The first part will assess how different configurations of HDPE fish cages behaves while being exposed to varying wave heights and current speeds. A software called Aquasim will analyze the fish cage and its deformations while being exposed to different environmental conditions. The change in cage volume will give important information on how the varying stocking densities can affect the fish welfare as presented in section 2.3.

The second part of this method uses a system-based approach to simulate the seawater phase of fish farming production. The Atlantic salmon are exposed to varying water temperatures, current speeds, and significant wave heights. These values come from environmental input data that has been retrieved from potential farming sites. The model also includes handling operations such as net cleaning and delousing. One uses Simulink, a program that is a part of MATLAB, to develop the simulation model.

The final part is implementing environmental-based welfare indicators introduced by NOFIMA (Noble et al. 2018) into the simulation model in Simulink. Using scientific knowledge about the salmon's preferences and tolerance limits related to different environmental conditions, one can use this as indirect welfare indicators. The final output is a plot that shows how the fish welfare varies throughout a specific period based upon the environmental conditions.

To gain insight into the fish welfare, one must analyze these plots and consider if the input data from a potential farming site has the right conditions for the salmon to thrive. It is also necessary to assess how the different configurations of HDPE cages behave at the potential locations to ensure that the deformations do not result in critical stocking densities.

3.1. Part I -Aquasim to analyze HDPE fish cage deformation

AquaSim is an analysis tool developed by Aquastructures AS. It utilizes the Finite Element Method (FEM) for calculation and simulation of structural response. The software calculates impacts on marine constructions subjected to different loads such as currents, wind, waves, impulse loads, operational conditions and resonance. Companies in the aquaculture industry widely use it, and typical applications are mooring analyses, net analyses and analyses of marine operations. Analyses are performed to meet the Norwegian Standard's dimensioning requirements for marine fish farms, NS9415. (Aquastructures 2017).

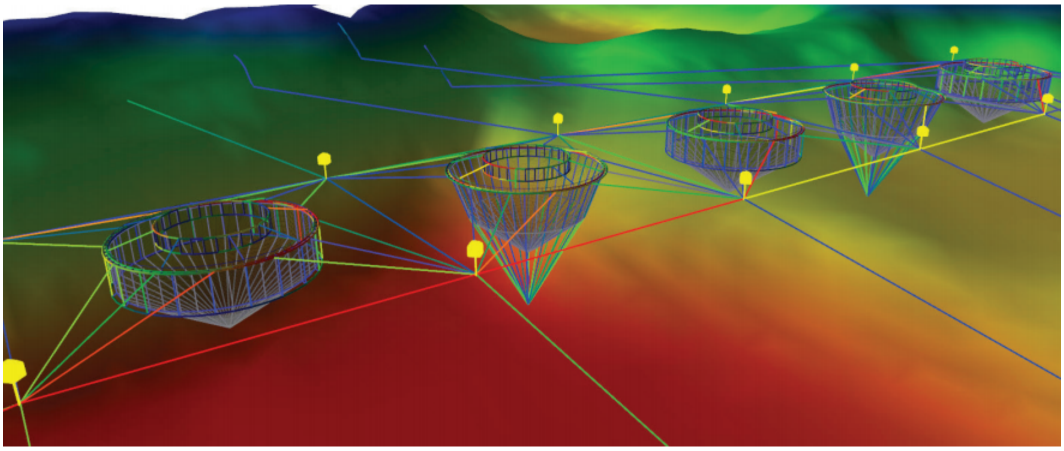


Figure 18.: Example results from an simulation in Aquasim (Aquastructures 2017). The colors can among other things represent the degree of deformations, forces or depth in model

The software can easily construct a numerical model with mooring systems, floating collars and nets. Aquasim has been chosen to analyze the net deformations resulting from circular HDPE cages exposed to different environmental conditions. The results will be used to assess the fish welfare in terms of the variable stocking density during the production phase in seawater.

3.1.1. Aquasim Package

A geometrical model is established through a graphical interface called *AquaEdit*. In this part the structural and hydrodynamical properties are defined and added to the model. The analysis model in AquaEdit is then computed by the *AquaSim Solver*. Here the forces and moments are calculated from the given properties, geometry and environmental loads. To view the results from the solver, one uses *AquaView* which presents the results graphically in 3D. Results presented in tables and diagrams can be found in *AquaTool*

3.1.2. Finite Element Method

The finite element method subdivides a large system into a finite number of elements. Finite element analysis (FEA) is used to establish static or hydrodynamic equilibrium at a given time instant for each element and the whole system. To obtain equilibrium, the internal forces in an element must be equal to the external forces (Aquastructures 2017).

To estimate the response of a fish cage in waves, where hydrodynamic forces are important, one needs to perform a dynamic analysis. To estimate the wave loads in the design of offshore structures, one can use The Morison equation (Morison, Johnson, and S.A.Schaaf 1950). The Morisons loads fluctuate with the relative velocity between the structure and water. To obtain equilibrium, as mentioned above, the equation that needs to be solved is:

$$\sum \mathbf{F} = \mathbf{R}_{ext} + \mathbf{R}_{int} + \mathbf{R}_{mass} + \mathbf{R}_{damp} = 0 \tag{3.1}$$

Here $\mathbf{R}_{ext}$ is the external static forces acting on the structure at a given time instant, $\mathbf{R}_{int}$ is the internal forces, $\mathbf{R}_{mass}$ and $\mathbf{R}_{damp}$ are forces originated from the structural mass and damping properties (Aquastructures 2017). The components in equation 3.1 are in general dependent on the displacement r, velocity of the structure $\dot{r}$ and the acceleration of the structure $\ddot{r}$.

3.1.3. Element Properties - Truss, Beams and Membranes

The HDPE cages in Aquasim are all built up of different types of elements that are linear-elastic. For instance, the cage collar consists of beam elements, the fishnet is made of membrane elements, and all ropes are modelled as truss elements. This section gives a brief introduction to the basic properties of the elements used in Aquasim.

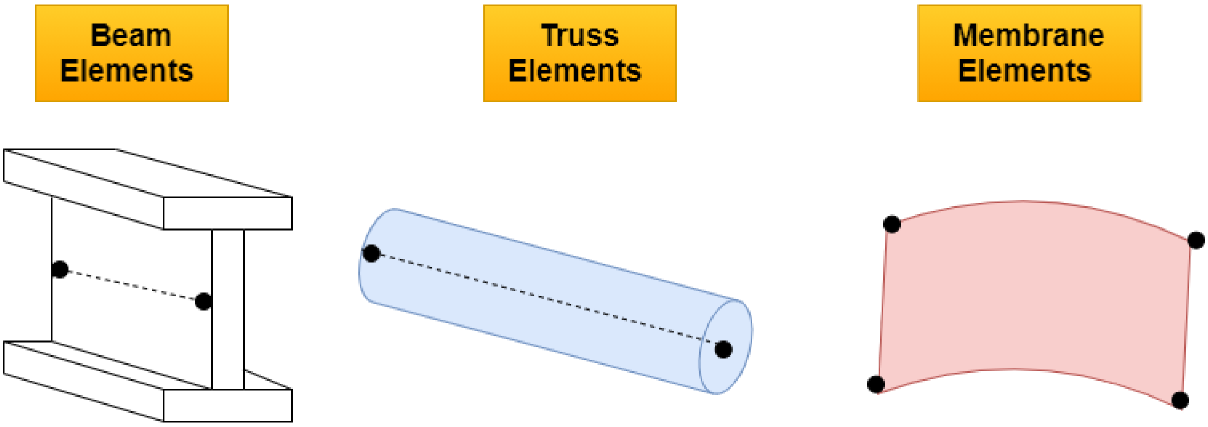


Figure 19.: Element types used in modelling the HDPE cages in Aquasim

Truss and beam elements are similar, and both consist of 2 nodes, but their main difference is that a truss element does not have bending resistance and can only take axial forces. A beam element is a slender structural member that has resistance towards forces and bending under applied loads. The beam resists moments at the connections, which is not the case for truss elements.

The beam elements should be used when the element has constant cross-sectional properties, must be able to transfer moments, and handle a load distributed across its length. One should use the truss elements when the length of the element is much greater than the width or depth, and it is connected to the rest of the model with hinges that do not transfer moments. The applied forces shall also only be at joints (AUTODESK 2017).

The membrane elements consist of three- or four-node elements which are formulated in three-dimensional space. These elements are used to model fabric-like objects, such as a net used for a fish cage. These elements should be used when the thickness of the element is minimal relative to the width or length, has no stress in the direction normal to the thickness and does not carry or transmit any moments (AUTODESK 2017).

3.2. Part II - Environmental based welfare indicators

From chapter 2.2, the fish welfare was assessed and different needs for salmon were established. However, it is not possible to ask the salmon how they are feeling and if they are satisfied with the fulfillment of needs. To simulate how fish is being affected in different sites with varying environmental conditions, it is important to find a method to assess their welfare.

A research project called *FISHWELL* has published a manual consisting of 328 pages on how to assess the welfare of farmed salmon in different production systems and husbandry practices (Noble et al. 2018). The goal is to provide the user with correct fit-for-purpose tools based upon sound science to measure the fish welfare during different conditions. The method is based upon the use of welfare indicators that are suitable for aquaculture, and these are called Operational Welfare Indicators (OWIs) or Laboratory Welfare Indicators (LABWIs). OWIs are indicators that are suitable to use during daily operations. LABWIs require samples to be sent to a laboratory, and the test results will give the farmer information about the salmon's state regarding welfare. There are several types of Welfare Indicators. The following section will go into each of them before some relevant indicators are chosen regarding the early-stage simulation for exposed fish farming.

The animal-based welfare indicators are attributes from the animal that indicate that one or more welfare needs have not been fulfilled. These animal-based indicators are more directly linked to the state of the fish than environmental indicators and are classified as direct welfare indicators. See appendix B for all of the direct welfare indicators and their relationship with the different welfare needs.

The environmental-based indicators can predict a problem, while animal-based indicators may only become apparent once the animal is already experiencing poor welfare. However, these are classified as indirect welfare indicators and are often very quick and easy to measure compared to the direct welfare indicators (Noble et al. 2018). This is also the main reason why environmental-based indicators are used in this thesis to assess welfare.

Based on scientific knowledge about the Atlantic salmon's preferences and tolerance limits for the various environmental factors, e.g., temperature, currents, and oxygen, it is possible to use the measurements of environmental factors as indirect welfare indicators. (Oldham et al. 2017, Remen et al. 2012, Oppedal 2020, Hvas, Folkedal, and Oppedal 2020). Most of the environmental parameters are related, and the effects are dependent upon the state of the fish. The environmental-based indicators introduced in the NOFIMA handbook are operational, well-proven, and general, making them useful in most farming situations. See appendix C for complete list.

3.2.1. Temperature

From previous studies, it has been stated that caged pre-smolts prefer temperatures around 17°C and avoid temperatures above 18°C (Oppedal et al. 2011). Temperatures above 18°C have been shown to affect appetite, performance and mortality negatively. Low temperatures could also be a problem, and below 6-7°C are avoided by post-smolts. These circumstances can harm growth, performance and increase the risk for winter ulcers (Noble et al. 2018).

Several articles discuss the preferred thermal range for caged post-smolts, and the intervals are varying from the different authors.

Post-smolts	**Range (°C)**	**References**
	8 - 14	MOWI 2019
	6 - 16	Handeland, Imsland, and Stefansson 2008
	10 - 15	Stien et al. 2013
	16-18	Johansson et al. 2009

Table 3.1.: The preferred thermal range for salmon post-smolts

Temperature is a cheap and easy indicator to use, and it explains many aspects of behavior, welfare, and the performance of salmon. It is important to consider that it also affects other

WIs like oxygen, critical swimming speed, and parasites.

3.2.2. Oxygen Saturation

The oxygen requirements for fish increase at higher temperatures since they are poikilothermic. When the oxygen saturation decreases below a certain level (DO$_{maxFI}$), appetite is reduced (Remen et al. 2012). See table 3 for the lower limit for oxygen saturation with maximal feed intake and the limiting oxygen saturation for Atlantic salmon post-smolts of 300-500 grams.

The oxygen saturation varies within the body of water in both space and time, and oxygen saturation measures should be done when and where it is expected to be lowest. A potential advantage with offshore fish farming is the stronger currents that may ensure a higher oxygen saturation level.

Table 3 have established tolerance limits related to the connection between oxygen saturation and fish welfare. However, it is pretty challenging to measure since it is dependent upon several parameters. The oxygen saturation varies with salmon size, water temperature, salmons' initial stress level, and amount of fish in a given area. Larger biomass will reduce the water flow through the cage.

3.2.3. Current speeds

Stronger currents in exposed locations are positive in terms of higher water quality and diluting of waste. However, the current speed also influences the swimming performance of fish. The fish are usually schooling, meaning they are together swimming in circles. As the current becomes stronger and stronger, the fish will be standing closer together. This is because the fish uses a longer time completing one *round* around the cage. A queuing system is created where the fish stand against the current (Oppedal 2020). Water current speeds that exceed the maximum sustainable swimming speed result in fish becoming exhausted, failing to hold their position, and being displaced into sub-optimal parts of the cage. See figure 20.

Sustained swimming has been defined as swimming speeds that the fish can maintain for 200 minutes. Malthe Hvas and Frode Oppedal performed swim tunnel respirometer experiments with groups of post-smolts with an average weight of 800 grams at a 13°C water temperature. The average critical swimming speed (U_{crit})was determined to 97.2 cm/s, and the Atlantic salmon was able to sustain continuous high-intensity swimming of at least $80\%\ U_{crit}$ (Hvas and Oppedal 2017). A newer article from Malthe Hvas considered the minimum Cost

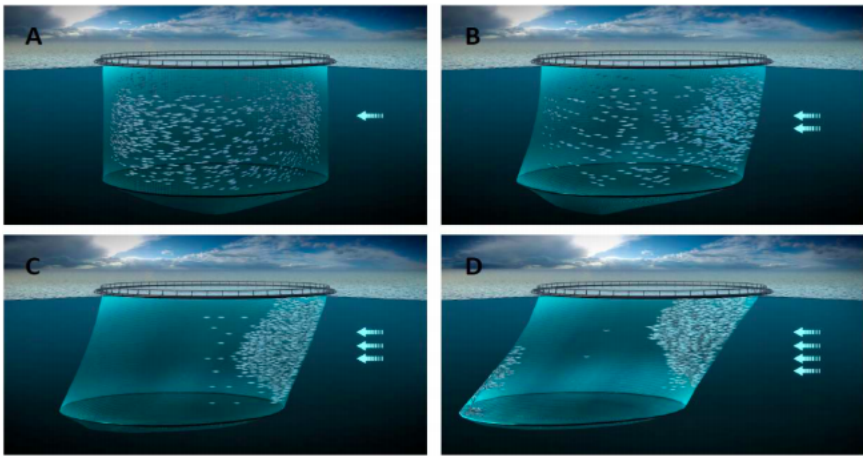


Figure 20.: Atlantic salmon group structure in sea cages in response to increasing current velocities(Hvas, Folkedal, and Oppedal 2020).

of Transport (CoT), meaning the cruising speed allowing the fish to travel the greatest distance while using the least amount of energy. Minimum CoT for Atlantic salmon post-smolts is approximately 60% of the critical swimming speed. Therefore, the current conditions at exposed locations should not exceed this limit (Hvas and Oppedal 2017) if a fish farm is being operated there. U_{crit} is highest for Atlantic salmon between 13 and 18 °C. At either thermal extreme, the critical swimming speed will decrease. See figure 21.

Current speeds that are too low may also hurt the Atlantic salmon. Post-smolts that have been forced to swim against a current velocity of 0.2 body lengths s^{-1} for six weeks have been observed to gain more fat and less protein (Noble et al. 2018). Other experiments regarding the fish swimming capacity have been summarized and are presented below:

Swimming type	Body length [cm]	Speed [cm sˆ-1]	body lengths sˆ-1
Absolute critical swimming speed	20	81	4.1
Absolute critical swimming speed	29	91	3.2
Absolute critical swimming speed	39	100	2.6
Absolute critical swimming speed	51	100	1.9
Max sustained swimming speed	30 - 50	90	2

Table 3.2.: Overview of different type of swimming speeds for post-smolts at different sizes (Noble et al. 2018)

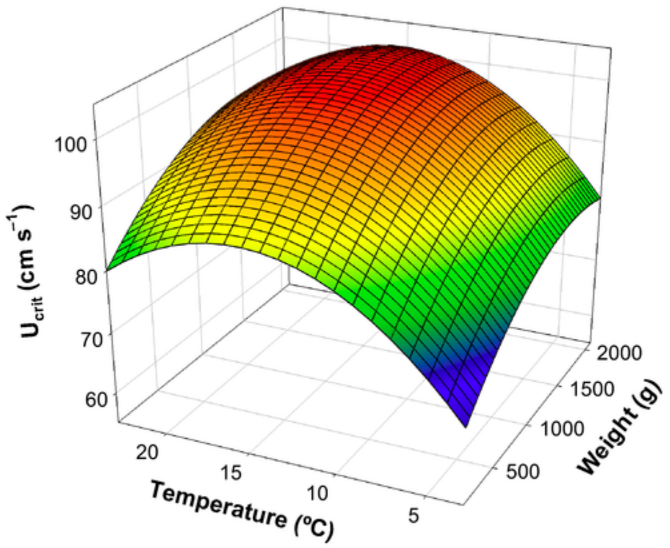


Figure 21.: U_{crit} of Atlantic salmon at different sizes and temperatures (Hvas, Folkedal, and Oppedal 2020).

3.2.4. Waves

There will be stronger currents and larger waves in exposed locations. It is one of the biggest concerns regarding vessel operability when executing necessary service tasks (Bjelland et al. 2015). There is very little research regarding the effect of the waves on fish welfare.

Waves are created by energy passing through water, causin it to move in a circular motion. The energy is most often coming from wind, and this type of wave is often referred to as surface waves. In this case, the waves are created by the friction between wind and surface water (NOAA 2018).

Since the sea cage structure will follow the movement of ocean waves, it is crucial to figure out whether farmed fish exposed to large waves will be able to avoid collision with both each other and the net. Johannesen et al. 2020 did a study on how the waves affected the fish behavior inside fish cages in exposed sites on the Faroe Islands. Behavioral observations showed that the fish moved away from the sides of the net in large waves and oriented their swimming according to waves instead of standing against the current as illustrated in figure 20.

The vertical distribution of salmon was different during weak current and waves compared to strong currents combined with waves. During strong currents and long-period waves, the fish moved upwards, and this behavior can be explained by an increased risk of a collision near the bottom of the cage as the long-period waves reach further down.

From wave studies in tanks, it has been shown that some individuals during more giant waves moved towards the bottom of the net, which could indicate that the fish are uncomfortable in the wave zone (Hvas, Folkedal, and Oppedal 2020). However, this could potentially affect the fish as it is usually swimming towards the surface layers during the night (Oppedal et al. 2011).

None of the studies has come with any direct ways of measuring fish welfare concerning waves at this current time. During the simulation, the wave height will mainly affect the duration of different service operations, further affecting the fish welfare.

3.2.5. Use of OWIs

Different welfare indicators have now been established, but how can they be used to assess the fish welfare of farmed salmon in different locations? The handbook (Noble et al. 2018) has developed a model on how to use the different welfare indicators at the production facility, see appendix

The method used to develop the simulation model in this thesis will be on the primary level based on environmental parameters that are currently available. Retrieving environmental data from two different locations, one exposed and one sheltered will set the starting point for the simulation. Data that are currently available are water temperature, current speed, and significant wave height.

3.3. Part III - Simulation Model in Simulink MATLAB

Simulink is a block diagram environment for multi-domain simulation and Model-Based Design. It supports system-level design, simulation, automatic code generation, and continuous test and verification of embedded systems. MATLAB and Simulink make it possible to use both textual and graphical programming to design a system in a simulation environment. This makes it easy for the user to run several simulations in Simulink and then analyze and visualize the data in MATLAB (MathWorks 2020).

A good model is made with minimal effort to provide the user with the information needed efficiently. This model would see how fish welfare is affected by the change of different environmental parameters over time and how the environmental parameters differ for various sites. Based on the results, where the fish welfare is the final output, one can see which types of inputs have the highest impact on welfare, which could be investigated further to develop new technology. An example would be that the input data from a sheltered location showed that the low oxygen saturation could be the main driver for the negative effect on fish welfare. When developing a new structure, one should consider technology that makes it possible to inject extra oxygen during the operational seawater phase.

Based on the established assumptions and known limitations related to the simulation tool, it is essential to verify the model. Checking that it is behaving as intended. This is done by making sure that the correct perception of the system is implemented. We are also trying to imitate the real system, and it is important to validate the model as it checks the accuracy of the simulation compared to the real world. This is done by answering questions like: Are the results similar to the natural system? How does the variation in parameters change the output, and does it change as expected? It could be difficult for the user to know the answers to these kinds of questions if they do not have the right amount of experience. It could be helpful to ask someone with knowledge within the specific area to assess the results.

3.3.1. System Description

The group of fish is generated as *one* primary entity that will be flowing through the simulation model. The simulation only considers environmental-based indicators and will not look at each fish as an individual.

It is assumed that the fish has been recently transported to the site and will have relatively *low* initial welfare as the fish is experiencing much stress. From here, it is assumed that the fish will be *swimming* in the fish cage, only being exposed to the varying water temperatures and current speeds for two weeks to get used to the environment before the service operations are being executed weekly. See figure 22 for illustration. The simulation model implemented in Simulink can be found in appendix E and F.

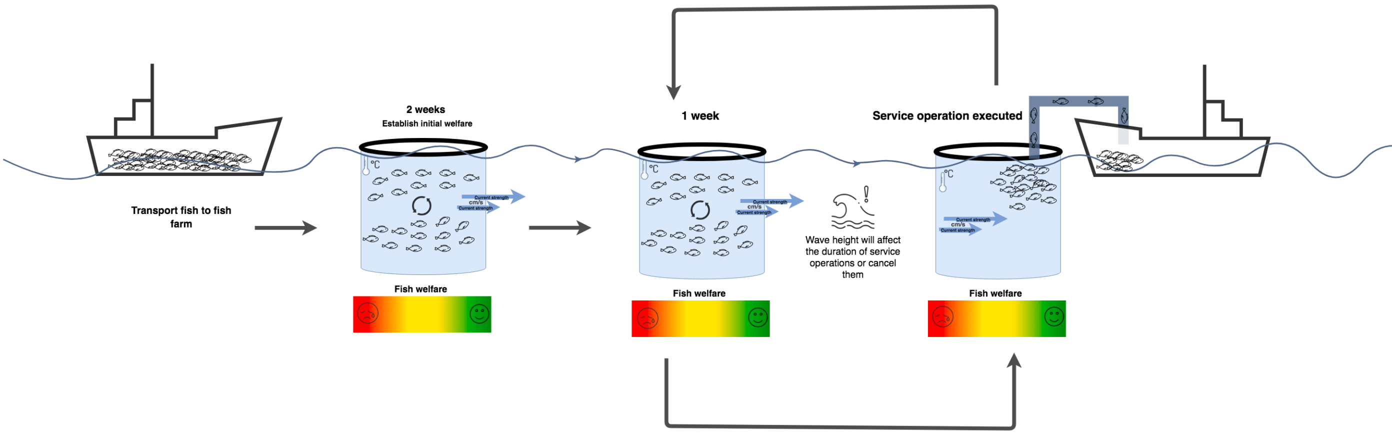


Figure 22.: Illustration of the simulation model

The fish farm will be subjected to different handling operations throughout the production cycle. It is assumed that service vessels will assist in net cleaning, delousing, and tension of the mooring system. The salmon are affected differently based on which operations there are crowding and pumping present, and the duration of execution depends on the wave height.

Operation	Frequency	How does it affect welfare	Impact category
Delousing	2-3 weeks	Crowding and pumping	1
Net cleaning	Weekly	Crowding	2
Tension of mooring	2-3 weeks	-	3

Table 3.3.: Overview of service operations on fish farm. It is assumed that delousing has the largest impact on the fish welfare, and tension of mooring system has the least.

