Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Hanne Buan

Simulation-Based Analysis of Salmon Encounters with Delousing Operations

Master's thesis in Marine Technology
Supervisor: Bjørn Egil Asbjørnslett
October 2020

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MASTER THESIS IN MARINE TECHNOLOGY

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For stud.techn.
Hanne Buan

Simulation-Based Analysis of Salmon Encounters with Delousing Operations

Background

On an international level, salmon farmed in Norway is a quality product in high demand. Annual production has surpassed 1,350,000 tons, and large volumes are exported to the European Union and Asia. To meet the world's increasing food demand in a sustainable way, further expansion of the salmon industry is predicted and desirable.

During growth in sea cages, salmon are exposed to lice and diseases, and measures to prevent these issues are needed. Moreover, salmon lice have shown a reduced susceptibility towards traditional medicinal treatments, and resistance to several medicines has been developed. In response to this, there has been a rapid growth of non-medicinal treatments, and new lice treatment technologies are in development. Thermal treatments were by far the most used method in 2019. However, the Norwegian Food Safety Authority has announced that thermal treatments can be banned within 2021 because the welfare of salmon is threatened.

In recent years, average mortality during the sea phase has been close to 15%, and if statistics from previous years continue in the same direction losses will pass 60 million salmon in 2020. The rates have stagnated, and the challenge with mortality in salmon farming can no longer be avoided. We need to obtain a better understanding of hazards for salmon during vessel operations, and identify the procedures and equipment that are too harmful to fish. With the trend of increased handling and more frequent vessel operations, it is necessary to find procedures that take fish welfare into account. The use of non-medicinal lice treatments is one of the main reasons for mortality and other welfare challenges in salmon farming.

Objective

The objective of this thesis is to develop and test a generic simulation model of a sea cage, including biological features with salmon and interactions between salmon and vessel operations. The model shall enable simulation of different management strategies at selected sites. The simulated results shall present the consequences for salmon from these strategies, and estimate net benefits compared to a baseline production. And ideally, one will be able to discover strategies that are more favourable for a given locality.

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Tasks

The candidate is recommended to cover the following parts in the project thesis:

a. Describe the challenges that arise when salmon encounter with vessel operations.
b. Review state of the art literature within the topic, with a focus on technology in context of biology.
c. Identify hazards for salmon in vessel operations by a preliminary hazard analysis, and propose risk reducing measures for salmon.
d. Develop a stochastic simulation model of salmon production from smolt release to harvest, including growth and health of salmon, and interactions between salmon and vessel operations.
e. Propose a stochastic process for generating health of salmon populations.
f. Propose a measurable health response for salmon after delousing operations.
g. Choose two localities in Norway with variations in environment and number of delousing operations, and implement their reported data.
h. Perform a case study with different management strategies, and combine the simulated results with a cost-benefit analysis.

General

In the thesis the candidate shall present his personal contribution to the resolution of a problem within the scope of the thesis work.
Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction.
The candidate should utilize the existing possibilities for obtaining relevant literature.
The thesis should be organized in a rational manner to give a clear statement of assumptions, data, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.
The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.
The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work.
The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

Supervision:
Main supervisor: Bjørn Egil Asbjørnslett

Date: 02.06.2020
Deadline: 23.10.2020

Preface

This thesis concludes my Master of Science degree in Marine Technology at the Norwegian University of Science and Technology (NTNU) and is written in 2020. The thesis examines challenges that arise when salmon encounters vessel operations by combining technology and biology in the research.

The idea of exploring welfare challenges and mortality came to life in the spring of 2020, due to the substantial increase of mechanical delousing. Based on the assumption that farmers continuously strive to improve their production, I see the importance of understanding and analysing farming procedures and equipment. The thesis is a continuance of my project thesis, where I examined welfare critical vessel operations and performed a risk analysis for salmon. The problems discussed in this thesis appear to be very relevant for the industry, and it has been inspiring to delve into the subject.

I would like to thank my supervisor, Professor Bjørn Egil Asbjørnslett, first for introducing me to this topic, but also for his guidance and support. Also, I would like to thank people who have supported my work, including Erik A. Næstvold from Optimeering Aqua and Ingunn F. Tvete from the Norwegian Computing Center. Finally, I would like to thank PhD Candidate Hans Tobias Slette for assistance with the simulation model.

I hope you enjoy reading!

Trondheim, October 23, 2020
Hanne