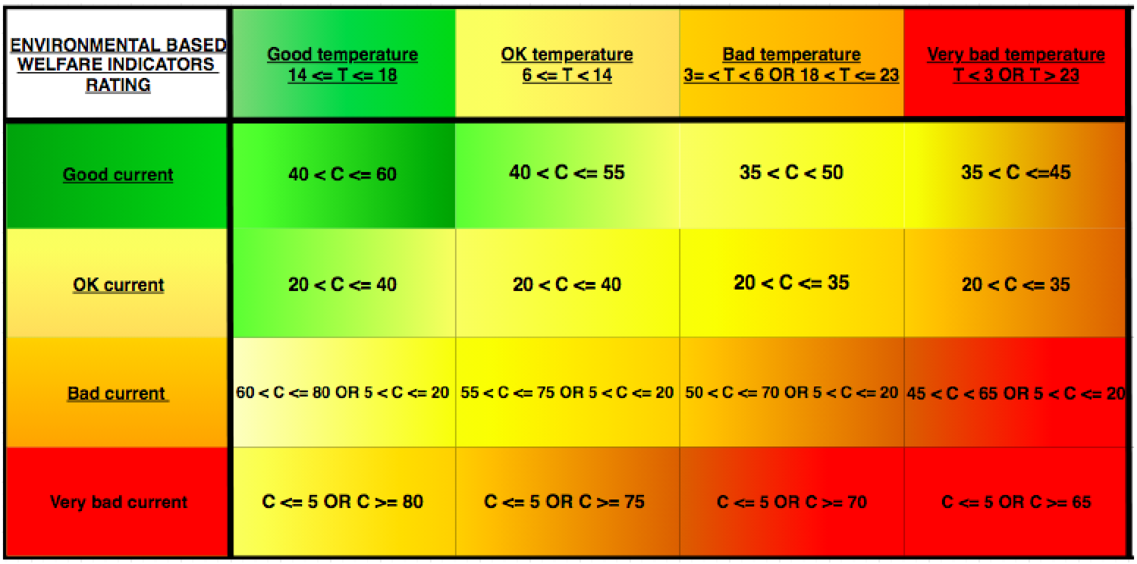
The crowding and pumping effect on fish is negligible if executed fast enough. However, more giant waves can delay the operation. Loss of behavioral control causes stress and can in some situations reduce the final quality of the meat. Low current speeds increase the risk of low oxygen levels, causing hypoxia and reduced welfare. Crowding may lead to skin damage and should be avoided at lower temperatures to reduce the risk of developing ulcers.

Delousing is the operation that has the highest impact on fish welfare compared to net cleaning and tension of the mooring system. Both crowding and pumping are present, and the different procedures all harm the salmon. It has therefore been assigned to impact category 1, see table 3.3.

Net cleaning has been assigned to impact category 2, as it only has crowding present and will not have such a harmful effect on the salmon compared to delousing. This operation is executed every week. To simplify the model it is assumed that net cleaning occurs together with both delousing and tension of the mooring system. It is assumed that the tensioning of the mooring system has the lowest impact on the fish welfare in this simulation.

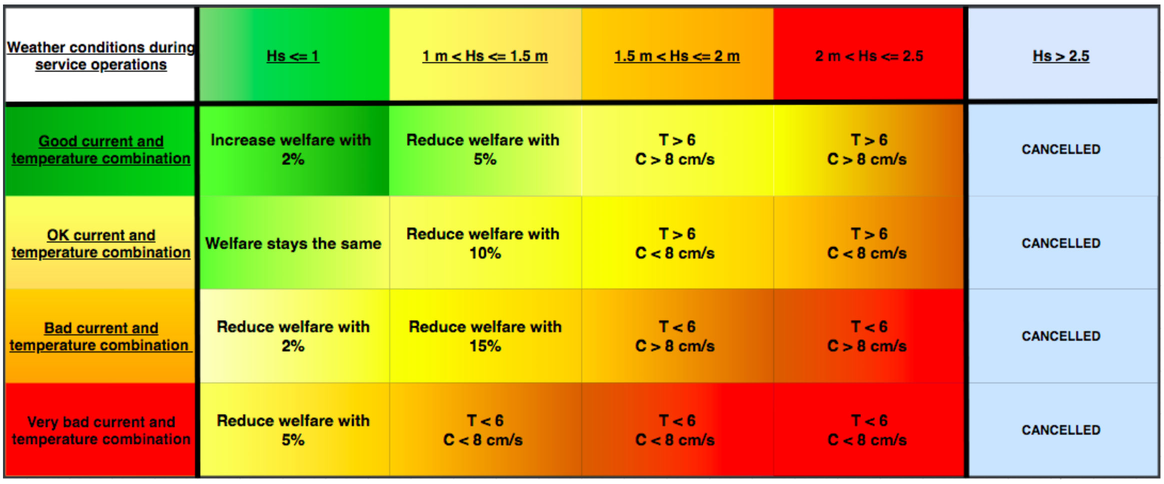
The model will therefore switch between two operations every week. Delousing and net cleaning will have an initial large impact on fish welfare and increase with higher wave heights. The tension of the mooring system and net cleaning will have a smaller initial impact on fish welfare, but the effect also increases with the wave heights as this delays the operations. It has been assumed an operational limit to a significant wave height of 2.5 meters, and values above this will postpone the operation until the weather conditions are suitable.

Based on the data and information about how the environmental-based indicators affect welfare, a table has been developed to show how the intervals of different temperature and currents combinations are better/worse than another. The temperature is the dominant indicator as it also decides the critical swimming speed and how the service operations affect welfare.



ENVIRONMENTAL BASED WELFARE INDICATORS RATING	Good temperature 14 <= T <= 18	OK temperature 6 <= T < 14	Bad temperature 3= < T < 6 OR 18 < T <= 23	Very bad temperature T < 3 OR T > 23
Good current	40 < C <= 60	40 < C <= 55	35 < C < 50	35 < C <=45
OK current	20 < C <= 40	20 < C <= 40	20 < C <= 35	20 < C <= 35
Bad current	60 < C <= 80 OR 5 < C <= 20	55 < C <= 75 OR 5 < C <= 20	50 < C <= 70 OR 5 < C <= 20	45 < C < 65 OR 5 < C <= 20
Very bad current	C <= 5 OR C >= 80	C <= 5 OR C >= 75	C <= 5 OR C >= 70	C <= 5 OR C >= 65

Figure 23.: Intervals of temperature (°C) and currents (cm/s) that are better/worse for fish welfare when combined

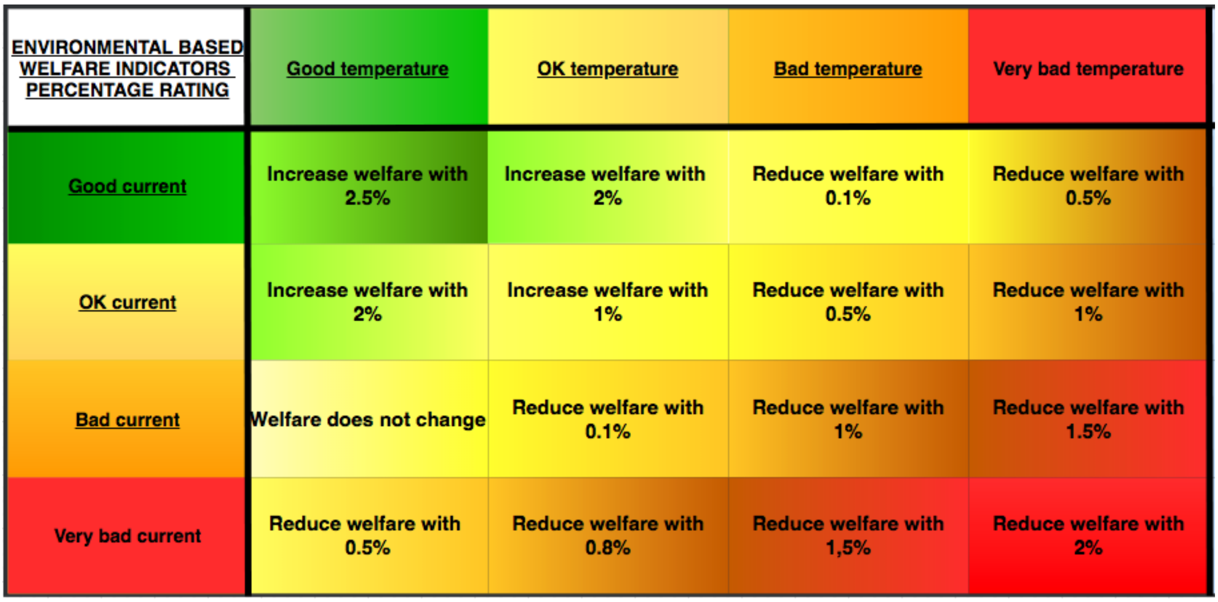


Weather conditions during service operations	Hs <= 1	1 m < Hs <= 1.5 m	1.5 m < Hs <= 2 m	2 m < Hs <= 2.5	Hs > 2.5
Good current and temperature combination	Increase welfare with 2%	Reduce welfare with 5%	T > 6 C > 8 cm/s	T > 6 C > 8 cm/s	CANCELLED
OK current and temperature combination	Welfare stays the same	Reduce welfare with 10%	T > 6 C < 8 cm/s	T > 6 C < 8 cm/s	CANCELLED
Bad current and temperature combination	Reduce welfare with 2%	Reduce welfare with 15%	T < 6 C > 8 cm/s	T < 6 C > 8 cm/s	CANCELLED
Very bad current and temperature combination	Reduce welfare with 5%	T < 6 C < 8 cm/s	T < 6 C < 8 cm/s	T < 6 C < 8 cm/s	CANCELLED

Figure 24.: Overview of how the different combinations of temperature, current speed and wave height is affecting the fish welfare during handling operations

The duration of service operations affects fish welfare, which is closely related to the wave height. If the significant wave height exceeds 2.5 meters, the operation is postponed. The consequence of this is a *penalty* that decreases welfare for each time unit the fish are *waiting*.

There are no specific data about how *much* the welfare is reduced/increased under different circumstances. However, we know that some conditions are better than others, see figure 23 and 24. One will use a percentage of reduced/increased welfare in the simulation, but these values are not based on scientific data. It is only used as a method to measure how some conditions are better than others. The literature study found that the parameter that affects the fish most regarding their critical swimming speed, oxygen limits, and welfare during different handling operations was the water temperature.



ENVIRONMENTAL BASED WELFARE INDICATORS PERCENTAGE RATING	Good temperature	OK temperature	Bad temperature	Very bad temperature
Good current	Increase welfare with 2.5%	Increase welfare with 2%	Reduce welfare with 0.1%	Reduce welfare with 0.5%
OK current	Increase welfare with 2%	Increase welfare with 1%	Reduce welfare with 0.5%	Reduce welfare with 1%
Bad current	Welfare does not change	Reduce welfare with 0.1%	Reduce welfare with 1%	Reduce welfare with 1.5%
Very bad current	Reduce welfare with 0.5%	Reduce welfare with 0.8%	Reduce welfare with 1,5%	Reduce welfare with 2%

Figure 25.: Percentage of reduced/increased welfare based upon environmental based welfare indicators

The logic behind the increase/decrease in welfare for a specific period is illustrated in figure 26, where the current speed and temperature have been categorized by figures 24 and 23. The results from Simulink will then be presented in the following plot based on the varying fish welfare. See figure 27 for an example plot based upon figure 26.

3.3.2. Weather data handling

There are several ways to implement weather data into a simulation model. The principle of the Markov Chain has been presented in previous classes to predict the weather in a stochastic simulation model easily. It is good to use for analyzing the performance of a system whose behavior depends on the interaction of random processes, which means processes that can be described using probability models.

A Markov chain is a stochastic model describing a sequence of possible events in which the probability of each event depends only on the state attained in the previous event (I 2019). It

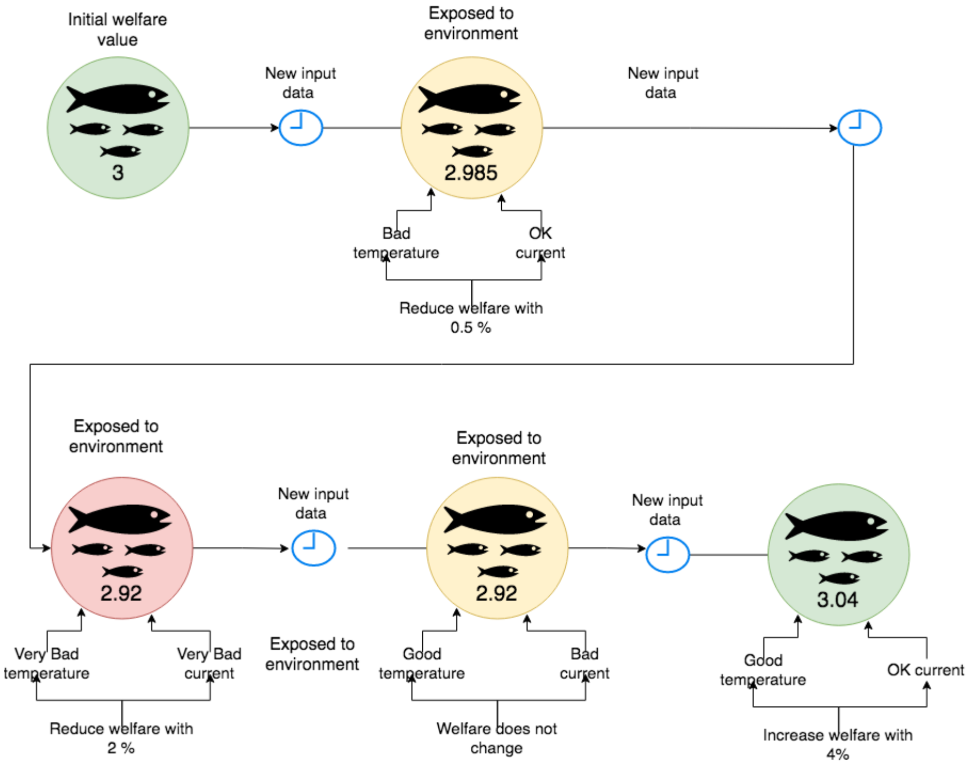


Figure 26.: Logic behind the simulation model showing how the fish welfare is varying according to the environmental conditions. In this case the fish welfare value starts at 3, before it either increases or decreases.

could be that a state in the Markov chain can represent the current sea state, where the states possible are low, moderate and high seas. The probabilities in this figure are just examples but based on the historical data one can find a probability model that fits. Based on the simulation model, the user can choose how often the state is going to change. If the historical data is based on measurements from every hour, it makes sense to change the state every hour.

Figure 28 shows the three states where the values on the arrows represent the probabilities that the different transitions will occur. These are just example values, but the sea state's probability going from low to high and vice versa is set to 0.1. It illustrates that low and high seas probably will not occur within a short period, such as an hour when one uses historical data.

Table 3.4 shows the corresponding transition matrix, where each row shows the probability of transitioning from one state to another. If the sea state is low and the random number is between 0-0.5, the next state is low. If the random number is between 0.5 - 0.9, the nest state is moderate. Some random number is sampled from a uniform distribution, and the outcome

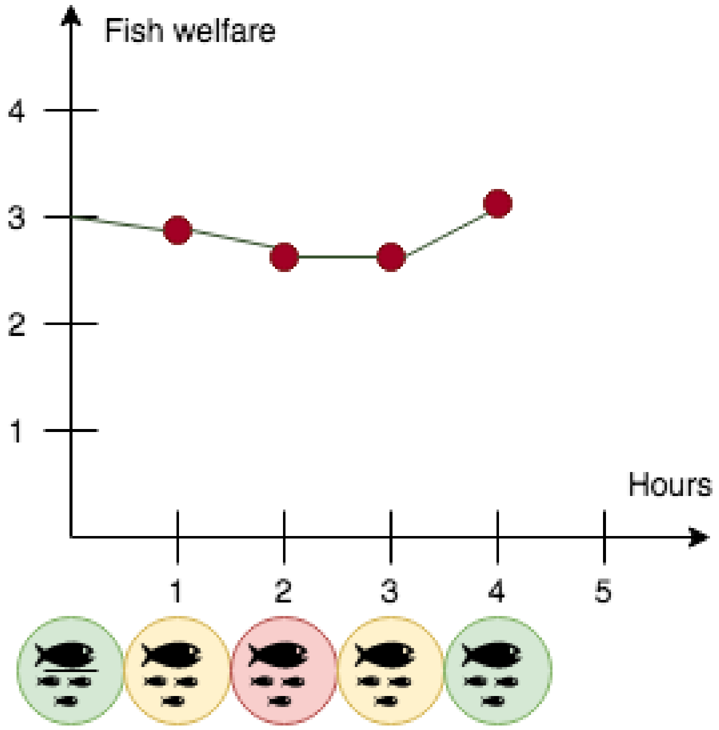


Figure 27.: Based on the varying welfare, the welfare value is presented in a plot to show if it is increasing or decreasing over time

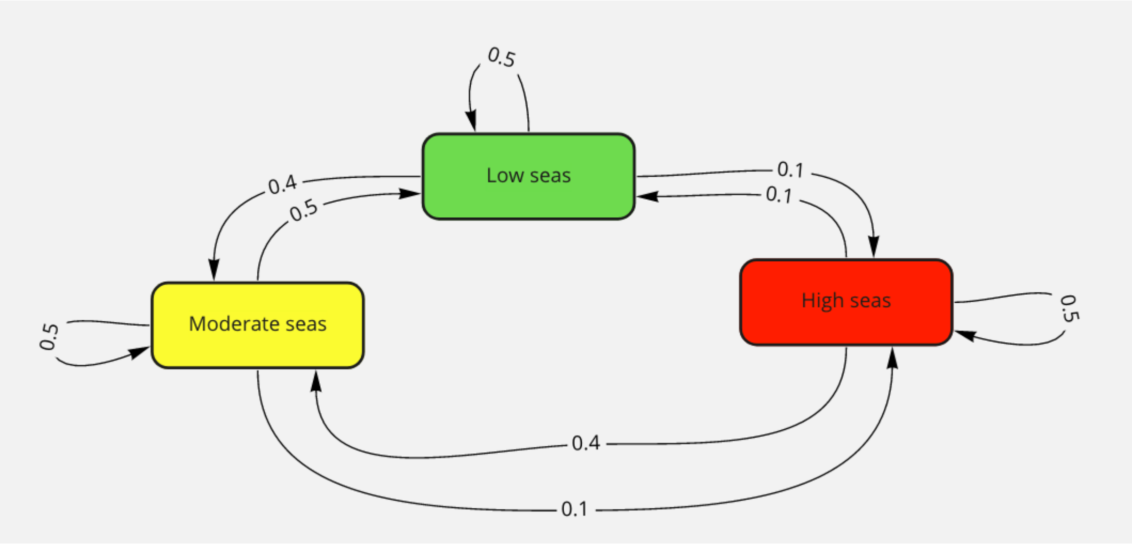


Figure 28.: Markov Chain transition diagram

is given. The sum of all probabilities in each row shall count to 1.

In the previous example, one uses only significant wave height as a parameter to predict the

Sea state	**Low**	**Moderate**	**High**
Low	0.5	0.4	0.1
Moderate	0.5	0.4	0.1
Rough	0.1	0.4	0.5

Table 3.4.: Transition matrix

weather. In the simulation model developed for this master thesis, several parameters are dependent on each other. The random outputs of current speed, water temperature, significant wave height, and salinity will not represent how the fish welfare will vary throughout a year.

It is assumed that the user of this simulation method has good historical data over a more extended period, where the relevant parameters are measured simultaneously to give a realistic overall picture of the environment at the potential farming site.

Chapter 4

Case Study

This case study will consist of modeling three HDPE cages with different dimensions, which will be subjected to different degrees of exposure levels defined by NS9515. Aquasim will analyze the cage deformations, which will be further used to assess the fish welfare concerning the varying stocking density. Finally, the whole production system will be simulated in Simulink, where the environmental-based welfare indicators are used to assess the fish welfare in regards to the environmental conditions only.

A possible outcome from the simulation could be that data retrieved from one location in the Simulink model indicates good welfare in terms of stronger currents and temperatures well within the salmons' tolerance limits. The cage could then be subjected to large deformations where the maximum stocking densities, found in chapter 2.3, are significantly exceeded, which could indicate reduced welfare. Therefore, it is important to have both of the simulations to understand the bigger picture better.

4.1. Cage modelling

For this study, it is assumed that every cage will initially contain a total of 200 000 fish which is the regulated limit from the government (fiskeridepartementet 2021), each with a slaughter weight of 4,5 kg. From the literature review in section 2.2, it was mentioned that the mortality rates were varying between 5 - 40% in the Norwegian fish farming industry. Therefore, it has been added a mortality rate of 15% to make this study more realistic, resulting in a total weight of 765 000 kg salmon close to harvest time.

The cages will have different dimensions, but visually they will all look very similar in AquaEdit, and they all consist of the same elements. Illustrations of a medium-sized cage can be found below. Here it is shown with and without the nets, including the frame and mooring system.

The cages will have a slighter higher volume compared to the initial illustrations in figure 32, due to the final design of the bottom part of the net, which is made slightly larger to be able to collect dead fish.

The cage characteristics and material properties related to the net will be taken from AKVAgroup due to their extensive portfolio of Polarcirkel plastic pens, all made of HDPE. A complete list of their model specifications can be found in appendix G.

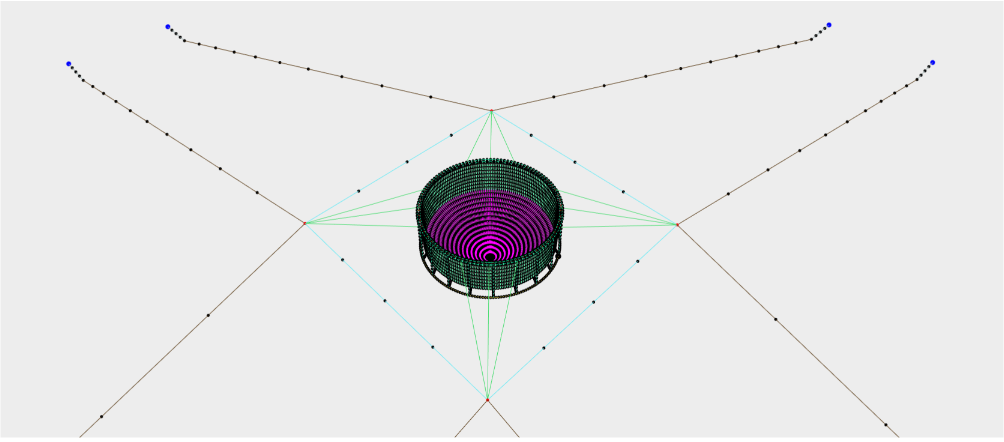


Figure 29.: Complete modelling of SMALL cage

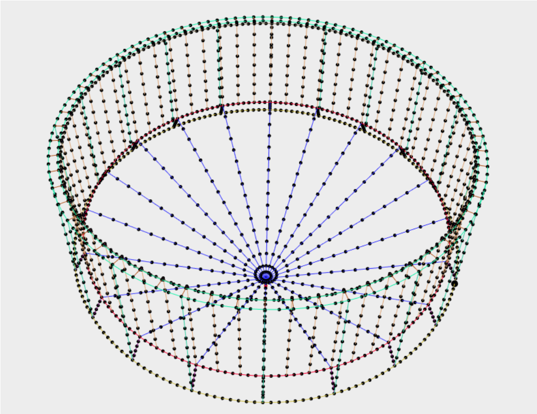


Figure 30.: Modelling of HDPE cage in AquaEdit. Here without the net implemented

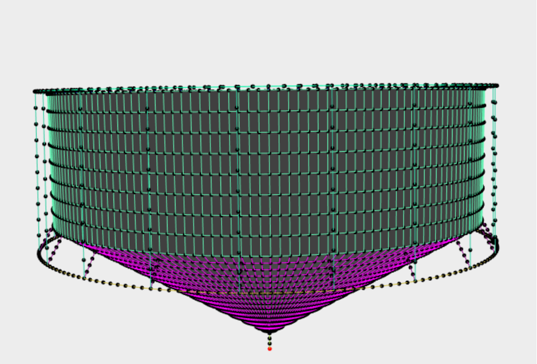


Figure 31.: Modelling of HDPE cage in AquaEdit which includes the net

The first cage is based on Polarcirkel 400 HDPE from AKVAgroup, where the floating pipe diameter is 400 mm. This cage will have a radius of 22.5 m and a total depth of 29 m. This cage is modeled to have a fish density of 24.95 kg/m^3 close to the highest fish density allowed, which is 25 kg/m^3 (fiskeridepartementet 2021). It is the smallest cage modeled in this study.

The second cage is based on Polarcirkel 500 HDPE from AKVAgroup, where the floating pipe diameter is 500 mm. This cage will have a radius of 26 m and a total depth of 30 m. This cage is modeled to have a fish density of 18.4 kg/m^3, which is quite far from the highest fish density allowed. It is modeled as the *medium* sized cage in this study. See figure 32.

The third and final cage is also based on Polarcirkel 500 HDPE from AKVAgroup, where the floating pipe diameter is 500 mm. This cage will have a radius of 26 m, just like cage 2, but it will go deeper with a total depth of 50 m. This cage is modeled to have a fish density of 12.7 kg/m^3, which is the lowest density in this study. It is modeled as the *largest* sized cage in this study. Due to the larger dimensions and corresponding mooring system, this cage will have the highest investment cost compared to the other cages. See figure 32.

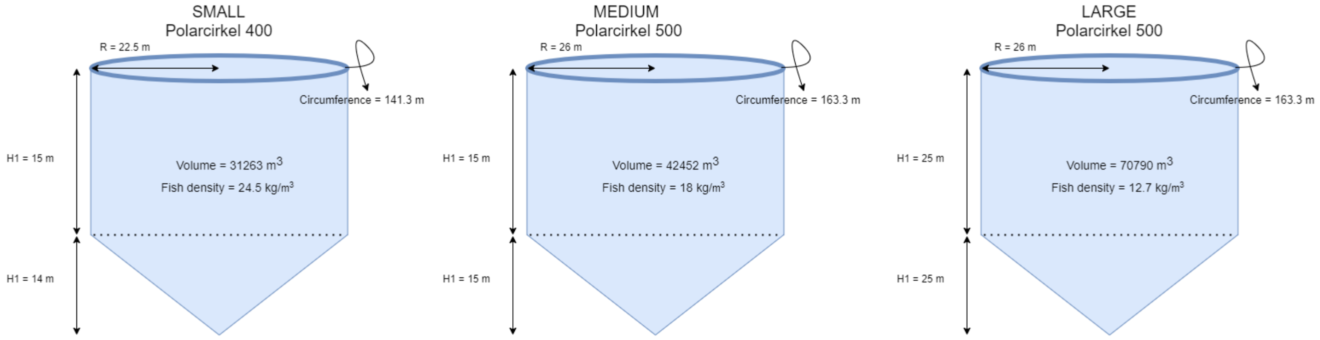


Figure 32.: Dimension overview of the 3 cages used in the Aquasim simulation

4.2. Cage Simulation

After the cages have been modeled in AquaEdit, they will be exposed to different environmental conditions that cause cage deformations. These results will be shown in AquaView, which illustrates how the cages behave being exposed to specific loads related to waves and currents.

The NS9415 definitions of the degree of site exposure are chosen for this study. These environmental conditions will make the deformation study of the cages more general than using metocean data from a limited number of specified locations. See table 2.1 and 2.2 for the NS9415 definitions. Each cage has been simulated for six cases, and the characteristics can be found in the table 4.1.

Simulation run	**Wave height (Hs) (m)**	**Peak wave period (Tp) (s)**	**Current speed (Vc) (m/s)**	**Site exposure level**
1	0.5	1.6	0.3	Low
2	0.7	2	0.4	Moderate
3	1	3.2	0.7	Substantial 1
4	1.5	4	0.85	Substantial 2
5	2	5.1	1	High 1
6	2.5	5.7	1.3	High 2

Table 4.1.: Simulation conditions for each cage based on Norwegian site classification - NS9415

Several test simulations were conducted before the use of NS9415 classifications. Using their definitions of site exposure level *Extreme* with currents speeds above 1.5 and waves above 3 m resulted in extreme deformations where the cage collar was not able to float above water at all times - resulting in the escape of fish and destruction of the construction. It was therefore decided to simulate the fish cages from a site exposure level going from *Low* to *High*. Here one avoids the most extreme loads as it would not be responsible or realistic to locate an HDPE fish cage in an area with similar conditions.

4.3. Cage deformation results

After the models in AquaEdit have been exported and subjected to given environmental loads, the results are illustrated in Aquaview that shows the deformation of the cages stepwise for 45 seconds. The color range going from blue to red shows the degree of displacement in meters for the HDPE fish cage throughout the simulation time. From figure 40 it can be seen that the largest displacement can be found at the bottom of the net, which is represented with a stronger orange color. From AquaView, it was also quite clear that the cage deformations were extremely varying, going from the first simulation run with a low exposure level to the last simulation run with a high exposure level. See the following figures 40 and 44 for the comparison.

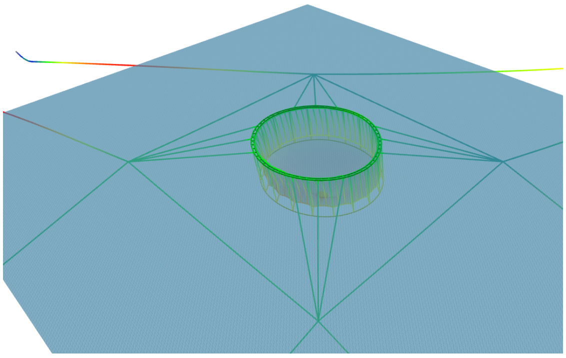


Figure 33.: Small cage for low exposure level (run 1) - max deformation

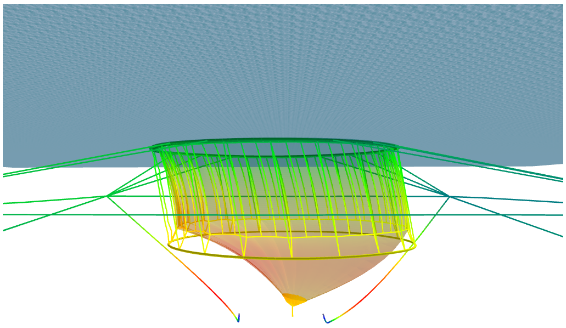


Figure 34.: Small cage for low exposure level (run 1) - max deformation

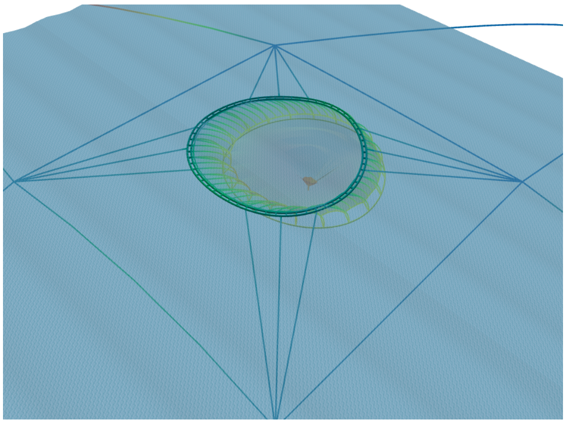


Figure 35.: Small cage for substantial exposure level (run 3) - max deformation

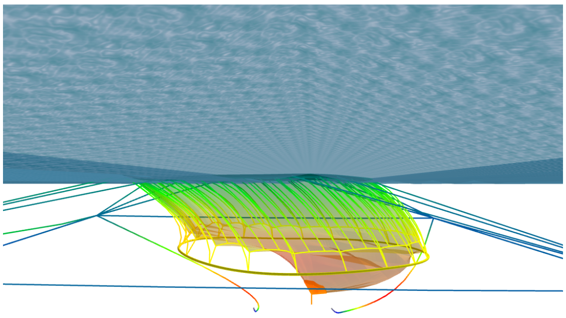


Figure 36.: Small cage for substantial exposure level (run 3) - max deformation

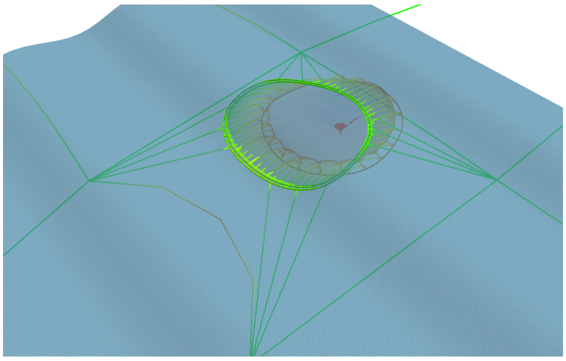


Figure 37.: Small cage for high exposure level (run 6) - max deformation

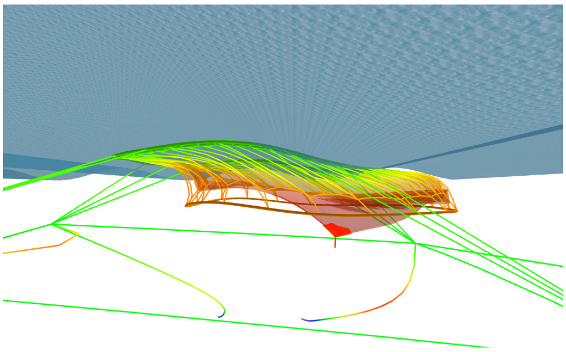


Figure 38.: Small cage for high exposure level (run 6) - max deformation

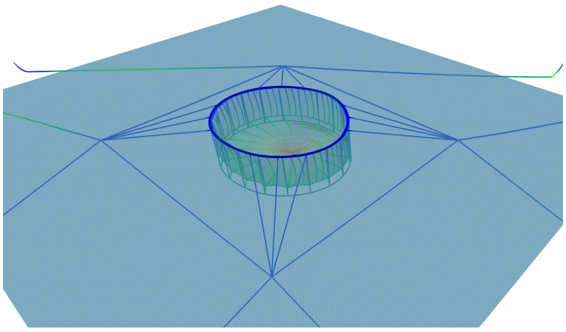


Figure 39.: Medium cage for low exposure level (run 1) - max deformation

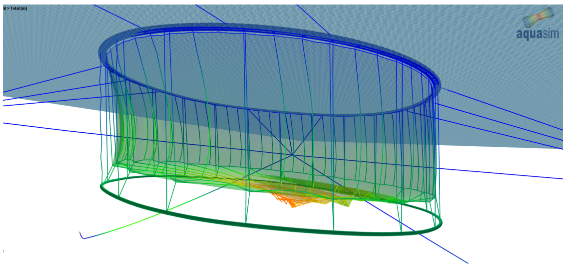


Figure 40.: Medium cage for low exposure level (run 1) - max deformation

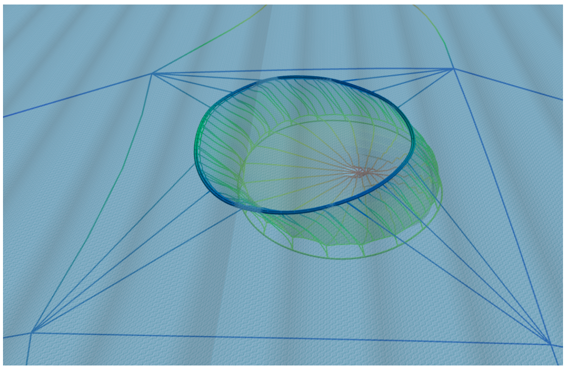


Figure 41.: Medium cage for substantial exposure level (run 3) - max deformation

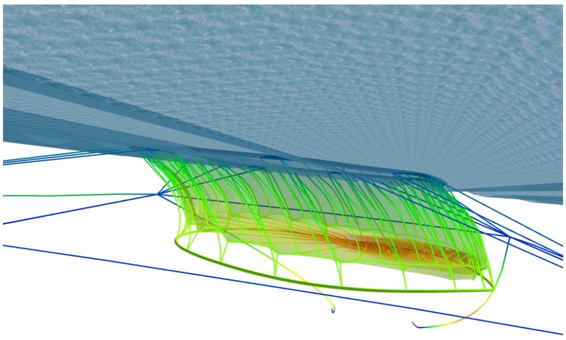


Figure 42.: Medium cage for substantial exposure level (run 3) - max deformation

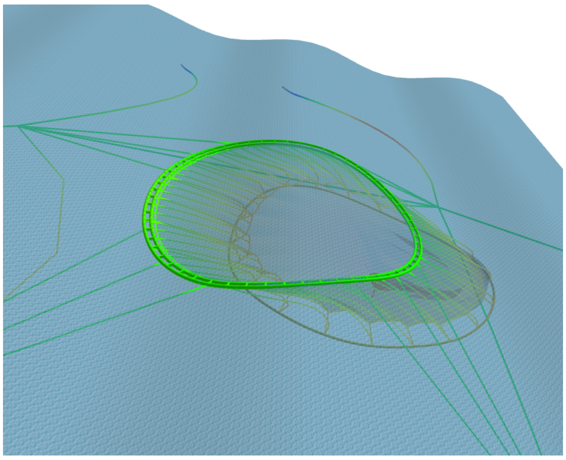


Figure 43.: Medium cage for high exposure level (run 6) - max deformation

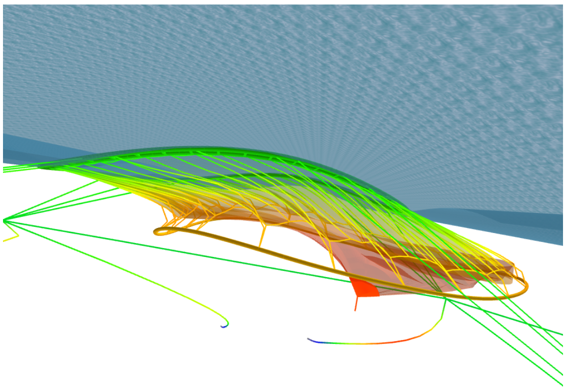


Figure 44.: Medium cage for high exposure level (run 6) - max deformation

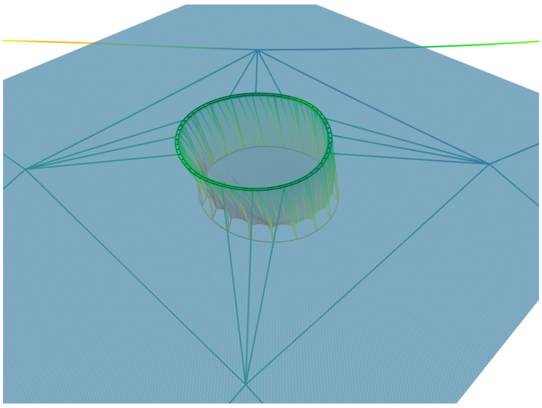


Figure 45.: Large cage for low exposure level

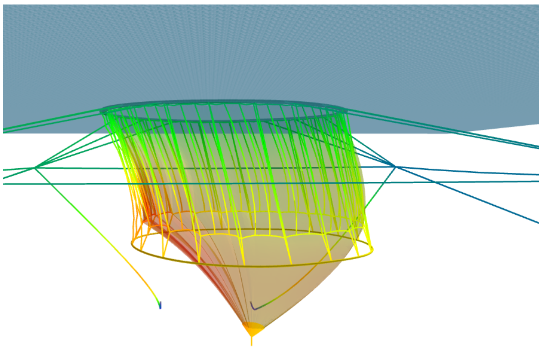


Figure 46.: Large cage for low exposure level

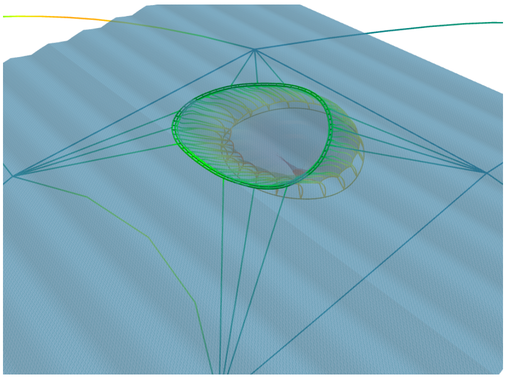


Figure 47.: Large cage for substantial exposure level

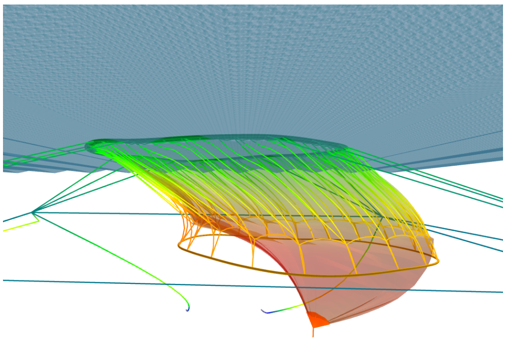


Figure 48.: Large cage for substantial exposure level

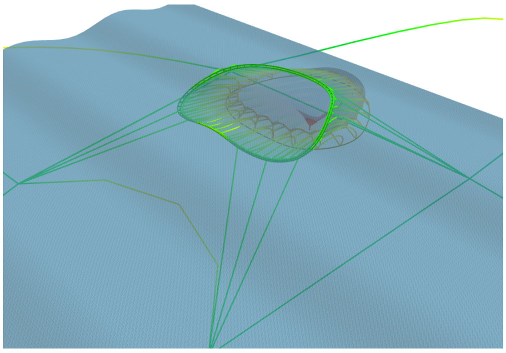


Figure 49.: Large cage for high exposure level (run 6) - max deformation

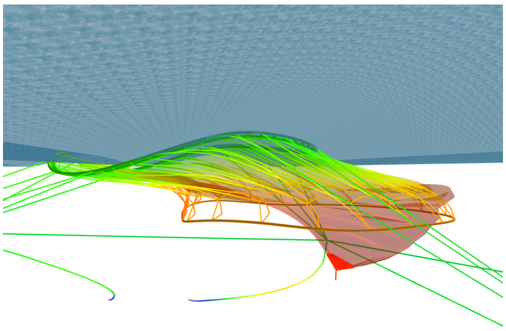


Figure 50.: Large cage for high exposure level

AquaView can extract the calculated volume from each time-step for the side-netting and bottom-net, respectively. Exporting the results to excel and performing simple calculations gave a quick overview of the different cages volumes under static equilibrium, their minimum volume during the maximum degree of deformation, and the largest fish density due to the deformations. The final results from the simulations are presented in the following tables below.

Simulation run	**Static equilibrium volume** m^3	**Min volume** m^3	**Fish density** kg/m^3	**Site exposure level**
1	31965	30110	25.4	Low
2	31965	28377	26.9	Moderate
3	31965	20461	37.4	Substantial
4	31965	17346.7	44.1	Substantial
5	31965	14718	52	High
6	31965	10998	70	High

Table 4.2.: Simulation results for Small sized cage

Simulation run	**Static equilibrium volume** m^3	**Min volume** m^3	**Fish density** kg/m^3	**Site exposure level**
1	42010	35466	21.5	Low
2	42010	33846	22.6	Moderate
3	42010	26450	28.9	Substantial
4	42010	21326	35.9	Substantial
5	42010	17549	43.6	High
6	42010	13500	56.6	High

Table 4.3.: Simulation results for Medium sized cage

Simulation run	**Static equilibrium volume** m^3	**Min volume** m^3	**Fish density** kg/m^3	**Site exposure level**
1	66183	63664	12	Low
2	66183	59660	12.8	Moderate
3	66183	40970	18.7	Substantial
4	66183	33763	22.7	Substantial
5	66183	28482	26.9	High
6	66183	23055	33.2	High

Table 4.4.: Simulation results for Large sized cage

From (fiskeridepartementet 2021) it is specified that the cages must be designed such that the stocking density does not exceed 25 kg/m^3. It does not take into account the deformations. The cage volume was reduced between 4% to 68% during the simulations. The medium-sized cage experienced a more significant reduction during the two first simulation runs than the small and large cage. The reason is unsure as there are no visible differences in the cage configurations in AquaEdit besides the dimensions.

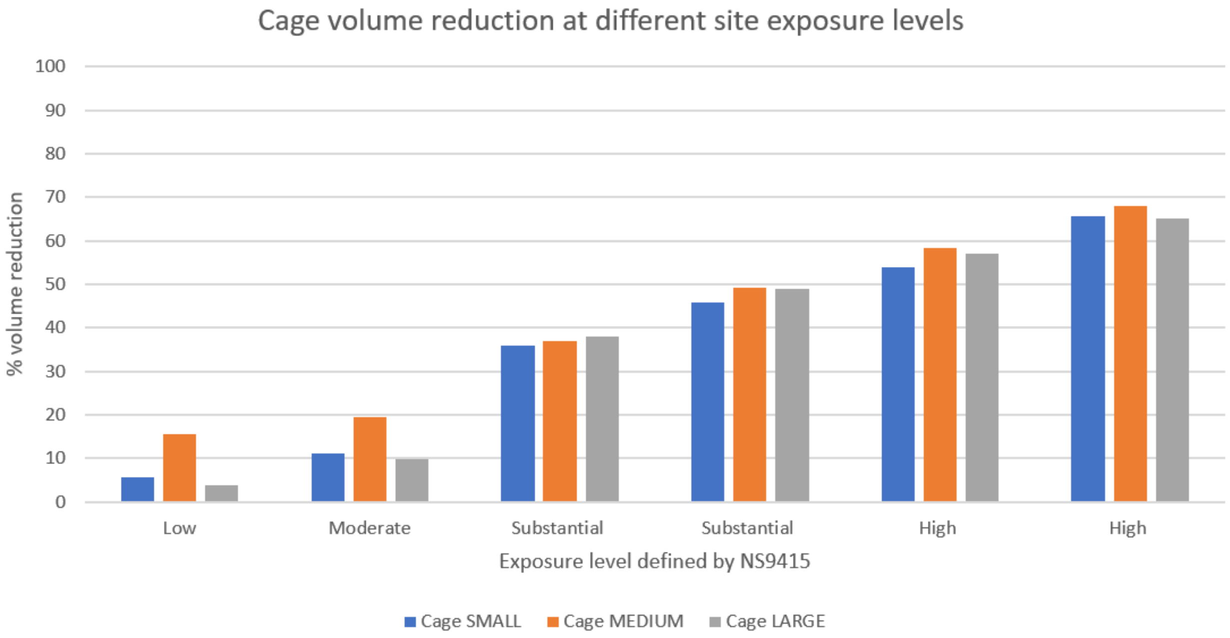


Figure 51.: Overview of the volume reduction in each cage at different site exposure levels

From the results, it is clear that the stocking density is varying greatly between the different cages. From the literature review about the stocking densities effect on fish welfare, specified limits from different scientific research studies were summarized in table 2.4. To use the stocking densities as a welfare parameter, one must develop a table describing the salmon's tolerance limits. Similar tables have been previously made to define the limits related to current speeds, temperature, and wave heights. See figure 23 and 24.

Using table 2.4 and the Aquasim results as a base, a graph has been developed showing the relationship between the available data. See 52. Most of the scientific studies suggest a maximum stocking density varying between 22 - 27 kg/m^3, except (Calabrese et al. 2017) which found that it was feasible to rear salmon at densities up to 75 kg/m^3 at a water temperature around $12°C$. There is no clear answer for the optimal limit, but taking the average from these studies gives a stocking density limit of approximately 37 kg/m^3.

From the simulation in Aquasim, the small and medium cage exceeded the density limits in

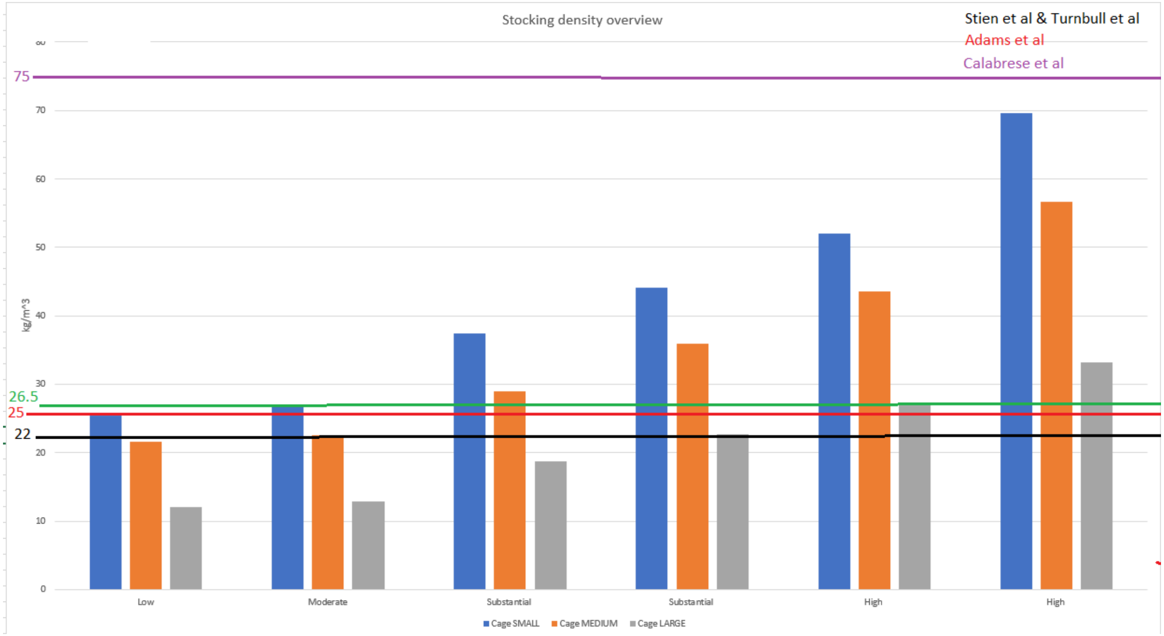


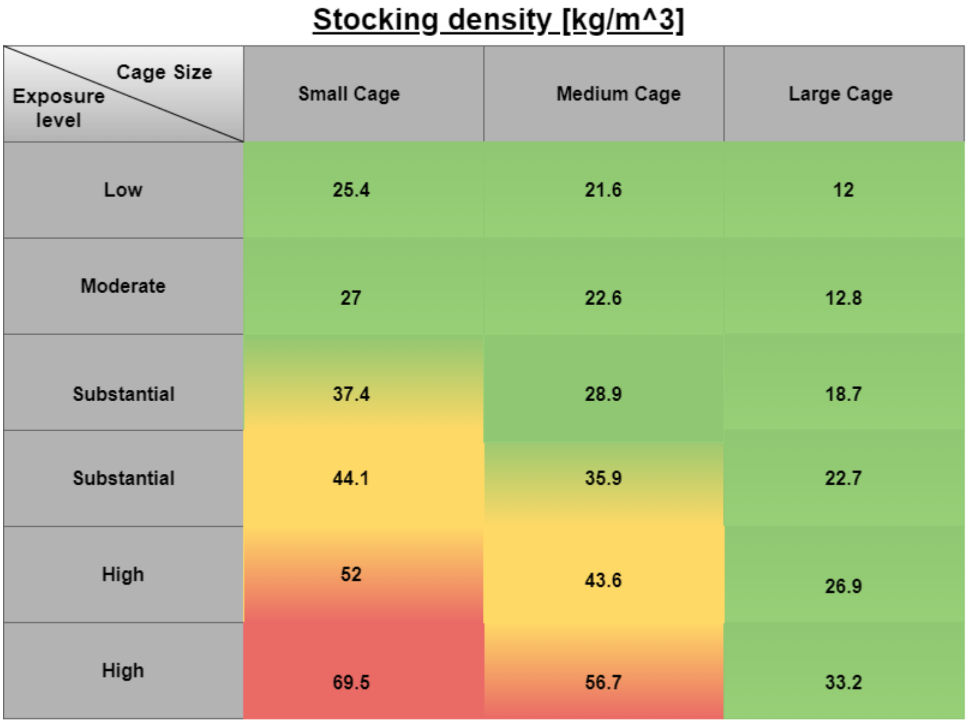
Figure 52.: Stocking densities overview with salmon tolerance limits from different studies

the 20 kg/m^3 range when the site exposure level was above moderate. Based on information about the possibilities of increased stocking density in environments with sufficient current speeds, the small and medium-sized cages could still be good choices for a fish farm in terms of fish welfare. A smaller cage would also reduce the costs related to investment and maintenance through less material and a smaller area of the net that needs to be cleaned due to the accumulation of biofouling. There are also benefits in terms of reducing the coastal areas used compared to larger cages.

4.4. Production Simulation - Simulink

The goal is to show how one can use different simulation tools to get insight into the fish welfare when selecting the cage size and site for a potential fish farm. For instance, a fish farmer could own four licenses, which gives the farmer the right to produce a total of 780 x 4 tons of salmon in most cases.

Several locations are being considered, and each site has buoys that have been measuring important parameters like current speed, water temperature, and significant wave heights from the past recent years. The farmer is aware of the environmental welfare indicators but finds it difficult to see the connection between all the parameters from a large amount of data simultaneously. Simulation is an easy and cheap tool to use when comparing the different



Stocking density [kg/m^3]

Cage Size Exposure level	Small Cage	Medium Cage	Large Cage
Low	25.4	21.6	12
Moderate	27	22.6	12.8
Substantial	37.4	28.9	18.7
Substantial	44.1	35.9	22.7
High	52	43.6	26.9
High	69.5	56.7	33.2

Figure 53.: Stocking density in each cage for different exposure levels due to deformation - welfare parameter

sites to each other to ensure the fish welfare as much as possible based on the information available.

Simulink will be used to simulate the production phase of Atlantic salmon, who are swimming inside an HDPE cage being exposed to the environmental conditions at a specified location. The main output will be the fish welfare that has been affected by the water temperature, current speed, handling operations, and significant wave height.

Based on these results, one can gain insight into how appropriate a potential site would be to host an entire fish farm. The fish farmer can further decide what size of an HDPE fish cage would be beneficial to use in securing a responsible stocking density. See section 3.3.1 for a total system description.

4.4.1. Site Selection

Today, most fish farms are located in fjords, where they are relatively sheltered from larger waves and stronger currents. Therefore, it would be appropriate to compare a sheltered site, which is regularly used today, against a more exposed location that holds much potential for the fish farming industry in the future.

NTNU is a partner in Exposed (EXPOSED 2019) and students can access the weather data available. The locations must be anonymous for possible publication, which also includes a Master's thesis. Data has been collected for varying degrees of exposure and different periods. These are typically mean values for hourly measurements, with maximum values for some of the parameters. The data was received in an Excel format for two different locations, which for now will be referred to as location **X** and **Y**.

4.4.2. Data handling - Location X and Y

The amount of data received from EXPOSED was noticeable different for locations X and Y. The relevant parameters were measured every hour for a specific period and contained the time, current speed at 4 meters depth, significant wave height and water temperature.

For location X, there was a total of 5040 data points that were measured between 21.11.2017 17:00 to 22.07.2018 12:00. A large amount of data could be challenging to use simultaneously in this simulation model where the welfare is affected continuously over such a long period. The change and variations in welfare could also be challenging to see when there is such a large set of data points in one plot. The logic behind the model could also affect the results wrongly. A more extended period of lower temperatures or weak currents can negatively dominate the fish welfare, making it difficult to see the periods of suitable environmental conditions for the fish and vice versa.

Location X consisted of 15302 points from 09.03.2016 - 15.12.2017. However, the water temperature was missing after the 830th measurement. As the temperature is such a vital parameter to assess the fish welfare, Barenswatch was used to approximate the temperature profile for the rest of the months. Using the average temperature based on historical data gathered from Barentswatch, one can compare location Y and X with the same amount of input. However, the temperatures from location X are not as accurate as the ones gathered from location Y, and this should be taken into account when assessing the results from the simulation.

The exposure levels used for the HDPE cage simulation in Aquasim have been defined for certain intervals and combinations of current speeds and significant wave heights. Based on this, the weather data from locations X and Y were analyzed and categorized into the different exposure levels to get an overview of what size of HDPE cage could be appropriate for each location.

4.5. Verification and Validation

From the literature study presenting the environmental-based welfare indicators, it has been stated several times that the water temperature is the most dominant parameter that affects the salmon's tolerance limits, for among other things, current speed. The results presented in chapter 5 are all affected by the initial assumptions and boundaries made trying to find a method to measure fish welfare in different environments.

Verification and validation are independent procedures that are used together for checking that a product, service, or system meets requirements and specifications and that it fulfills its intended purpose (Force 2004). The Institute of Electrical and Electronics Engineers (IEEE 2011) has adopted a standard called the PMBOK Guide, which defines verification and validation as the following:

- *Validation* (IEEE) is the assurance that a product, service, or system meets the needs of the customer and other identified stakeholders. It often involves acceptance and suitability with external customers.
- *Verification* (IEEE) is the evaluation of whether or not a product, service, or system complies with a regulation, requirement, specification, or imposed condition. It is often an internal process.

Definitions made by the Computational Fluid Dynamics Committee on Standards of the American Institute of Aeronautics and Astronautics (AIAA) (Trucano et al. 2006) is presented as:

- *Verification* (AIAA) is the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model.
- *Validation* (AIAA) is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

As previously mentioned in the thesis, there is no official way to measure fish welfare. However, the literature study has established how the salmon reacts to different environmental conditions. Based on this logic, the resulting plot indicates that in periods with increasing fish welfare, the environment is good for the fish. In periods of decreasing value in welfare,

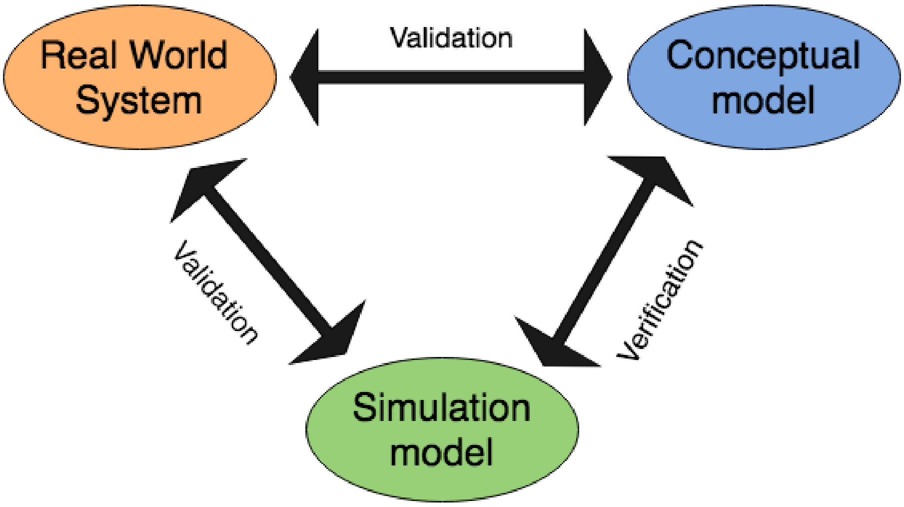


Figure 54.: Verification and validation overview

it could indicate lower temperature or too low/high current speeds. To verify that the simulation model is coded correctly, a manual inspection was performed in terms of having an output that corresponds to the given requirements.

By looking at the resulting plots against the corresponding input data, including water temperature, significant wave height, and current speed, one could easily see if the model output was consistent with the initial logic behind using environmental-based welfare indicators. The verification process was quite simple due to the simulation running time being low. By performing several test runs with a different input while developing the simulation model, one could see errors and misinterpretations early in the process. The result is a simulation model that seems to accurately represent the developer's conceptual description of the model and the solution to the model.

The verification process will help to determine whether the simulation model is error-free and of good quality, but it will not ensure that the system is useful. This is where the term *validation* becomes relevant. Validation is the process of checking that the simulation model captures the customer's needs. In this case, the main goal was to use simulation to gain insight into fish welfare at potential farming sites.

There are different techniques to perform validation of the simulation model. One of these techniques is to have a continuous dialog with system experts while designing and also have them supervise the output. During the simulation model development, the author has been in regular contact with the master thesis supervisor, discussing possible errors and challenges to verify the model.

As mentioned previously, validation is a process to see that the system meets the customer's needs, and therefore should the model interact with them throughout the process. It has not been possible during the writing of this master thesis, but for further work and development, one should include relevant people from the fish farming industry.

A second technique to perform validation of the simulation model is to determine the expected output. It can be done by determining how close the simulation output is to the real system output. However, there is no official method to measure a salmon's welfare during operation, so there is no real-life system to compare with the simulation output. With the increasing focus on fish welfare and collecting more data, it could be possible to use this technique in the future for similar models.

One can also use sensitivity analysis to perform validation of the simulation model. Here one can observe the effect of change in output when significant changes are made in the input data. In this case study, a sensitivity analysis is performed using a set of made-up data that contains more extreme combinations of the different parameters. A more extended period of very good water temperature combined with very bad currents speeds and large wave heights could potentially lead to misleading results or reveal other sensitive parameters that significantly affect the simulation model.

The sensitivity analysis consist of a total of 5 simulation runs with different combinations of the input data. A detailed overview of the input data for each run can be found in table 4.5. The input data are based on figure 23, which shows how the different combinations of the environmental parameters affect fish welfare. For the sensitivity study, more extreme combinations of input data were used to assess any significant changes in output compared to the simulation runs that used actual data from two potential locations.

Run nr #	Temperature Range	Current speed Range	Significant Wave Height Range
1	Good	Very Bad	Very Bad
2	Very Bad	Good	Good
3	Good	Good	Very Bad
4	Good - Very Bad - Good	Very Bad - Good - Good	Very Bad - Good - Very Bad
5	Good - Very Bad - Good	Good - Good - Very Bad	Very Bad - Good - Very Bad

Table 4.5.: Environmental parameters used for the sensitivity analysis

Chapter 5

Results

The results from the production simulation is presented below for location X and Y. This includes the varying fish welfare over time based upon the environmental input data, and an overview of the degree of exposure level based upon NS9415's definitions.

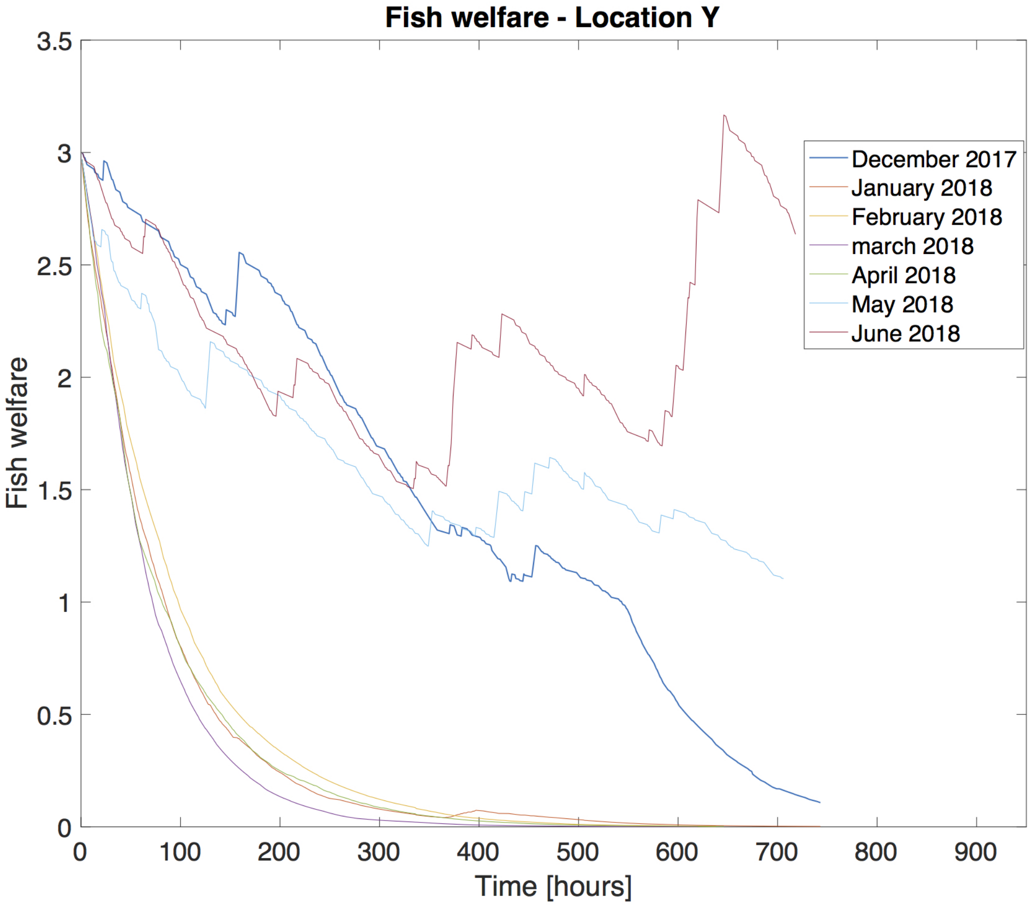


Figure 55.: **Location Y:** Fish welfare using input from each month individually for a total of 7 simulation runs. June and May have a significant better environment in regards to the fish welfare compared to February, March and April.

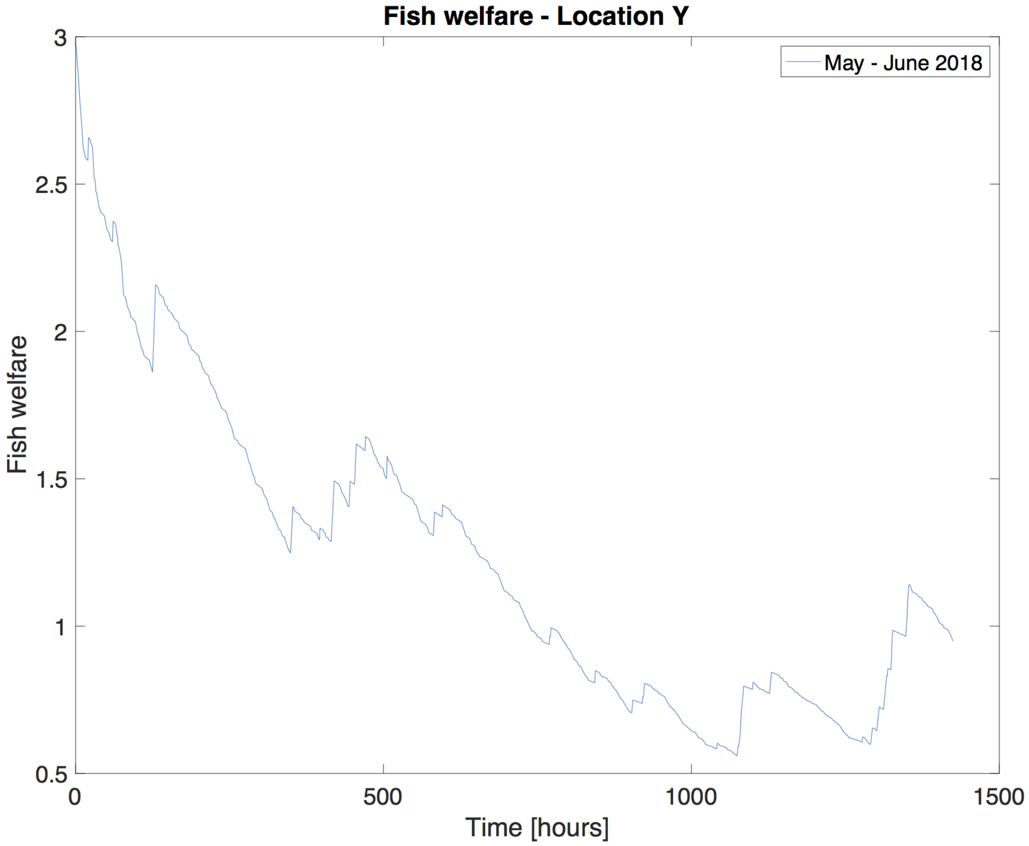


Figure 56.: **Location Y:** Fish welfare using input from may and June together in one simulation run. Varying fish welfare with periods of good environmental conditions.

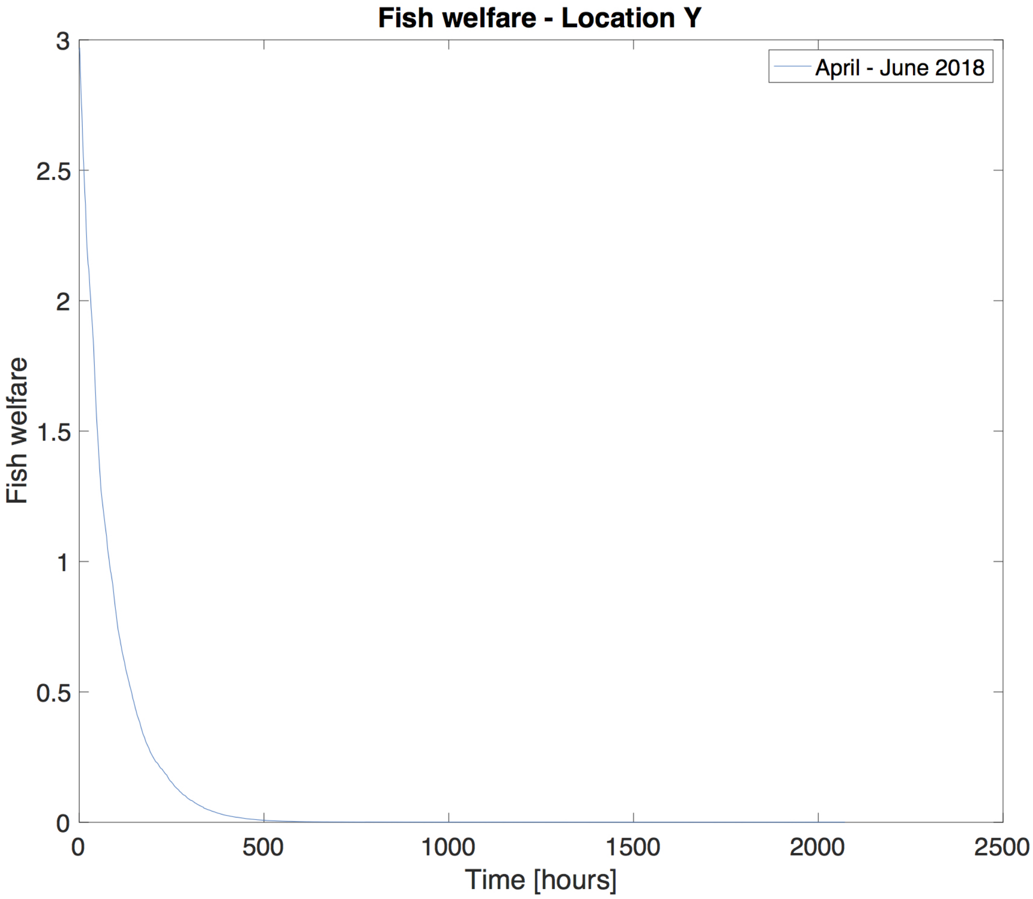


Figure 57.: **Location Y:** Fish welfare using input from April to June in one simulation. The fish welfare significantly decreases and stays at a low value indicating poor welfare due to the environmental conditions

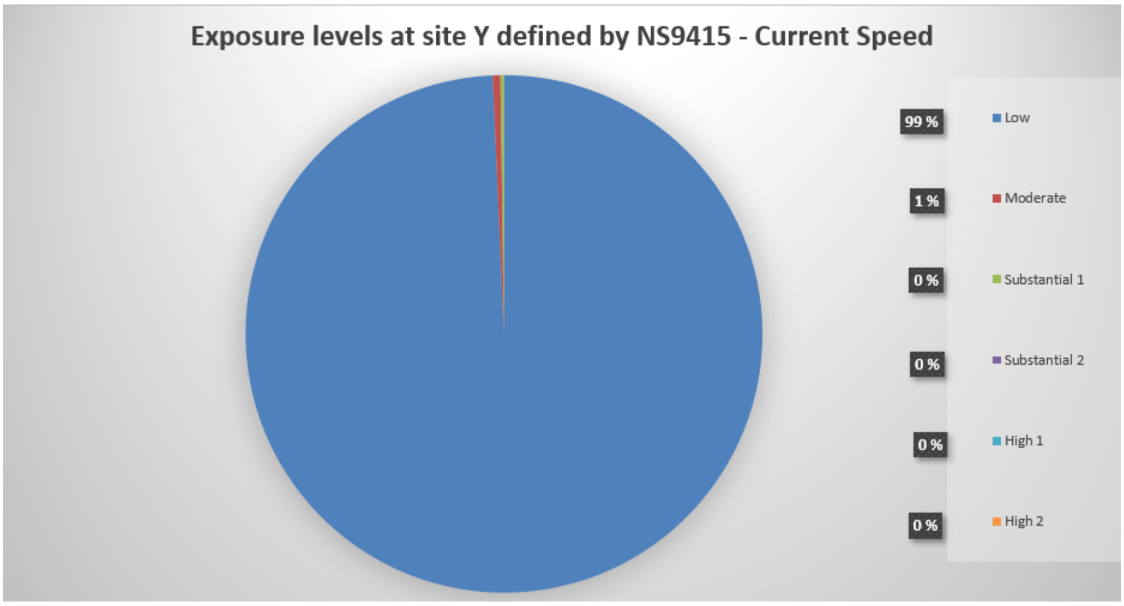


Figure 58.: **Location Y:** Fraction of time on what exposure level site Y was on based on NS9415 definitions - significant wave height

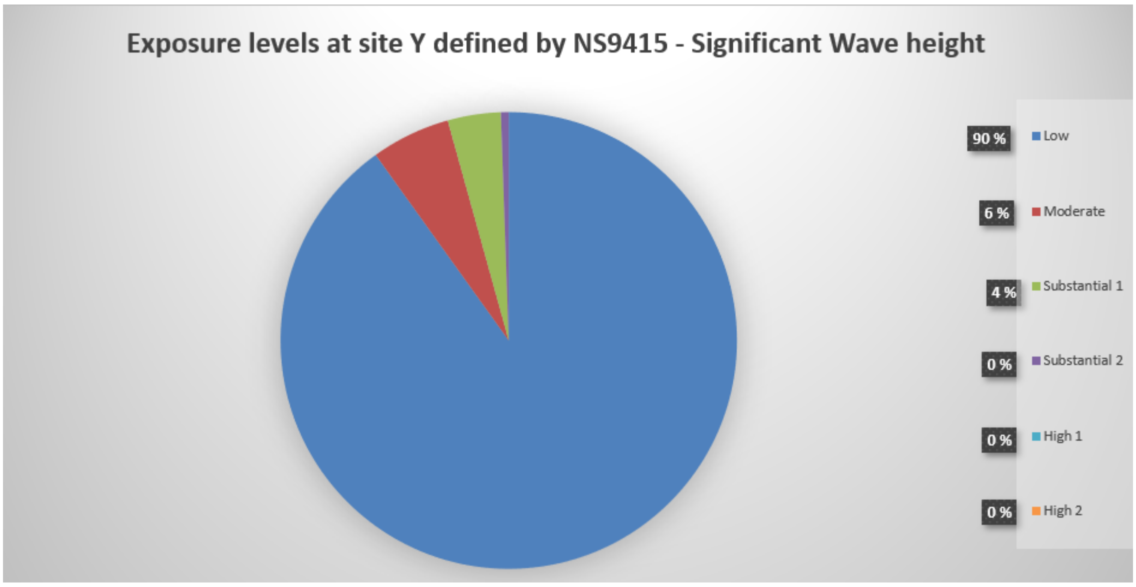


Figure 59.: **Location Y:** Fraction of time on what exposure level site Y was on based on NS9415 definitions - current speed

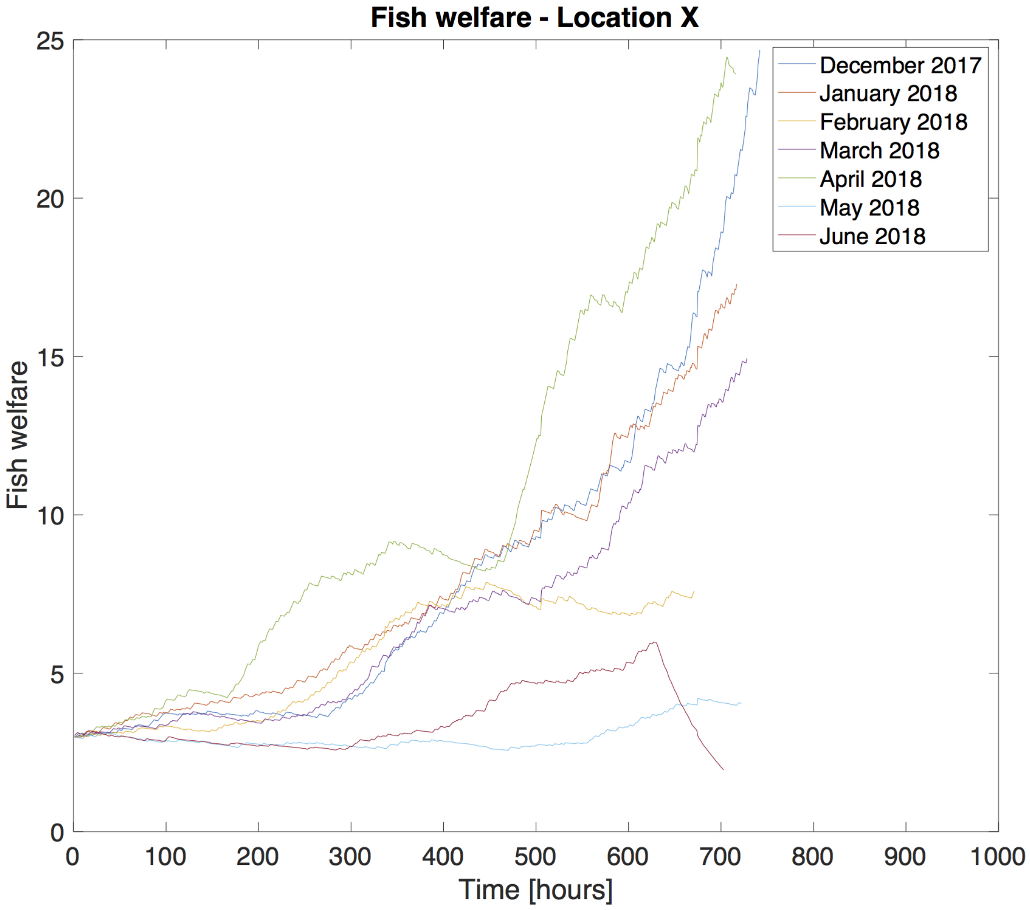


Figure 60.: **Location X:**Fish welfare using input from each month individually for a total of 7 simulations. The plots shows a significant better welfare for most of the months compared to location Y.

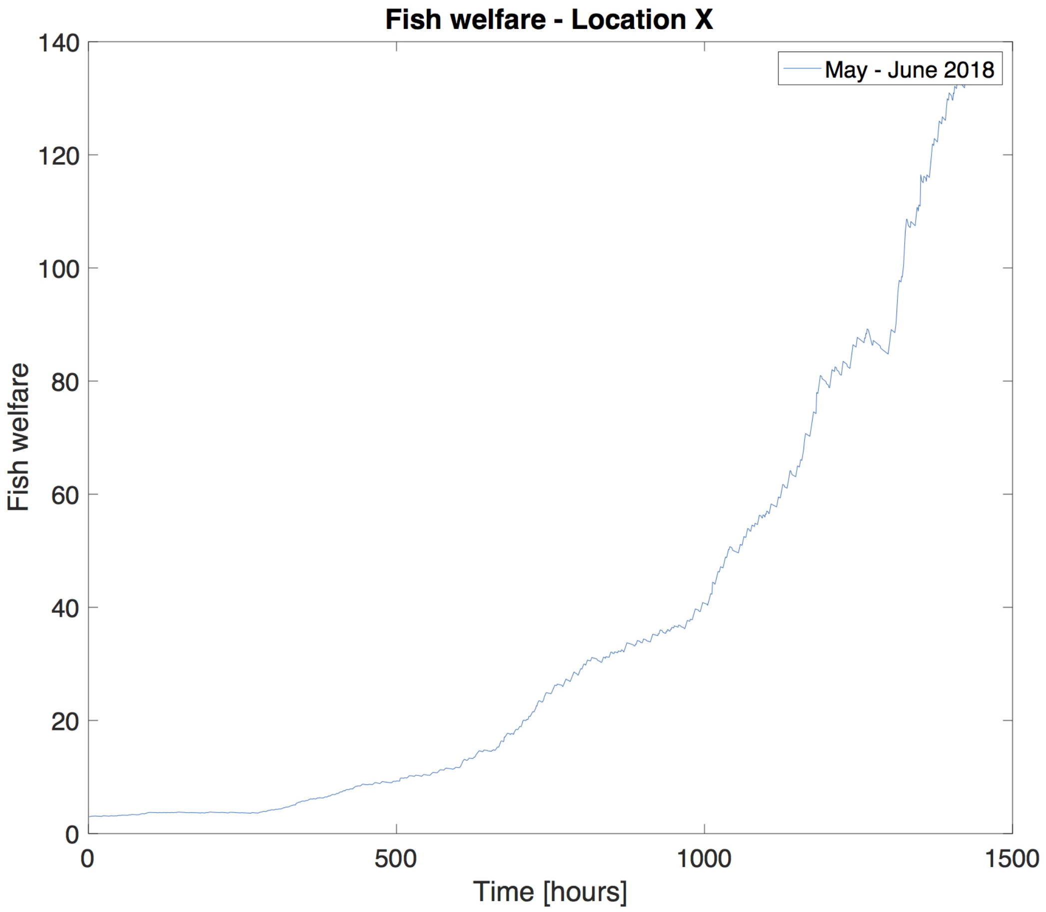


Figure 61.: **Location X:**Fish welfare using data from May and June as input in one simulation run. The welfare is continuously increasing, indicating good environmental conditions related to the salmons needs.

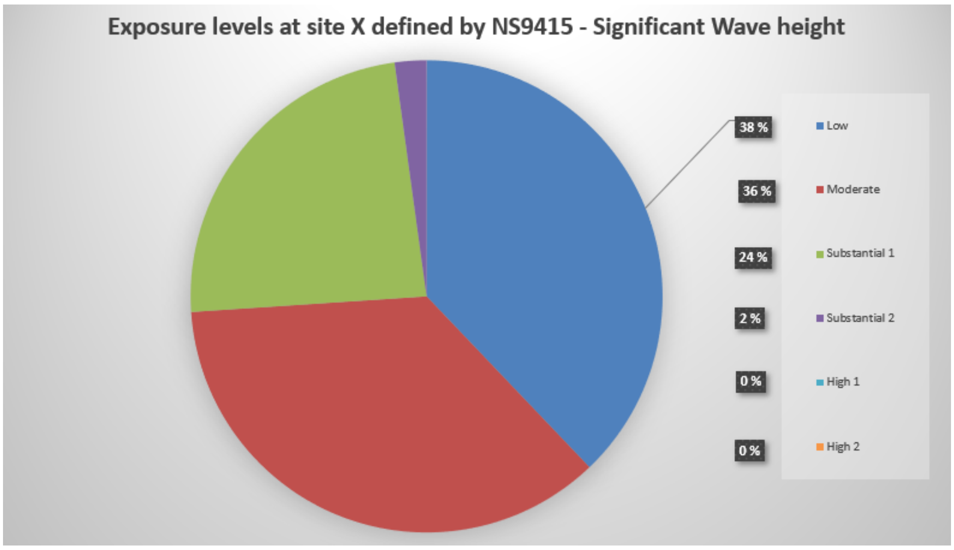


Figure 62.: **Location X:**Fraction of time on what exposure level site X was on based on NS9415 definitions - significant wave height

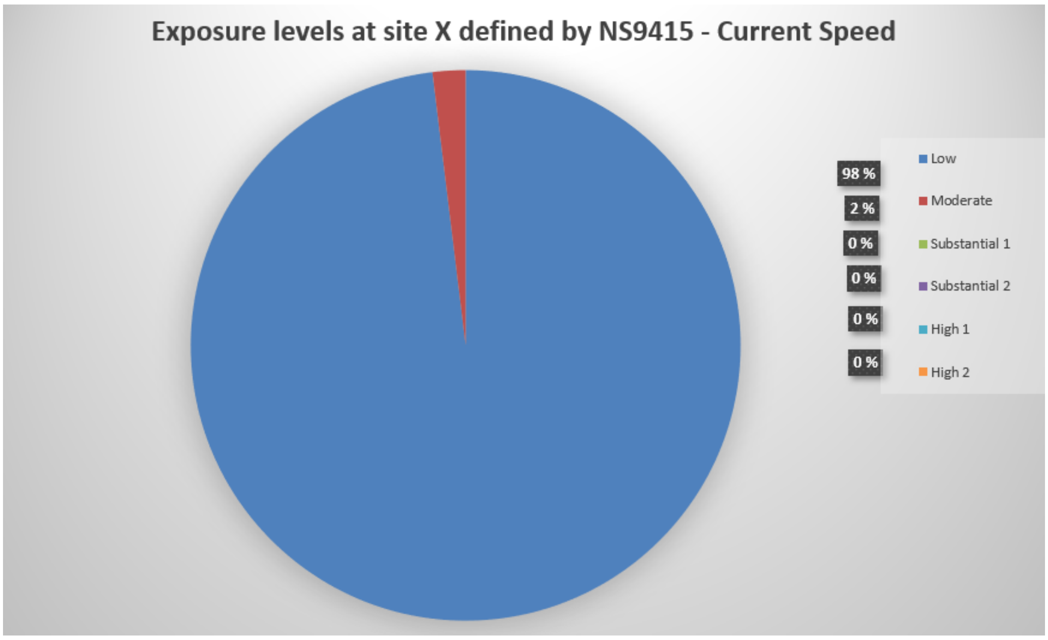


Figure 63.: **Location X:**Fraction of time on what exposure level site X was on based on NS9415 definitions - significant wave height

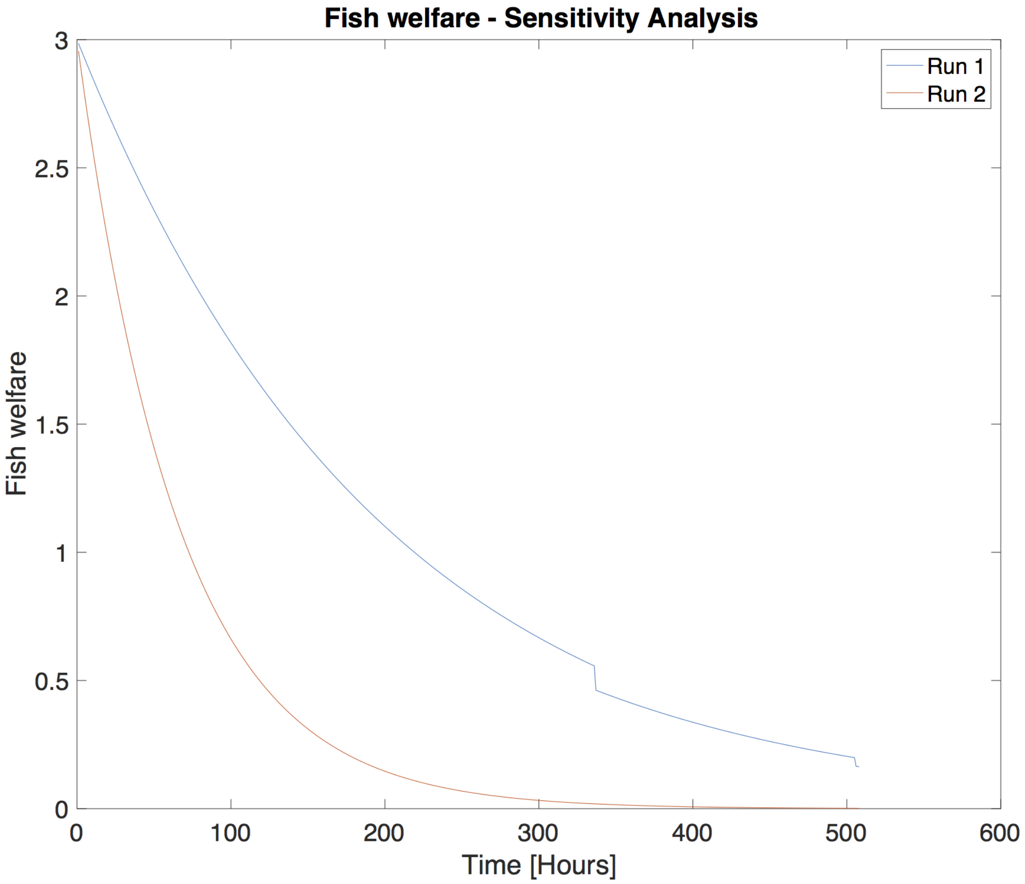


Figure 64.: Welfare results using significant changes in the input. Information about Run 1 and 2 presented in table 4.5

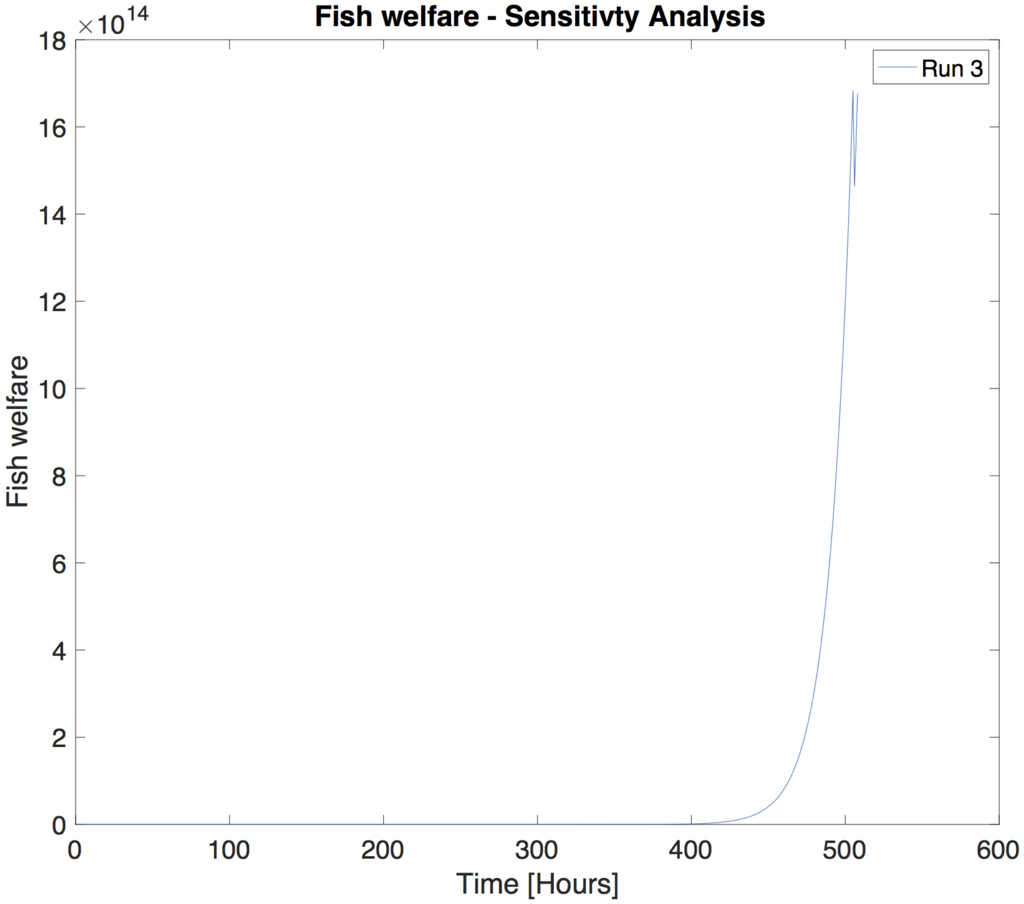


Figure 65.: Welfare results using input data where the temperature and current speed are good and the significant wave height are categorized as very bad

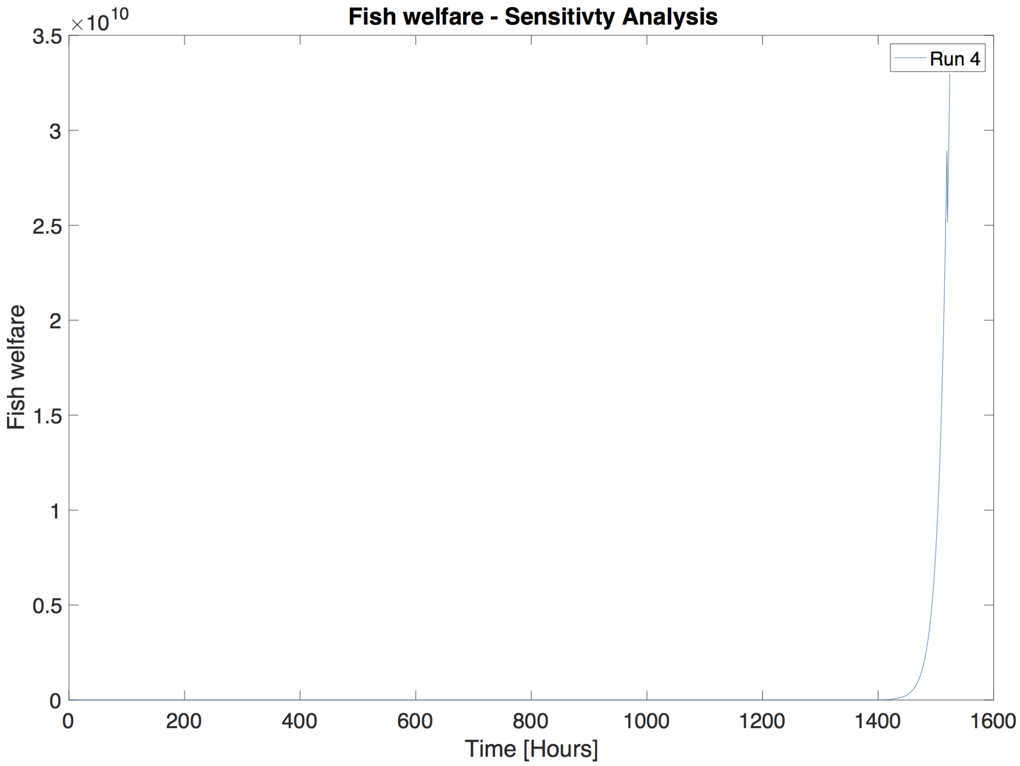


Figure 66.: Welfare results using a combinations of all the input data from simulation run 1 to 3, resulting in a longer simulation time

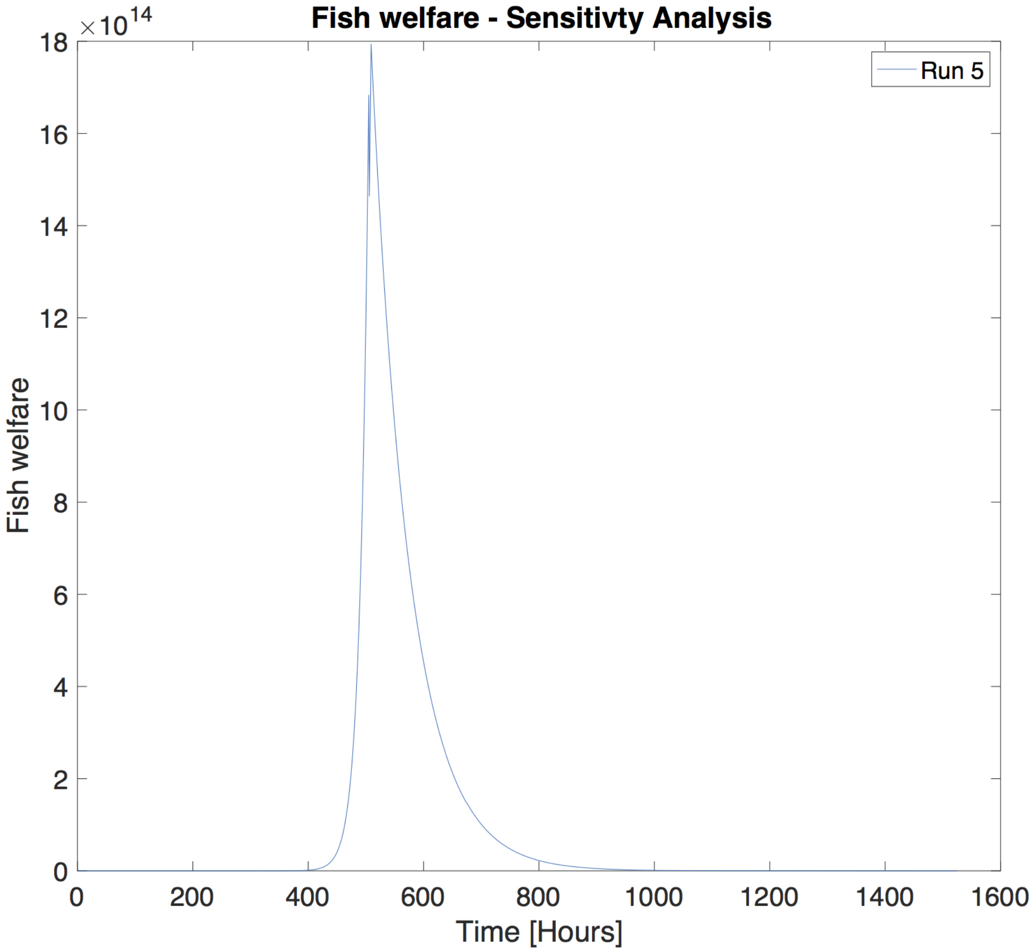


Figure 67.: Welfare results using a combinations of all the input data from simulation run 1 to 3, in a different combination than simulation run 4, resulting in a longer simulation time

Chapter 6

Discussion

This chapter will discuss the results from the simulation performed in Simulink using input data from two locations X and Y. The varying fish welfare will be assessed. Based on the site's exposure levels, an assessment covering the choice of HDPE fish cage will be discussed based upon the preliminary assumptions, expectations, and results. Finally, the results from the sensitivity analysis are discussed where possible weaknesses and strengths of the simulation model are presented.

6.1. Location Y

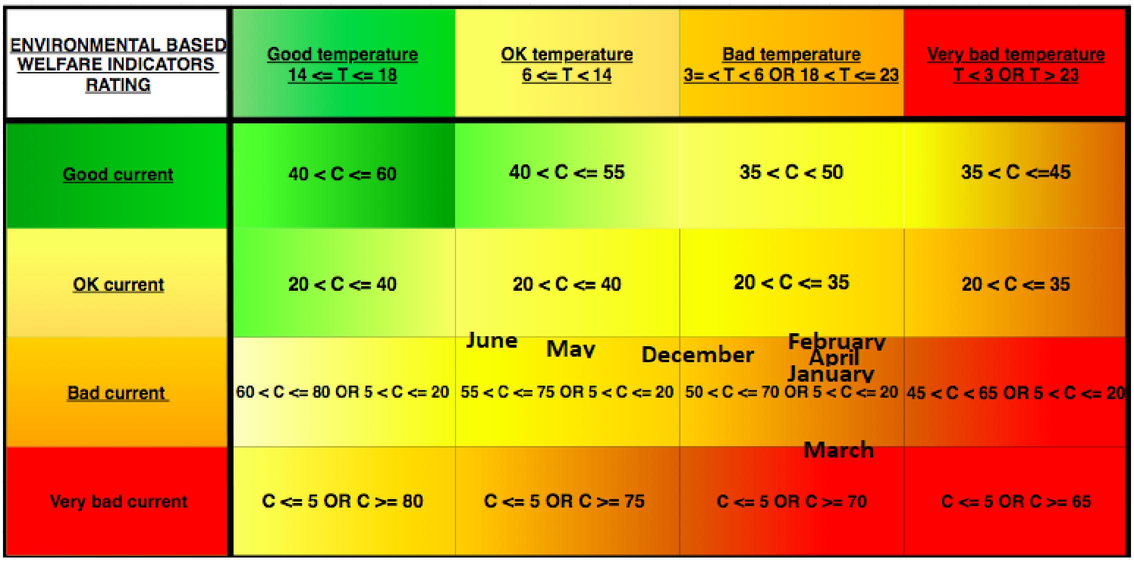
Location Y was the site with a relatively large amount of data available. A time period covering seven months starting from December 2017 was used as input in Simulink to assess the fish welfare by environmental-based welfare indicators.

Having one large simulation using all the available data continuously resulted in a complicated plot to predict. At first glance, it could seem that this was a terrible location to place a fish farm as the fish welfare decreases significantly in a short amount of time before it stabilizes at a low value compared to the initial starting point.

Due to the chosen logic behind calculating the fish welfare, explained in figure 26, a longer period of lower currents or temperatures dominates the fish welfare. Having a period with good conditions after a long bad one will not be visible in a resulting plot. This can be seen in figures 57 and 56. Looking at just May and June individually in figures 55 and 68, one can see that they have primarily good conditions for the fish to thrive in compared to the resulting fish welfare in April that goes downhill from the start.

Plot 57 uses data from April to June as input, and there are no visible variations in the fish welfare besides it decreasing significantly. Plot 56 also has a significant decrease in fish welfare from the start, but here it is possible to see more in detail how the graph varies up and down throughout the simulation. Due to better environmental conditions in terms of fish welfare, the smaller amount of data points makes it easier to see the changes in detail.

The results in 68 corresponds to the overview on how the different months are rated against each other using the environmental-based welfare indicators as a basis. The currents have a high degree of variation over time, so the months in the *environment data matrix* are based upon mean values. Based on this, site Y is not a good choice for placing a fish farm due to the lower currents and colder temperatures. However, it is essential to keep in mind that this is based upon a small amount of data for a specific year, only considering December to June. The model is also very temperature-driven, meaning that the temperature is the parameter that has the highest effect on fish and affects the way current speed influences welfare.



ENVIRONMENTAL BASED WELFARE INDICATORS RATING	Good temperature 14 <= T <= 18	OK temperature 6 <= T < 14	Bad temperature 3= < T < 6 OR 18 < T <= 23	Very bad temperature T < 3 OR T > 23
Good current	40 < C <= 60	40 < C <= 55	35 < C < 50	35 < C <=45
OK current	20 < C <= 40	20 < C <= 40	20 < C <= 35	20 < C <= 35
Bad current	60 < C <= 80 OR 5 < C <= 20	June May 55 < C <= 75 OR 5 < C <= 20	December February April January 50 < C <= 70 OR 5 < C <= 20	45 < C < 65 OR 5 < C <= 20
Very bad current	C <= 5 OR C >= 80	C <= 5 OR C >= 75	March C <= 5 OR C >= 70	C <= 5 OR C >= 65

Figure 68.: Overview of the different months conditions rated against the environmental based welfare indicators

A different approach could here be to adjust the *improvement* of fish welfare to a higher level, making it more visible on the plot how the welfare varies. However, it is not easy to see detailed variations in a plot that goes over such a long time due to the large amounts of data points.

A measure to see a more detailed overview of the environmental conditions’ effect on fish welfare was done using less data, only looking at a shorter period. See figure 55. Here each month was used as input for their individual simulation run. Due to this move, the fish welfare starts at the same point each time, meaning that it does not consider the continuous change in fish welfare over time, giving a misleading image of the welfare situation. However, looking at a shorter period, one can use the results to predict when the fish needs extra supervision and attention due to harsher weather conditions.

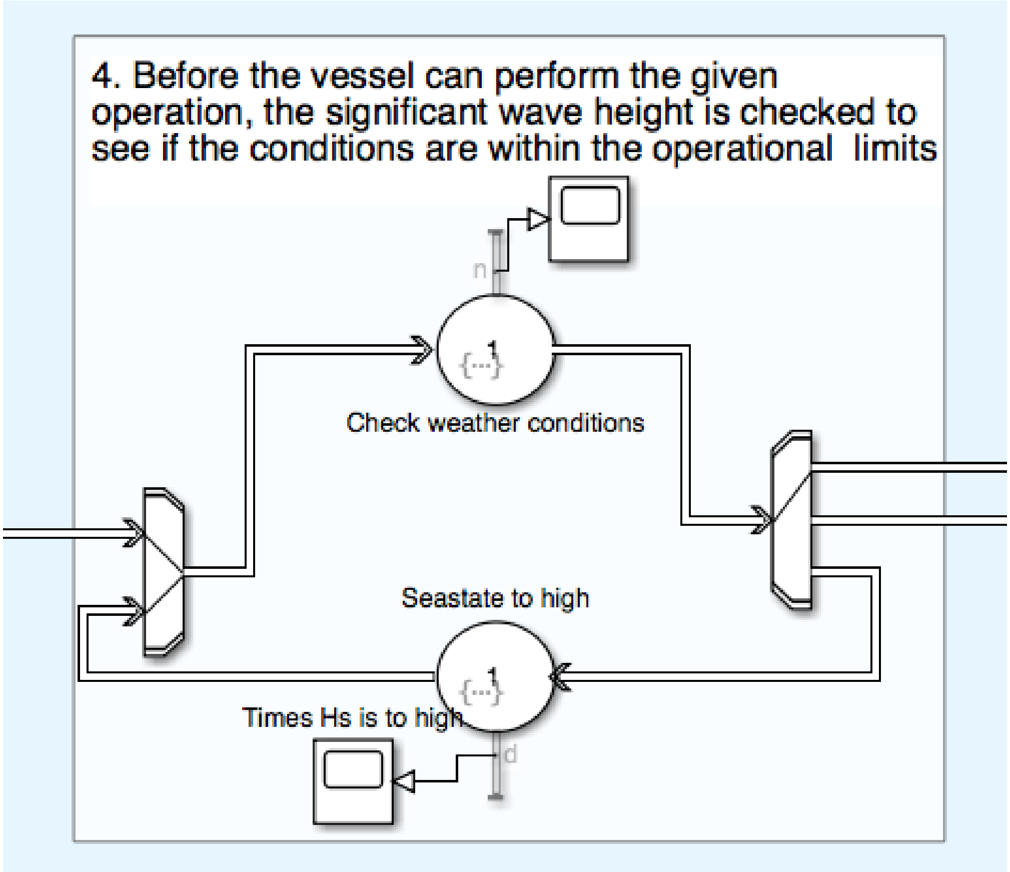


Figure 69.: Waiting loop in simulation model

It is crucial to ensure that the support vessels can conduct the different handling operations necessary when choosing a site. A waiting loop was implemented in the simulation model to track the number of times where the sea states are exceeding the support vessels' operational limits, see figure 69. Much time goes by waiting on weather in the offshore industry, but in the fish farming industry, where one deals with living creatures, the time waiting on weather must be minimal. Figure 70 shows the results where one can see that significant wave height never exceed 2.5 m, and it was possible to execute the operations according to plan.

The handling operations do have a larger impact on the fish welfare when executed during certain environmental conditions. See figure 24 for a complete overview. Looking at the fish welfare results, the time where delousing has been executed is marked with green and net

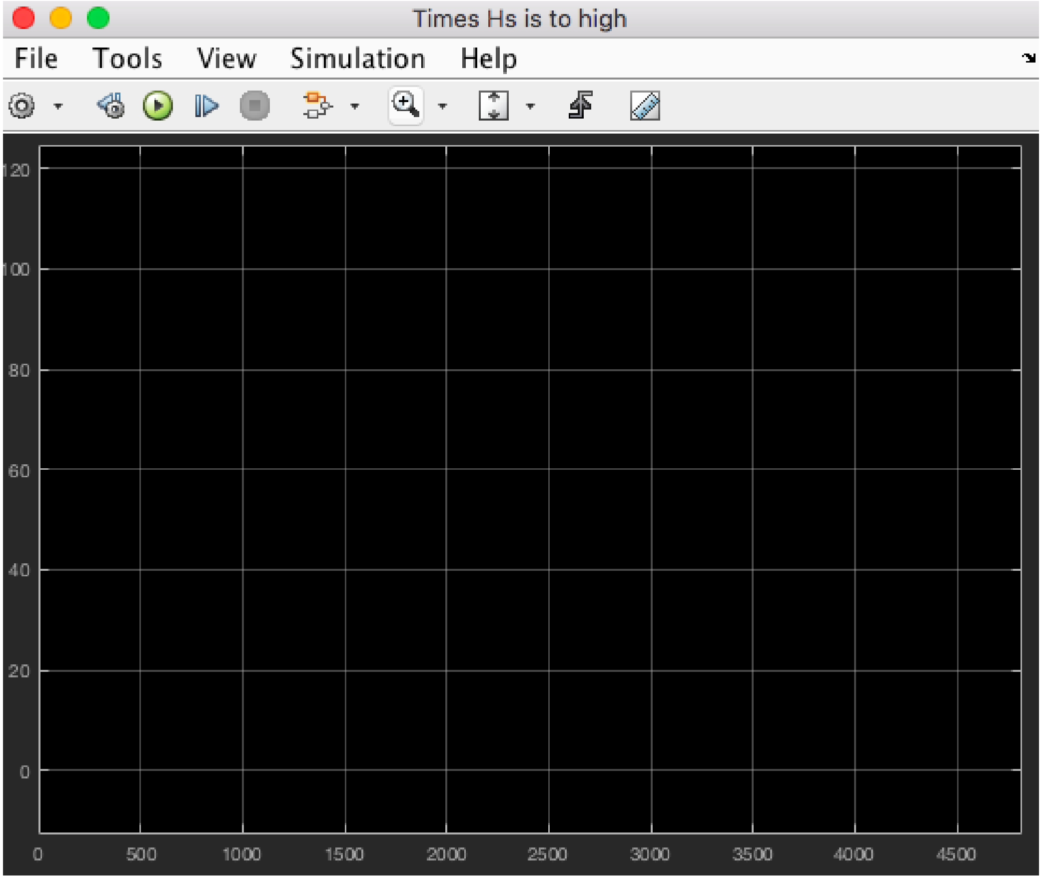


Figure 70.: Simulation results using environmental input data from location Y.

cleaning has been marked with red. See figure 71. Due to many data points, it is not easy to see the exact impact handling operations have on welfare based on a visual representation of the plot. It is a great tool when using fewer data. Suppose one can see large drops in welfare. In that case, it may be easily explained by an operation, and one can use the results to go further into detail and analyze the environmental conditions together with a certain handling operation.

Based on the figures 59 and 58, location Y is 99% of the time at a *low* exposure level in terms of current speed. There is a higher variation in the significant wave height where the site experience a *low* exposure level 90% of the time, 6% and 4% of the time it is moderate and substantial, respectively. Based on figure 2.3, all of the cages seem suitable for location Y, and if fish farmers want to minimize the investment costs, a small cage seems to be fitting in this case. However, it is important to emphasize that we only use data from December to June for one specific year. We have no idea about the environmental conditions the other half of the year, making it difficult to justify using a small cage or having a fish farm at location Y at all.

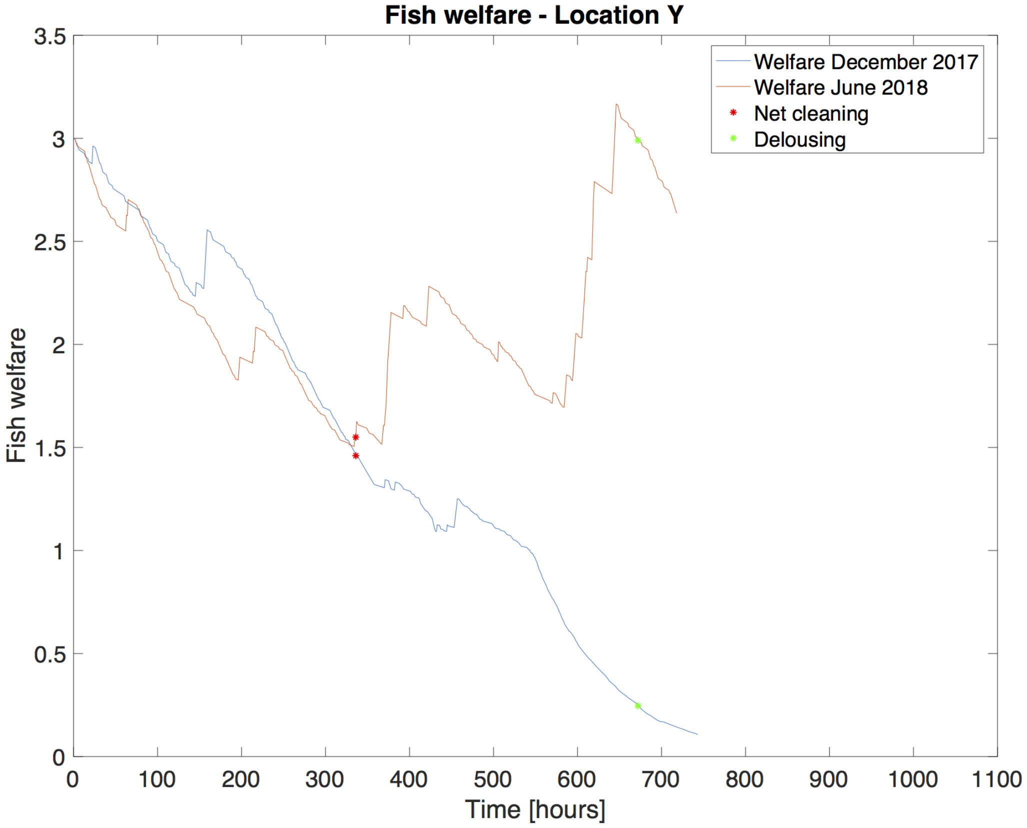


Figure 71.: Overview of fish welfare in June and December with points indicating handling operations

6.2. Location X

From chapter 4, it was found that the temperature measures were missing from location X after the 830th measurement. The remaining temperatures were collected from Barentswatch, which are based upon historical data using average values. It will highly affect the output in the simulation due to the temperature being the dominant parameter as it has the most significant effect upon fish welfare. From Barentswatch, it was found that the temperature between December to June were all between 6 to 14 C°, meaning that all input will be categorized within *OK temperature* and will have a positive effect upon fish welfare unless the current speed is significantly low.

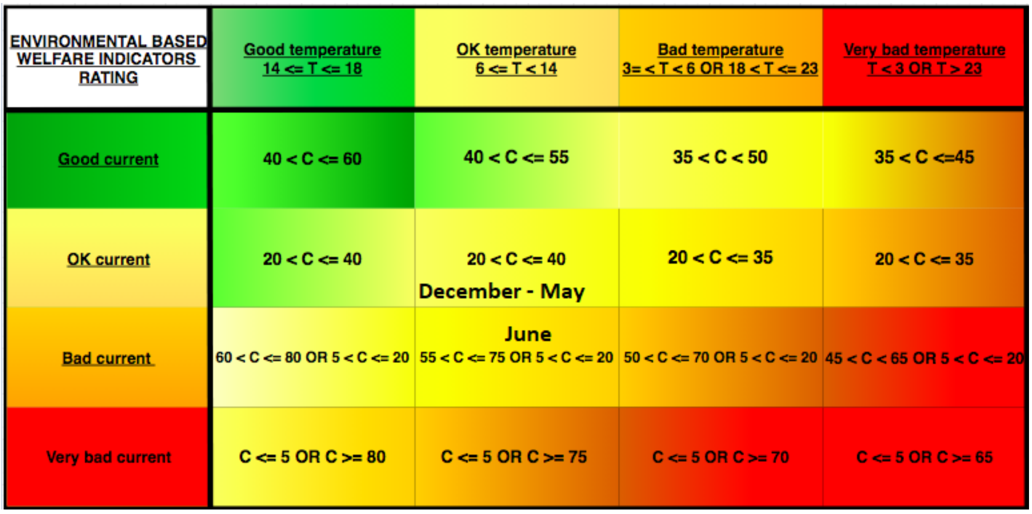
Based on the experience from the simulation runs for location Y, the data points were divided into smaller blocks, and the model was using input from each month individually to make the plots easier to interpret. As mentioned in the discussion section for site Y, it will not give a continuous picture of how welfare varies for a more extended period. However, it can still assess how some months may have more challenging weather conditions than others regarding fish welfare.

Simulation using the same basis as site Y shows that the fish welfare seems significantly better for location X. In figure 60, all months except June 2018 have increasing fish welfare throughout the simulation time. The value for fish welfare varies between 23 and 2.7 for site X, compared to location Y, which varies between 3 and 0.004. When having a continuous simulation run that contains input data from May to June 2018, see figure 61, one can see that it is continuously increasing to around 9.2 before the environmental conditions for June drive the fish welfare downwards to welfare of around 3.3. By analyzing the input data for June, the current speeds are significantly lower compared to the remaining months. As previously mentioned, current speed was the only negative impact on fish welfare because the temperature is always stable and relatively good. Compared to site Y, the temperatures were heavily varying throughout the months, with temperature in both the *bad* and *very bad* category. From table 23, one can see that this would have a negative impact on fish welfare no matter how good the current speeds are.

The results in 72 corresponds to the overview on how the different months are rated against each other using the environmental-based welfare indicators as a basis. The currents have a high degree of variation over time, so the months in the *environment data matrix* are based upon mean values. Compared to the corresponding table for location Y, site X has a better environment regarding salmons' preferable tolerance limits for water temperature and current speeds. Again, it is essential to consider that we are only simulating using environmental data based on six months out of a whole year. Therefore, there is not enough information to conclude that one site is better than the other. One could say that site X seems like a better fit than site Y based on these results and given limitations in the simulation model.

To get insight into the support vessel's ability to conduct the necessary handling operations at site X, one can use the information from the waiting loop, previously explained in figure 69. However, based on the results showing site X exposure levels, it can be seen that the location never exceeds *Substantial 2*, which from table 4.1 means significant wave heights below 2 m. Figure 24 shows that the handling operations are canceled when the significant wave height exceeds 2.5 meters. This corresponds to the model where no entities are waiting throughout the entire simulation time using data from December to June, see figure 73. Therefore, it could seem like there is no problem with vessel operability if someone chose location X to operate a fish farm. However, more data should be included if the model were to be further developed as a decision-making tool.

Assessing the handling operations further is done by looking at the fish welfare results where



ENVIRONMENTAL BASED WELFARE INDICATORS RATING	Good temperature 14 <= T <= 18	OK temperature 6 <= T < 14	Bad temperature 3= < T < 6 OR 18 < T <= 23	Very bad temperature T < 3 OR T > 23
Good current	40 < C <= 60	40 < C <= 55	35 < C < 50	35 < C <=45
OK current	20 < C <= 40	20 < C <= 40 December - May	20 < C <= 35	20 < C <= 35
Bad current	60 < C <= 80 OR 5 < C <= 20	June 55 < C <= 75 OR 5 < C <= 20	50 < C <= 70 OR 5 < C <= 20	45 < C < 65 OR 5 < C <= 20
Very bad current	C <= 5 OR C >= 80	C <= 5 OR C >= 75	C <= 5 OR C >= 70	C <= 5 OR C >= 65

Figure 72.: Overview of the different months conditions rated against the environmental based welfare indicators

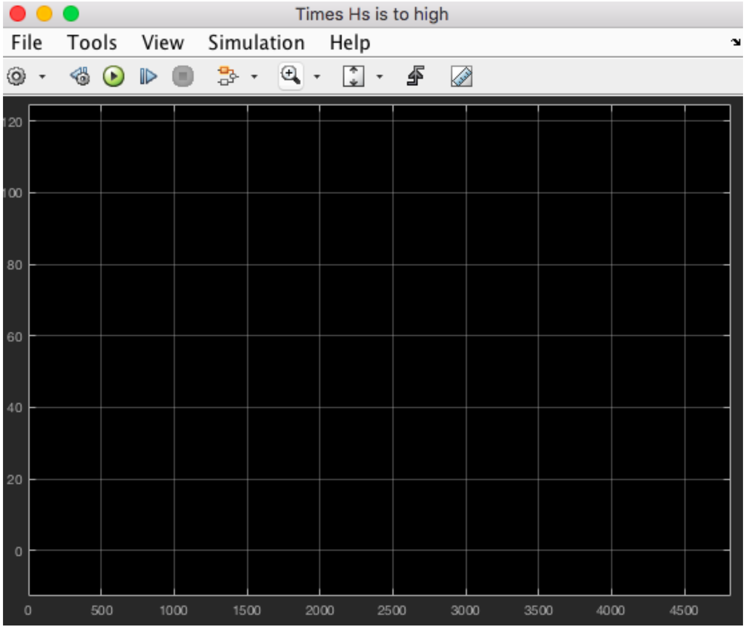


Figure 73.: Simulation results using environmental input data from location Y.

the points in which handling operations have been executed have been implemented in the plots. Delousing is marked with green and net cleaning has been marked with red. See figure 74. Due to many data points, it is not easy to see the exact impact a handling operation has on welfare based on a visual representation of the plot. It is a great tool when using fewer data. Suppose one can see significant drops in welfare. In that case, it may be easily explained by an operation, and one can use the results to go further into detail and analyze the environmental conditions together with a specific handling operation.

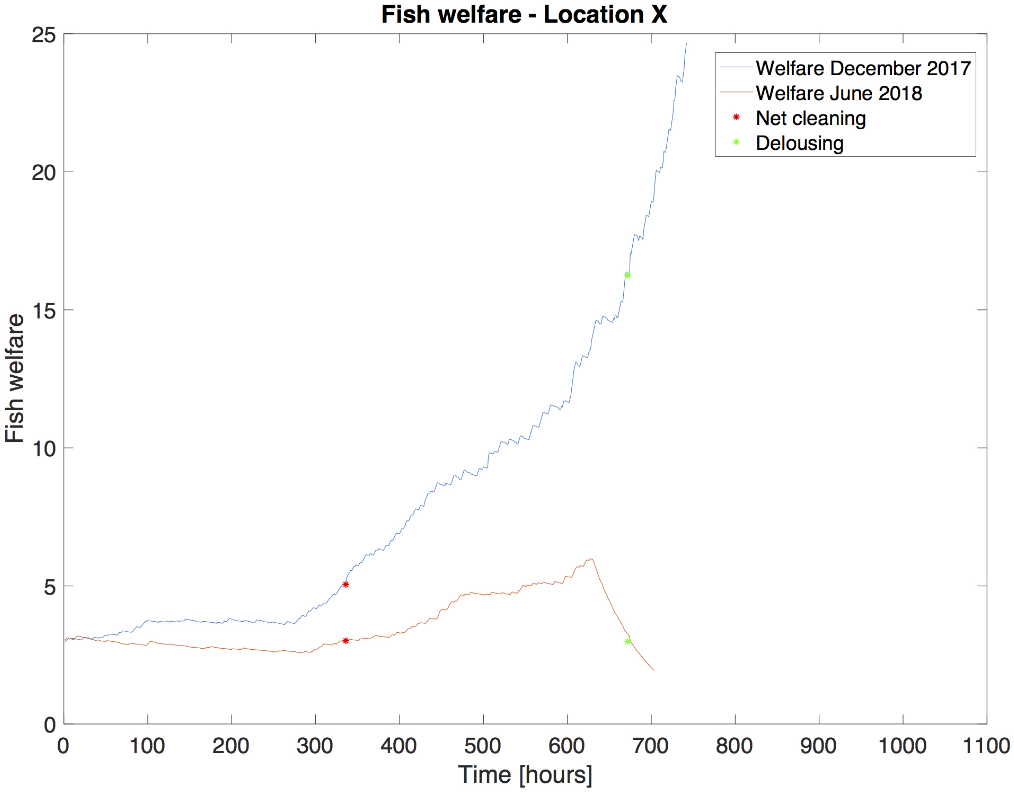


Figure 74.: Overview of fish welfare in June and December with points indicating handling operations

Based on the figures 62 and 63, location X is 98% of the time at a *low* exposure level in terms of current speed. There is a higher variation in the significant wave height where the site experience exposure levels defined as *low*, *moderate* and *substantial 1* most of the time. For rare occasions, one can see conditions that are defined as *substantial 2*. Based on figure 2.3, all of the cages seem suitable for site X in terms of current speed. However, suppose significant wave height is taken into account. In that case, one should consider a medium-sized cage, as the small one could face challenges in having the floating collar stable over water at all times. This recommendation is only based upon the given results and does not consider that the amount of data is minimal and only looking at six months out of a specific year.

6.3. Sensitivity Analysis

This section discusses the sensitivity analysis results that use a different set of input data that contains extreme values for the environmental parameters. The goal was to assess possible weaknesses and challenges related to the simulation model.

The results using environmental conditions presented in table 4.5, one can see from the plot in figure 64 that simulation run 1 has a *better* welfare results compared to simulation run 2. This confirms that the boundaries implemented in the simulation model value a good temperature over a good current speed and significant wave height. It is based upon the literature study in chapter 2 that summarizes the salmon's tolerance limits for different environmental parameters. The significant wave height only affects the fish welfare during handling operations, and the resulting blue graph from run 1 shows how a *very bad* Hs gives a significant drop in welfare. Simulation run 1 has a *good* temperature combined with a *very bad* current speed, and it is vice versa for simulation run 2. However, one can observe an overall decrease in welfare over time.

The results from the simulation run 3 presented in figure 65 shows *good* conditions for both water temperature and current speed throughout the entire running time. It results in an exponential graph, where it looks like the fish welfare has an extreme increase in value from the 420th hour. It reveals a significant weakness in the model, where the chosen logic explained previously can not be applied in every situation due to a possible accumulation of fish welfare.

Logic has been to not focus on the specific fish welfare *value*, but rather assessing when the graph is convex or concave to say something about the environmental conditions at a given site for a specific period. From simulation run 3, not considering the low welfare value, from time 0 to 420, it looks like the environmental conditions are OK, not giving either an increase or decrease in welfare. However, by looking at the low values, one could assume a poor environment compared to the significant difference in the welfare value between the 420th hour to 510th hour.

Neither of these two interpretations corresponds to the actual input data, representing excellent conditions for the fish to grow throughout the entire period. This is critical for the model and something the author was unaware of before conducting a sensitivity analysis. It emphasizes the importance of verifying a model and validating it to make sure that the system meets the needs of the customer, which in this case confirms that it does not do during extreme combinations of different environmental parameters.

Simulation runs 4 and 5 had a more extensive range of input using the data from simulation run 1, 2, and 3 together. See figure 66 and 67. The combinations are presented in table 4.5.

The plot for simulation run 4 has a similar result as for simulation run 3. During the period, 1420th - 1520th hour, the extremely large welfare values overshadow the varying fish welfare from 0 - 1420th hour. See figure 66. From simulation run 1 and 2, one can see the gradual decrease in fish welfare. This does not come to light in either simulation run 4 and 5 due to extremely high values resulting from the input data used for the simulation run 3. It utterly confirms the model's weakness when being exposed to excellent environmental conditions where the fish welfare continuously increases.

From the sensitivity analysis, it is clear that the biggest weakness this model has is if the input has the same *extreme* environmental conditions over time, either being good or very bad. See figure 23. If the welfare is good, it is good. The salmon will never experience an infinite increase in welfare. At some point they will reach their maximum welfare. This logic is also the same for salmon experiencing poor welfare. Welfare can not decrease to the infinite. At one point the salmon will hit an all-time low, indicating death.

One can implement a maximum welfare value to prevent an exponential increase in welfare. After this point, the welfare will no longer increase and stay stable until the model experience worse conditions for the fish to thrive. This plot could easier observe sudden changes in welfare over a more extended period.

The most important part is not to find the periods where the fish are feeling good but rather identify the reasons for why and when the salmon are experiencing reduced welfare. A fish farmer needs this information before making big decisions about the farming location and size of the HDPE cage. Trying to minimize the periods and circumstances contributing to bad welfare will also minimize the risk for mass mortality and ultimately loss of income.

Chapter 7

Conclusions

All of the designed HDPE fish cages were not appropriate for most extreme exposure levels as the cage collar went beneath the water surface, resulting in fish escaping. However, in terms of stocking density, it is possible to use the small cage for *low* to *moderate* exposure levels. The medium cage was appropriate in cases where the are *substantial* exposure levels. The large cage did not exceed a stocking density that negatively affected the fish welfare during any simulation runs. However, it is much more expensive and area demanding compared to the small and medium cage.

Based on the results from Simulink, it seems like location X has better conditions compared to location Y in terms of higher values for the resulting fish welfare. However, it is not easy to draw any conclusions as the historical data used were from a short period. If one were to use this model as a decision-making tool, it would also be necessary to collect data from several years. As the fish welfare either increased or decreased by percentage for each round of input data, it was difficult to see minor changes in the plot for a more extended time. It means that the model is only helpful for a smaller amount of data, which indicates individual simulation runs for each month or having data for each day instead of each hour to cover a more extended period at once.

The verification and validation process for the simulation model was performed firstly by a manual check for the results in the case study. Periods of low welfare in the plot resulted from low temperatures and bad current conditions from the input data. It was also vice versa for the periods of increasing welfare, resulting from suitable temperatures and current speeds at the given location. It corresponded to the assumptions and logic that were based upon the literature study assessing fish welfare.

7.1. Recommendations for Further Work

For further work, one should assess and collect data for several welfare indicators. The fish welfare is quite complex, and the simulation model should include more relevant parameters that affect the welfare of Atlantic salmon. It could be information about oxygen saturation and salinity at a potential farming site over a more extended period.

The model had a significant weakness observed during the sensitivity analysis, where an accumulation of fish welfare occurred during more extended periods of either extremely good or bad environmental conditions. It resulted in a plot that was not possible to interpret due to the significant differences in the welfare value. It can be solved by having a maximum value for the fish welfare or finding a different way to measure welfare in a more relative matter.

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Appendix A

Welfare needs of salmon

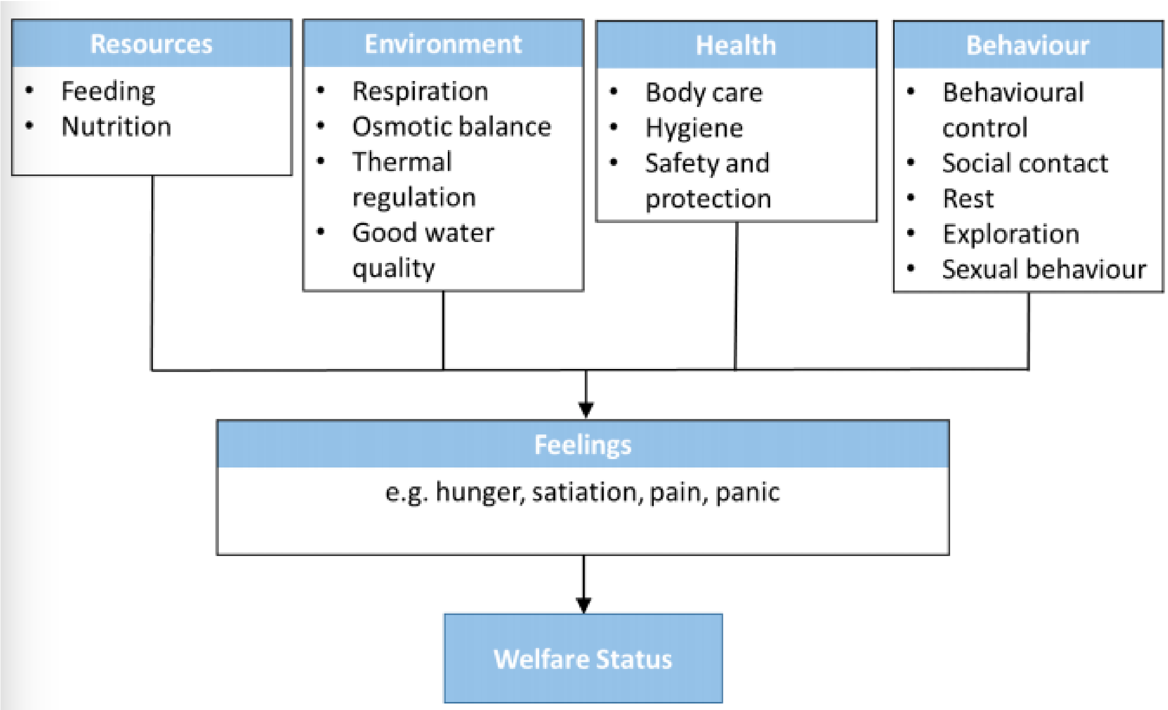
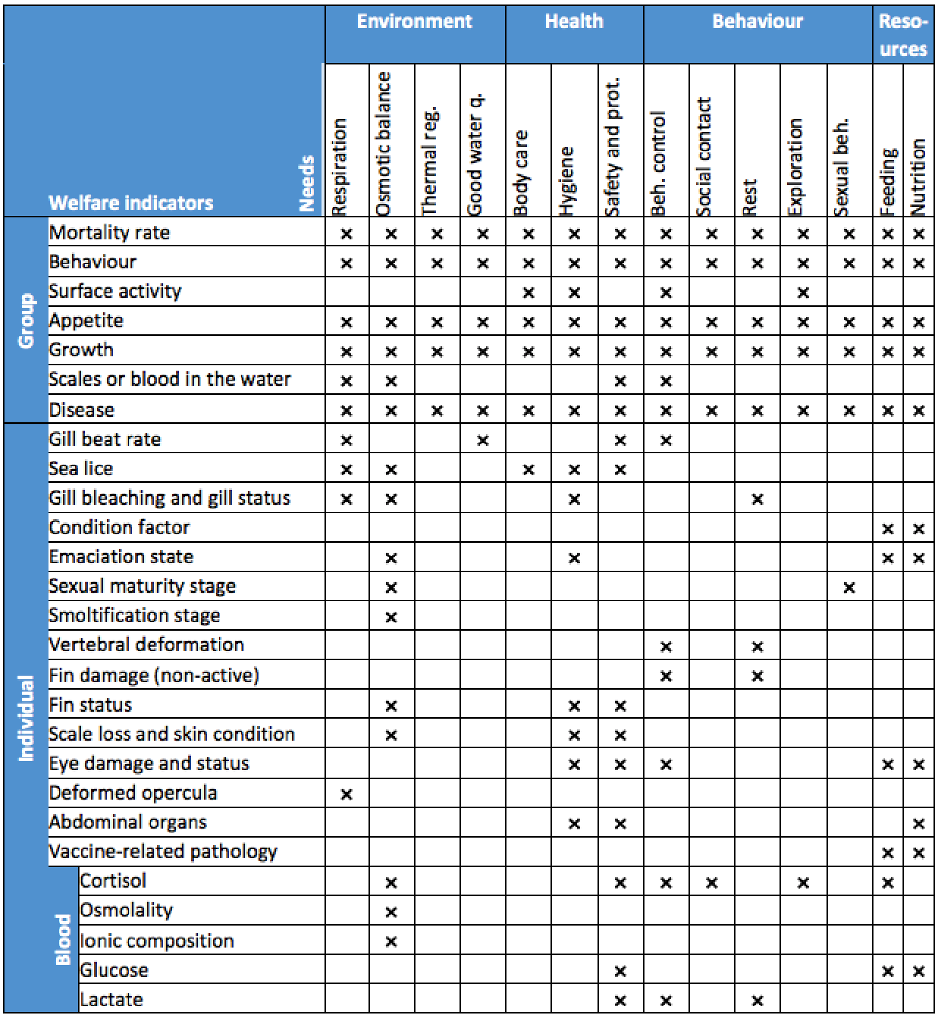


Figure 75.: The welfare needs of salmon (Noble et al. 2018)

Appendix B

Animal based WIs

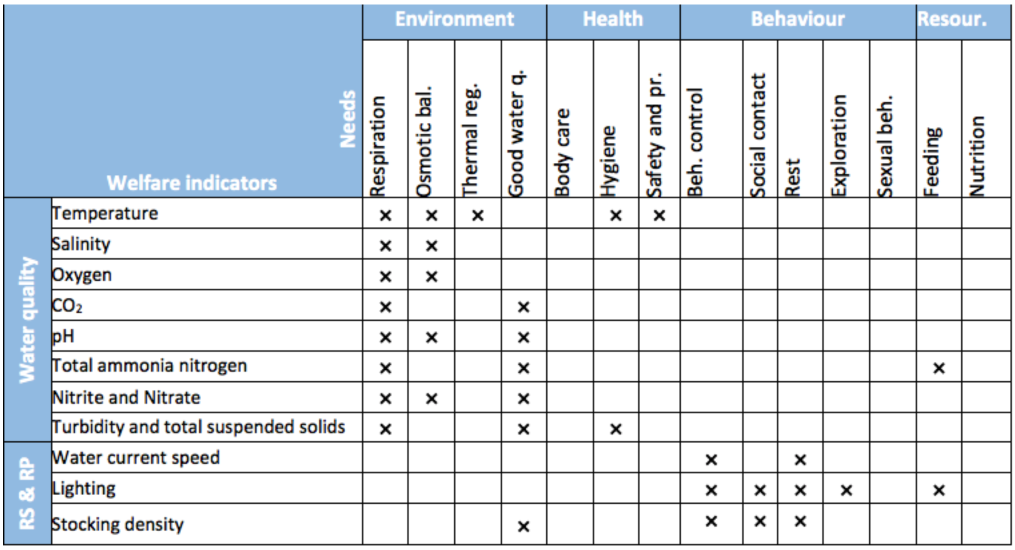


		Welfare indicators / Needs	Environment				Health			Behaviour					Resources	
			Respiration	Osmotic balance	Thermal reg.	Good water q.	Body care	Hygiene	Safety and prot.	Beh. control	Social contact	Rest	Exploration	Sexual beh.	Feeding	Nutrition
Group		Mortality rate	×	×	×	×	×	×	×	×	×	×	×	×	×	×
		Behaviour	×	×	×	×	×	×	×	×	×	×	×	×	×	×
		Surface activity					×	×		×			×			
		Appetite	×	×	×	×	×	×	×	×	×	×	×	×	×	×
		Growth	×	×	×	×	×	×	×	×	×	×	×	×	×	×
		Scales or blood in the water	×	×					×	×						
		Disease	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Individual		Gill beat rate	×			×			×	×						
		Sea lice	×	×			×	×	×							
		Gill bleaching and gill status	×	×				×				×				
		Condition factor													×	×
		Emaciation state		×				×							×	×
		Sexual maturity stage		×										×		
		Smoltification stage		×												
		Vertebral deformation								×		×				
		Fin damage (non-active)								×		×				
		Fin status		×				×	×							
		Scale loss and skin condition		×				×	×							
		Eye damage and status						×	×	×					×	×
		Deformed opercula	×													
		Abdominal organs						×	×							×
		Vaccine-related pathology													×	×
	Blood	Cortisol		×					×	×	×		×		×	
		Osmolality		×												
		Ionic composition		×												
		Glucose							×						×	×
		Lactate							×	×		×				

Figure 76.: Animal based welfare indicators and their relationship to different welfare needs (Noble et al. 2018)

Appendix C

Environmental based WIs



	Needs	Environment				Health			Behaviour					Resour.	
	Welfare indicators	Respiration	Osmotic bal.	Thermal reg.	Good water q.	Body care	Hygiene	Safety and pr.	Beh. control	Social contact	Rest	Exploration	Sexual beh.	Feeding	Nutrition
Water quality	Temperature	×	×	×			×	×							
	Salinity	×	×												
	Oxygen	×	×												
	CO_2	×			×										
	pH	×	×		×										
	Total ammonia nitrogen	×			×									×	
	Nitrite and Nitrate	×	×		×										
	Turbidity and total suspended solids	×			×		×								
RS & RP	Water current speed								×		×				
	Lighting								×	×	×	×		×	
	Stocking density				×				×	×	×				

Figure 77.: List of environmental based welfare indicators and which welfare needs of Atlantic salmon they affect directly (Noble et al. 2018).

Appendix D

OWIs and LABWIs

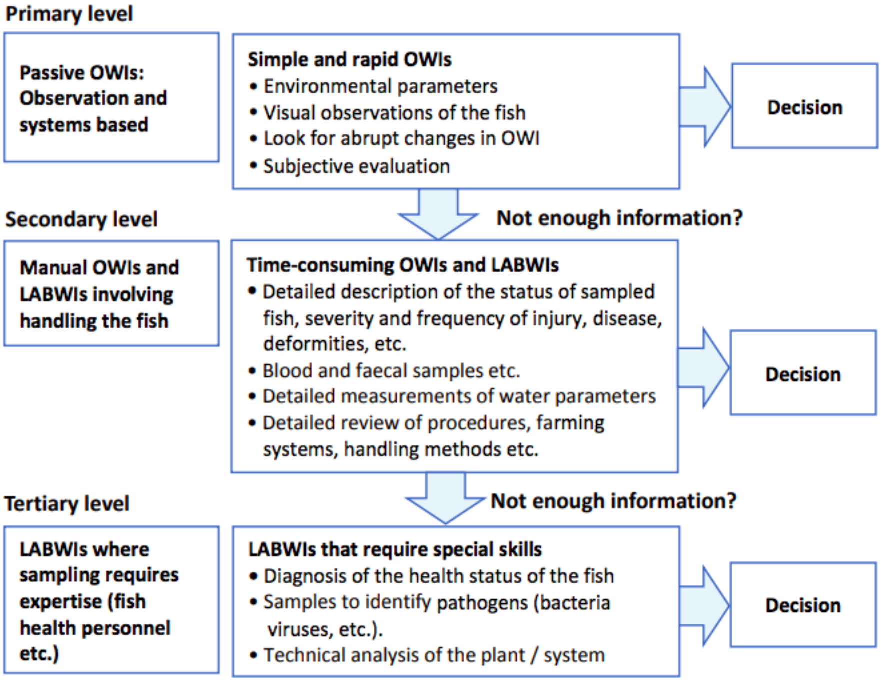


Figure 78.: How to use OWIs and LABWIs at the farm to detect Early Warning Signals for reduced fish welfare

Appendix E

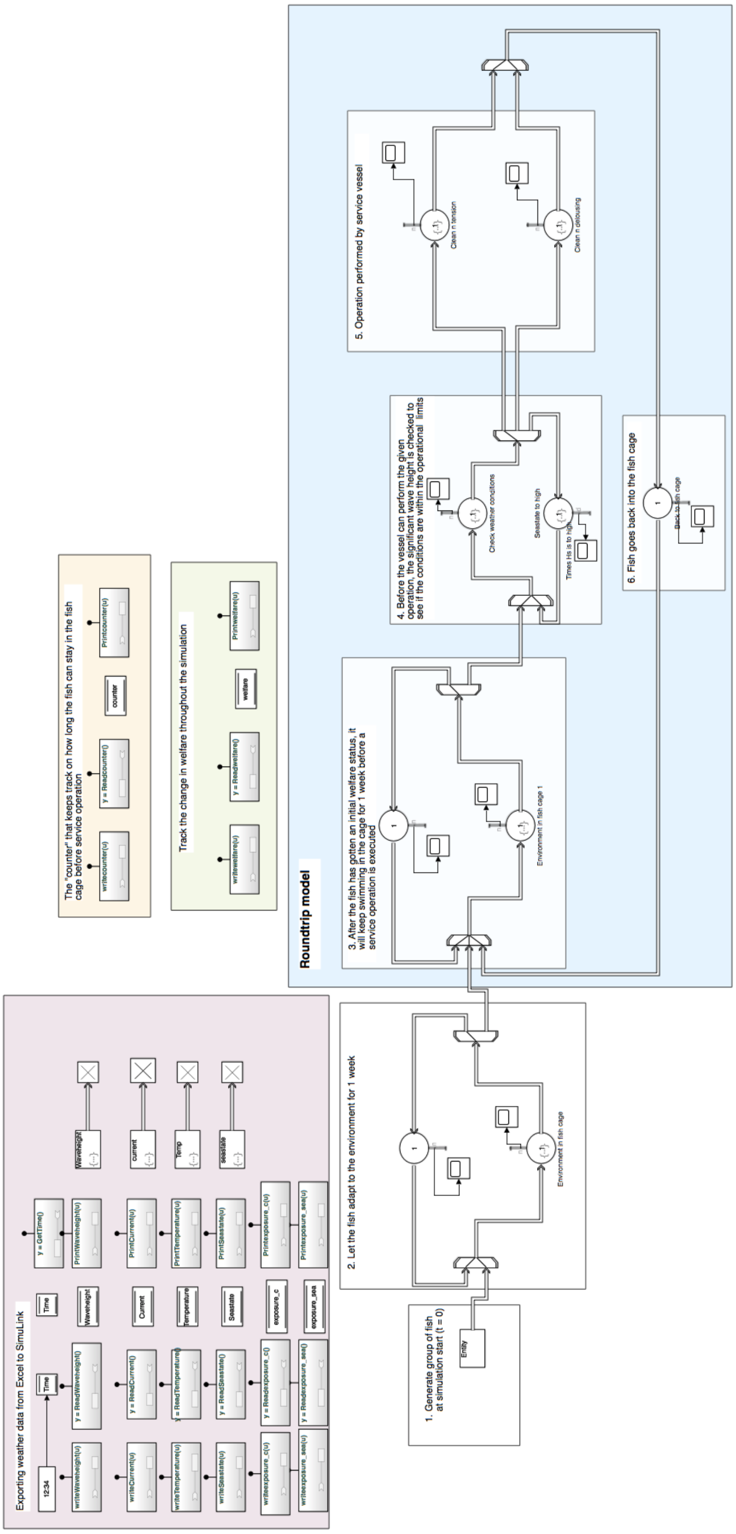


Figure 79.: Simulation model from Simulink

Appendix F

Simulation Model

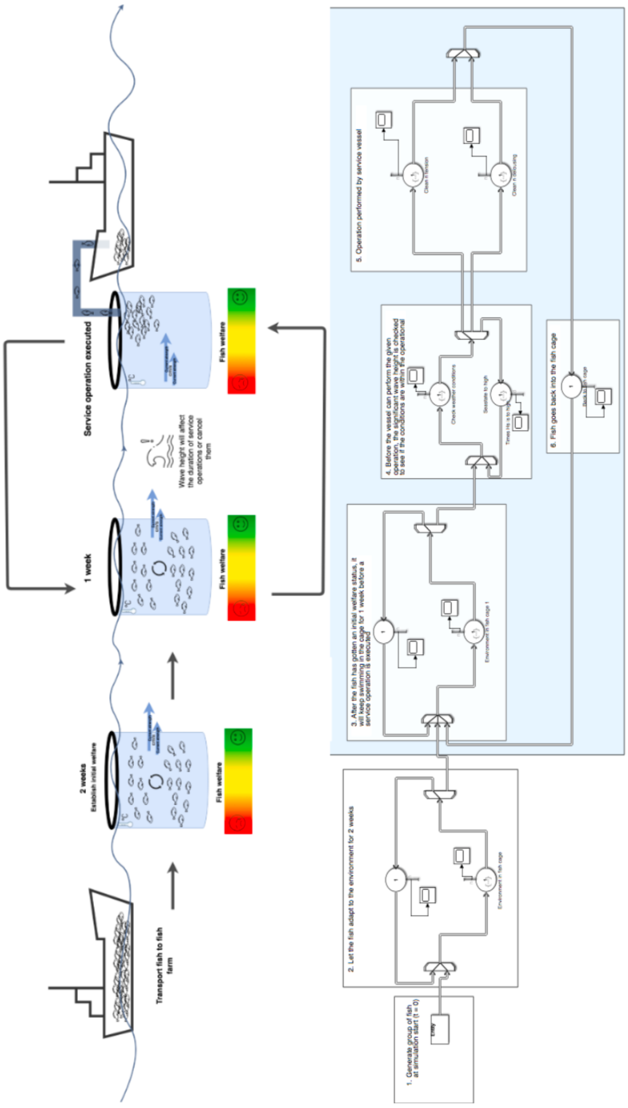


Figure 80.: Simulation model together with the system description

Appendix G

Polarcircel plastic pen model

MODEL SPECIFICATIONS

Cage Models:	225/250	315	400	450	500	630	Comments
Cage sizes – Floating pipe diameter:	225/250mm (9"/10")	315mm (12")	400mm (16")	450mm (18")	500mm (20")	630mm (26")	Imperial sizes to be confirmed.
Cage sizes – Standard circumferences:	40 - 90m (130 - 300')	60 - 100m (200 - 330')	90 - 160m (300 - 530')	120 - 160m (400 - 530')	130 - 200m (430 - 660')	160 - 260m (530 - 860')	New from 2019: The circumference is measured on the inside of the inner floating pipe.
Cage sizes – Standard diameters:	13 – 29m (42 – 94')	19 – 32m (63 – 104')	29 – 51m (94 – 167')	38 – 51m (125 – 167')	41 – 64m (136 – 209')	51 – 83m (167 – 272')	At centre of inner floating pipe.
Center - center distance between floating pipes:	52cm (20")	66cm (26")	85cm (33")	100cm (39")	110cm (43")	140cm (56")	-
Bracket – PE Injection Moulded (new PIM Type):	*	Yes	Yes	Yes	Yes	Yes	PIM Bracket (Pressure Injection Moulded Bracket) with plastic uprights.
Connection for bird net support poles:	Yes	Yes	Yes	Yes	Yes	Yes	Available as option.
Standard distance between brackets:	2m (6' 7")	2m (6' 7")	2.5m (8' 2")	2.5m (8' 2")	2.7m (8' 6")	2.7m (8' 6")	Can be customized to fit nets.
Dimension – PE Handrail Upright:	125mm (5")	125mm (5")	160mm (6,5")	160mm (6,5")	160mm (6,5")	200mm (8,1")	-
Dimension – Handrail Pipe:	110mm (4,5")	110mm (4,5")	140mm (5,5")	140mm (5,5")	140mm (5,5")	180mm (7,3")	-
Net hook on uprights:	PE (SS opt.)	PE (SS opt.)	Stainless Steel (12mm)	Stainless Steel (12mm)	Stainless Steel (12mm)	Stainless Steel (12mm)	One single hook per upright included.
Polystyrene Safety Floatation added:	Only inner pipe	Only inner pipe	Only inner pipe	Only inner pipe	Only inner pipe	Only inner pipe	Custom hooks available
Available with – Secondary Safety Chain (redundancy):	Inside outer pipe	Inside outer pipe	Inside outer pipe	Inside outer pipe	Inside outer pipe	Inside outer pipe	Available in all floating pipes on request.
Materials used – PE80 & PE100:	Yes	Yes	Yes	Yes	Yes	Yes	Continuous internal safety chain inside the outer floating pipe for extra safety
Norwegian Standard – NS9415 Certified:	Yes	Yes	Yes	Yes	Yes	Yes	The Polarcirkel factory is ISO 9001 and ISO 14001 certified.
Available as Two-Ring Cage:	Yes	Yes	Yes	Yes	Yes	Yes	Mandatory for Norway only.
Available as Three-Ring Cage:	Yes	-	-	-	-	-	Standard Cage

Figure 81.: Polarcircel plastic pen model specification from AKVAgroup

Appendix H

Code for welfare results - location X

```
%%Export welfaredata to excel for further analysis
Welfare = out.welfare; %Get the welfare data from simulation
Exposure_sea = out.Exposure_sea; %Get exposure levels in terms of Hs
Exposure_c = out.Exposure_c; %Get exposure levels in terms on current speed
Temperature = out.Temperature; %Get temperature levels

%Write the results into an excel sheet

writematrix(Welfare,'Simulation_RES_X.xlsx','Range','M3:M1428'); %%Change this to write all relevant results for each simulation run
writematrix(Exposure_sea, 'Simulation_RES_X.xlsx', 'Range', 'B3:B831');
writematrix(Exposure_c, 'Simulation_RES_X.xlsx', 'Range', 'C3:C831');
writematrix(Temperature, 'Simulation_RES_X.xlsx', 'Range', 'E3:E831');

%Results
 Fishwelfare_X_December = xlsread('Simulation_RES_X.xlsx','E3:E744');
 Fishwelfare_X_Jan = xlsread('Simulation_RES_X.xlsx','F3:F719');
 Fishwelfare_X_Feb = xlsread('Simulation_RES_X.xlsx','G3:G673');
 Fishwelfare_X_March = xlsread('Simulation_RES_X.xlsx','H3:H730');
 Fishwelfare_X_April = xlsread('Simulation_RES_X.xlsx','I3:I718');
 Fishwelfare_X_May = xlsread('Simulation_RES_X.xlsx','J3:J724');
 Fishwelfare_X_June = xlsread('Simulation_RES_X.xlsx','K3:K705');
 Fishwelfare_Total = xlsread('Simulation_RES_X.xlsx','L3:L11355');
 Fishwelfare_MayJune = xlsread('Simulation_RES_X.xlsx','M3:M1428');

  %Plot the results
figure;
plot(Fishwelfare_X_December);
```

```
hold on
plot(Fishwelfare_X_Jan);
plot(Fishwelfare_X_Feb);
plot(Fishwelfare_X_March);
plot(Fishwelfare_X_April);
plot(Fishwelfare_X_May);
plot(Fishwelfare_X_June);
xlabel('Time [hours]');
ylabel('Fish welfare');
title('Fish welfare - Location X');

legend({'December 2017', 'January 2018', 'February 2018', 'March 2018',
   'April 2018', 'May 2018', 'June 2018'});
hold off

 %Plot the results
figure;
plot(Fishwelfare_Total);
hold on
xlabel('Time [hours]');
ylabel('Fish welfare');
title('Fish welfare - Location X');

legend({'Total Dec - June'});
hold off



figure;
plot(Fishwelfare_MayJune);
hold on
xlabel('Time [hours]');
ylabel('Fish welfare');
title('Fish welfare - Location X');
legend({'May - June 2018'});
hold off

figure;
plot(Fishwelfare_X_December);
hold on
plot(Fishwelfare_X_June);
xlabel('Time [hours]');
ylabel('Fish welfare');
title('Fish welfare - Location Y');
plot(336,5.055,'r*'); %plot points for handling operations
plot(672,16.247,'g*');
```

```
plot(672,2.99,'g*');
plot(336,3.0148,'r*');
legend({'Welfare December 2017', 'Welfare June 2018', 'Net cleaning'
    'Delousing',});
hold off
```

Appendix I

Code for welfare results - location Y

```
%%Export welfaredata to excel for further analysis
Welfare = out.welfare; %Get the welfare data from simulation


writematrix(Welfare,'Simulation_RES_Y.xlsx','Range','L3:L1427'); %Change
   this to write all relevant results for each simulation run


 Fishwelfare_dec = xlsread('Simulation_RES_Y.xlsx','D3:D745');
 Fishwelfare_jan = xlsread('Simulation_RES_Y.xlsx','E3:E745');
 Fishwelfare_feb = xlsread('Simulation_RES_Y.xlsx','F3:F640');
 Fishwelfare_march = xlsread('Simulation_RES_Y.xlsx','G3:G622');
 Fishwelfare_april = xlsread('Simulation_RES_Y.xlsx','H3:H648');
 Fishwelfare_may = xlsread('Simulation_RES_Y.xlsx','I3:I708');
 Fishwelfare_june = xlsread('Simulation_RES_Y.xlsx','J3:J720');
 Fishwelfare_spring = xlsread('Simulation_RES_Y.xlsx','K3:K2074');
 Fishwelfare_mayjune = xlsread('Simulation_RES_Y.xlsx','L3:L1427');
 Exposure_level_Hs_Y = xlsread('Simulation_RES_Y.xlsx','B3:B5452');
 Exposure_level_current_Y = xlsread('Simulation_RES_Y.xlsx','C3:C5254');
 Fishwelfare_total_Y = xlsread('Simulation_RES_Y.xlsx','A3:A5254');

 %Results from the total year


 %Plot the results
figure;
plot(Fishwelfare_dec);
hold on
plot(Fishwelfare_jan);
```

```
plot(Fishwelfare_feb);
plot(Fishwelfare_march);
plot(Fishwelfare_april);
plot(Fishwelfare_may);
plot(Fishwelfare_june);
xlabel('Time [hours]');
ylabel('Fish welfare');
title('Fish welfare - Location Y');
legend({'December 2017', 'January 2018', 'February 2018', 'march 2018',
   'April 2018', 'May 2018', 'June 2018'});
hold off


figure;

%plot exposurelevel Hs and Current speeds
plot(Exposure_level_Hs_Y);
hold on
plot(Exposure_level_current_Y);
xlabel('Time [hours]');
ylabel('Exposure levels');
title('Exposure levels defined by NS9415');
legend({'Hs','Current'});
hold off


figure;
plot(Fishwelfare_spring);
hold on
%plot(Fishwelfare_X);
xlabel('Time [hours]');
ylabel('Fish welfare');
title('Fish welfare - Location Y');
legend({'April - June 2018'});
hold off

figure;
plot(Fishwelfare_mayjune);
hold on
%plot(Fishwelfare_X);
xlabel('Time [hours]');
ylabel('Fish welfare');
title('Fish welfare - Location Y');
%plot(112,5.59,'r*'); %plot some points with sudden drops to dicuss in
   report
%plot(169,8.852,'r*');
```

```
legend({'May - June 2018'});
hold off

figure;
plot(Fishwelfare_dec);
hold on
plot(Fishwelfare_june);
%plot(Fishwelfare_X);
xlabel('Time [hours]');
ylabel('Fish welfare');
title('Fish welfare - Location Y');
plot(336,1.46,'r*'); %points where handling operations are being executed.
plot(672,0.246,'g*');
plot(672,2.99,'g*');
plot(336,1.55,'r*');
legend({'Welfare December 2017', 'Welfare June 2018', 'Net cleaning'
   'Delousing',});
hold off

figure;
plot(Fishwelfare_dec);
hold on
plot(Fishwelfare_jan);
plot(Fishwelfare_april);
%plot(Fishwelfare_X);
xlabel('Time [hours]');
ylabel('Fish welfare');
title('Fish welfare');
legend({'December 2017', 'January 2018', 'April 2018'});
hold off

figure;
plot(Fishwelfare_total_Y);
hold on
xlabel('Time [hours]');
ylabel('Fish welfare');
title('Fish welfare - Location Y');
legend({'December 2017 - June 2018'});
hold off
```

Appendix J

Code for Sensitivity Analysis

```
%%Export welfaredata to excel for further analysis - SENSITIVTY ANALYSIS
Welfare = out.welfare; %Get the welfare data from simulation
Exposure_sea = out.Exposure_sea; %Get exposure levels in terms of Hs
Exposure_c = out.Exposure_c; %Get exposure levels in terms on current
   speed
Temperature = out.Temperature; %Get temperature levels

%Write the results into an excel sheet

writematrix(Welfare,'Simulation_RES_SA.xlsx','Range','E3:E1526'); %welfare

%Results
 Fishwelfare_SA_Run1 = xlsread('Simulation_RES_SA.xlsx','A3:A510');
 Fishwelfare_SA_Run2 = xlsread('Simulation_RES_SA.xlsx','B3:B510');
 Fishwelfare_SA_Run3 = xlsread('Simulation_RES_SA.xlsx','C3:C510');
 Fishwelfare_SA_Run4 = xlsread('Simulation_RES_SA.xlsx','D3:D1526');
 Fishwelfare_SA_Run5 = xlsread('Simulation_RES_SA.xlsx','E3:E1526');


  %Plot the results
figure;
plot(Fishwelfare_SA_Run1);
hold on
plot(Fishwelfare_SA_Run2);
%plot(Fishwelfare_SA_Run3);
xlabel('Time [Hours]');
ylabel('Fish welfare');
title('Fish welfare - Sensitivity Analysis');
legend({'Run 1', 'Run 2'});
```

```
hold off

 %Plot the results
figure;
plot(Fishwelfare_SA_Run3);
hold on
xlabel('Time [Hours]');
ylabel('Fish welfare');
title('Fish welfare - Sensitivty Analysis');
legend({'Run 3'});
hold off

 %Plot the results
figure;
plot(Fishwelfare_SA_Run4);
hold on
xlabel('Time [Hours]');
ylabel('Fish welfare');
title('Fish welfare - Sensitivty Analysis');
legend({'Run 4'});
hold off

 %Plot the results
figure;
plot(Fishwelfare_SA_Run5);
hold on
xlabel('Time [Hours]');
ylabel('Fish welfare');
title('Fish welfare - Sensitivty Analysis');
legend({'Run 5'});
hold off
```

Appendix K

SIMULINK codes

```
%%Code for the SIMULINK model

%% Entity server 1 - Code for how the welfare is affected when salmon is
    swimming inside HDPE cage.

%Determine the time the fish is staying inside the fish cage before a
    vessel comes.
%This is done by counting roundtrips

persistent counter

if isempty(counter)
    counter = 1;
else
    counter = counter + 1;
end

%writeopercounter(opercounter);
writecounter(counter);
counter = Readcounter();
Printcounter(counter);

if counter >= 168;
    entity.Portswitch = 2;
    counter = 0;
else
    entity.Portswitch = 1;
end
```

```
%Read temperature and current data
Temperature = ReadTemperature();
Current = ReadCurrent();
Waveheight = ReadWaveheight();
%Divide the different intervals into blocks where 1 is bad and 4 is good,
    temp = 5 indicates error

if Temperature <= 3 | Temperature >23
    Tempen = 1;
elseif (Temperature <= 6 && Temperature > 3) | (Temperature >18 &&
    Temperature <= 23)
    Tempen = 2;
elseif Temperature >6 && Temperature <=14
    Tempen = 3;
elseif Temperature >14 && Temperature <= 18
    Tempen = 4;
else
    Tempen = 5; %if Tempen is 5 there is an error in the code
end

%How current affects fishwelfare when the temperature is very bad

if Tempen == 1 && Current >= 65 | Current <= 5
    entity.welfare = entity.welfare * 0.98;
elseif Tempen == 1 && (Current <= 65 && Current > 45) | (Current <= 20 &&
    Current > 5)
    entity.welfare = entity.welfare * 0.985;
elseif Tempen == 1 && Current <= 35 && Current > 20
    entity.welfare = entity.welfare * 0.99;
elseif Tempen == 1 && Current <= 45 && Current > 35
    entity.welfare = entity.welfare * 0.995;

%How current affects fishwelfare when the temperature is bad

elseif Tempen == 2 && Current >= 70 | Current <= 5
    entity.welfare = entity.welfare * 0.985;
elseif Tempen == 2 && (Current <= 70 && Current > 50) | (Current <= 20 &&
    Current > 5)
    entity.welfare = entity.welfare * 0.99;
elseif Tempen == 2 && Current <= 35 && Current > 20
    entity.welfare = entity.welfare * 0.995;
elseif Tempen == 2 && Current <= 50 && Current > 35
    entity.welfare = entity.welfare * 0.999;

%How current affects fishwelfare when the temperature is ok
```

```
elseif Tempen == 3 && Current >= 75 | Current <= 5
    entity.welfare = entity.welfare * 0.995;
elseif Tempen == 3 && (Current <= 75 && Current > 55) | (Current <= 20 &&
   Current > 5)
    entity.welfare = entity.welfare * 0.999;
elseif Tempen == 3 && Current <= 40 && Current > 20
    entity.welfare = entity.welfare * 1.03;
elseif Tempen == 3 && Current <= 55 && Current > 40
    entity.welfare = entity.welfare * 1.06;

%How current affects fishwelfare when the temperature is GOOD

elseif Tempen == 4 && Current >= 80 | Current <= 8
    entity.welfare = entity.welfare * 0.995;
elseif Tempen == 4 && (Current <= 80 && Current > 60) | (Current <= 20 &&
   Current > 5)
    entity.welfare = entity.welfare * 1;
elseif Tempen == 4 && Current <= 40 && Current > 20
    entity.welfare = entity.welfare * 1.04;
elseif Tempen == 4 && Current <= 60 && Current > 40
    entity.welfare = entity.welfare * 1.07;
% done
else
    entity.welfare = entity.welfare;
end
%Keep track on the exposure levels in terms of wave height and current
   speeds - due to stocking density in fish cage

if Waveheight <= 0.5 && Waveheight >=0
    entity.Exposure_wave = 1;
elseif Waveheight <= 0.7 && Waveheight >0.5
    entity.Exposure_wave = 2;
elseif Waveheight <= 1 && Waveheight >0.7
    entity.Exposure_wave = 3;
elseif Waveheight <= 1.5 && Waveheight >1
    entity.Exposure_wave = 4;
elseif Waveheight <= 2 && Waveheight >1.5
    entity.Exposure_wave = 5;
elseif Waveheight <= 2.5 && Waveheight >2
    entity.Exposure_wave = 6;
else
    entity.Exposure_wave = 7; %if exposure wave height is 7 it is not
       possible to have HDPE cage at that site
end

if Current <= 30 && Current >=0
```

```
    entity.Exposure_current = 1;
elseif Current <= 40 && Current >30
    entity.Exposure_current = 2;
elseif Current <= 70 && Current >40
    entity.Exposure_current = 3;
elseif Current <= 85 && Current >70
    entity.Exposure_current= 4;
elseif Current <= 100 && Current >85
    entity.Exposure_current = 5;
elseif Current <= 130 && Current >100
    entity.Exposure_current = 6;
else
    entity.Exposure_current = 7; %if exposure current is 7 it is not
        possible to have HDPE cage at that site
end

%Print results to see if the code runs properly

Printwelfare(entity.welfare);
PrintTemperature(Tempen);
PrintCurrent(Current);
Printexposure_sea(entity.Exposure_wave);
Printexposure_c(entity.Exposure_current);
PrintWaveheight(Waveheight)

%% Entity server two is the same as entity server 1
%% Code for checking if the significant wave height is to high

%Read Seastate

Seastate = ReadSeastate();

%Check weather state and then decide which operation to be executed
if Seastate > 2.5
    entity.Operation = 3 %To rough weather
elseif Seastate <= 2.5 && entity.ChooseOper == 2;
    entity.Operation = 1; %Next operation is clean n tension
elseif Seastate <= 2.5 && entity.ChooseOper == 1;
    entity.Operation = 2; %Next operation is delousing
else
    entity.Operation = 3;
end

%% Code for handling operations - Clean and Tension of mooring system

%Read significant waveheight, temperature and current
```

```
Seastate = ReadSeastate();
Temperature = ReadTemperature();
Current = ReadCurrent();
Waveheight = ReadWaveheight();

%OPERATION DURING SIGNIFICANT WAVEHEIGHT BETWEEN 3-4 M
if Seastate <= 4 && Seastate >= 3 && Temperature < 6 && Current < 8
    entity.welfare = entity.welfare * 0.7;
elseif Seastate <= 4 && Seastate >= 3 && Temperature < 6 && Current > 8
    entity.welfare = entity.welfare * 0.75;
elseif Seastate <= 4 && Seastate >= 3 && Temperature > 6 && Current < 8
    entity.welfare = entity.welfare * 0.8;
elseif Seastate <= 4 && Seastate >= 3 && Temperature > 6 && Current > 8
    entity.welfare = entity.welfare * 0.85;

%OPERATION DURING SIGNIFICANT WAVEHEIGHT BETWEEN 2-3 M
elseif Seastate <= 3 && Seastate >= 2 && Temperature < 6 && Current < 8
    entity.welfare = entity.welfare * 0.75;
elseif Seastate <= 3 && Seastate >= 2 && Temperature < 6 && Current > 8
    entity.welfare = entity.welfare * 0.8;
elseif Seastate <= 3 && Seastate >= 2 && Temperature > 6 && Current < 8
    entity.welfare = entity.welfare * 0.83;
elseif Seastate <= 3 && Seastate >= 2 && Temperature > 6 && Current > 8
    entity.welfare = entity.welfare * 0.87;

%OPERATION DURING SIGNIFICANT WAVEHEIGHT BETWEEN 1.5 - 2 M
elseif Seastate <= 2 && Seastate >= 1.5 && Temperature < 6 && Current < 8
    entity.welfare = entity.welfare * 0.8;
elseif Seastate <= 4 && Seastate >= 3 && Temperature < 6 && Current > 8
    entity.welfare = entity.welfare * 0.85;
elseif Seastate <= 4 && Seastate >= 3 && Temperature > 6 && Current < 8
    entity.welfare = entity.welfare * 0.9;
elseif Seastate <= 4 && Seastate >= 3 && Temperature > 6 && Current > 8
    entity.welfare = entity.welfare * 0.95;

%OPERATION DURING SIGNIFICANT WAVEHEIGHT under 1.5 m
elseif Seastate <= 1.5 && Temperature < 6 && Current < 8
    entity.welfare = entity.welfare * 0.95;
elseif Seastate <= 1.5 && Temperature < 6 && Current > 8
    entity.welfare = entity.welfare * 0.995;
elseif Seastate <= 1.5 && Temperature > 6 && Current < 8
    entity.welfare = entity.welfare * 1;
elseif Seastate <= 1.5 && Temperature > 6 && Current > 8
    entity.welfare = entity.welfare * 1.05;
else
    entity.welfare = entity.welfare;
```

```
end

entity.ChooseOper = 1; %make sure next operation is clean n delousing

PrintCurrent(Current);
PrintTemperature(Temperature);
PrintSeastate(Seastate);
Printwelfare(entity.welfare);


%Keep track on the exposure levels in terms of wave height and current
   speeds - due to stocking density in fish cage

if Waveheight <= 0.5 && Waveheight >=0
    entity.Exposure_wave = 1;
elseif Waveheight <= 0.7 && Waveheight >0.5
    entity.Exposure_wave = 2;
elseif Waveheight <= 1 && Waveheight >0.7
    entity.Exposure_wave = 3;
elseif Waveheight <= 1.5 && Waveheight >1
    entity.Exposure_wave = 4;
elseif Waveheight <= 2 && Waveheight >1.5
    entity.Exposure_wave = 5;
elseif Waveheight <= 2.5 && Waveheight >2
    entity.Exposure_wave = 6;
else
    entity.Exposure_wave = 7; %if exposure wave height is 7 it is not
       possible to have HDPE cage at that site
end

if Current <= 30 && Current >=0
    entity.Exposure_current = 1;
elseif Current <= 40 && Current >30
    entity.Exposure_current = 2;
elseif Current <= 70 && Current >40
    entity.Exposure_current = 3;
elseif Current <= 85 && Current >70
    entity.Exposure_current= 4;
elseif Current <= 100 && Current >85
    entity.Exposure_current = 5;
elseif Current <= 130 && Current >100
    entity.Exposure_current = 6;
else
    entity.Exposure_current = 7; %if exposure current is 7 it is not
       possible to have HDPE cage at that site
end
```

```
%Print results to see if the code runs properly

Printexposure_sea(entity.Exposure_wave);
Printexposure_c(entity.Exposure_current);
PrintWaveheight(Waveheight)

%% Code for handling operation - clean and delousing

%Read significant waveheight, temperature and current
Seastate = ReadSeastate();
Temperature = ReadTemperature();
Current = ReadCurrent();
Waveheight = ReadWaveheight();

%OPERATION DURING SIGNIFICANT WAVEHEIGHT BETWEEN 3-4 M
if Seastate <= 4 && Seastate >= 3 && Temperature < 6 && Current < 8
    entity.welfare = entity.welfare * 0.7;
elseif Seastate <= 4 && Seastate >= 3 && Temperature < 6 && Current > 8
    entity.welfare = entity.welfare * 0.75;
elseif Seastate <= 4 && Seastate >= 3 && Temperature > 6 && Current < 8
    entity.welfare = entity.welfare * 0.8;
elseif Seastate <= 4 && Seastate >= 3 && Temperature > 6 && Current > 8
    entity.welfare = entity.welfare * 0.85;

%OPERATION DURING SIGNIFICANT WAVEHEIGHT BETWEEN 2-3 M
elseif Seastate <= 3 && Seastate >= 2 && Temperature < 6 && Current < 8
    entity.welfare = entity.welfare * 0.75;
elseif Seastate <= 3 && Seastate >= 2 && Temperature < 6 && Current > 8
    entity.welfare = entity.welfare * 0.8;
elseif Seastate <= 3 && Seastate >= 2 && Temperature > 6 && Current < 8
    entity.welfare = entity.welfare * 0.83;
elseif Seastate <= 3 && Seastate >= 2 && Temperature > 6 && Current > 8
    entity.welfare = entity.welfare * 0.87;

%OPERATION DURING SIGNIFICANT WAVEHEIGHT BETWEEN 1.5 - 2 M
elseif Seastate <= 2 && Seastate >= 1.5 && Temperature < 6 && Current < 8
    entity.welfare = entity.welfare * 0.8;
elseif Seastate <= 4 && Seastate >= 3 && Temperature < 6 && Current > 8
    entity.welfare = entity.welfare * 0.85;
elseif Seastate <= 4 && Seastate >= 3 && Temperature > 6 && Current < 8
    entity.welfare = entity.welfare * 0.9;
elseif Seastate <= 4 && Seastate >= 3 && Temperature > 6 && Current > 8
    entity.welfare = entity.welfare * 0.95;

%OPERATION DURING SIGNIFICANT WAVEHEIGHT under 1.5 m
elseif Seastate <= 1.5 && Temperature < 6 && Current < 8
```

```
    entity.welfare = entity.welfare * 0.95;
elseif Seastate <= 1.5 && Temperature < 6 && Current > 8
    entity.welfare = entity.welfare * 0.995;
elseif Seastate <= 1.5 && Temperature > 6 && Current < 8
    entity.welfare = entity.welfare * 1;
elseif Seastate <= 1.5 && Temperature > 6 && Current > 8
    entity.welfare = entity.welfare * 1.05;
else
    entity.welfare = entity.welfare;
end

entity.ChooseOper = 2; %Make sure that next operation executed is Clean n
   tension

PrintCurrent(Current);
PrintTemperature(Temperature);
PrintSeastate(Seastate);
Printwelfare(entity.welfare);


%Keep track on the exposure levels in terms of wave height and current
   speeds - due to stocking density in fish cage

if Waveheight <= 0.5 && Waveheight >=0
    entity.Exposure_wave = 1;
elseif Waveheight <= 0.7 && Waveheight >0.5
    entity.Exposure_wave = 2;
elseif Waveheight <= 1 && Waveheight >0.7
    entity.Exposure_wave = 3;
elseif Waveheight <= 1.5 && Waveheight >1
    entity.Exposure_wave = 4;
elseif Waveheight <= 2 && Waveheight >1.5
    entity.Exposure_wave = 5;
elseif Waveheight <= 2.5 && Waveheight >2
    entity.Exposure_wave = 6;
else
    entity.Exposure_wave = 7; %if exposure wave height is 7 it is not
       possible to have HDPE cage at that site
end

if Current <= 30 && Current >=0
    entity.Exposure_current = 1;
elseif Current <= 40 && Current >30
    entity.Exposure_current = 2;
elseif Current <= 70 && Current >40
    entity.Exposure_current = 3;
```

```
elseif Current <= 85 && Current >70
    entity.Exposure_current= 4;
elseif Current <= 100 && Current >85
    entity.Exposure_current = 5;
elseif Current <= 130 && Current >100
    entity.Exposure_current = 6;
else
    entity.Exposure_current = 7; %if exposure current is 7 it is not possible to have HDPE cage at that site
end
%Print results to see if the code runs properly

Printexposure_sea(entity.Exposure_wave);
Printexposure_c(entity.Exposure_current);
PrintWaveheight(Waveheight);
```

Appendix L

Scope of Work

MASTER THESIS IN MARINE TECHNOLOGY

SPRING 2021

FOR STUD.TECN.

MARIA CRISTINA DANIELSEN

Insight into fish welfare at potential farming sites
A simulation-based approach

Background

The world needs to produce 70% more food within 2030, and only 2% of the food energy for human consumption comes from the sea (Commission 2017). The animal protein produced from aquaculture uses fewer resources and is more environmentally friendly compared to livestock. Increased aquaculture production is a part of the plan to feed future generations (Bjelland et al. 2015). This thesis aims to study how one can use the available research and findings regarding the farming of Atlantic Salmon to gain insight into the fish welfare at potential farming sites. The fish farming industry faces many challenges related to high mortality rates, diseases and environment. The purpose of this master thesis is to propose methods to gain insight into the welfare of farmed salmon at different sites. By doing so, the industry can further develop methods and decision-making tools based on maintaining a sufficient level of fish welfare.

Objectives

The objective of this thesis is to study how one can use the available research about the farming of Atlantic Salmon to gain insight into the fish welfare at potential farming sites. This is done through a simulation based approach.

Tasks

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

1. Describe the problem to be modeled
2. Review and present relevant literature
3. Design different configurations of HDPE fish cages and analyze their behaviour being exposed to different environmental conditions using Aquasim.
4. Develop a simulation model using Simulink MATLAB which describes the simplified version of the real problem
5. Collect relevant data necessary to use as input in the simulation model
6. Verification and validation to test the performance of the model.

Supervision:

Main supervisor: Bjørn Egil Asbjørnslett

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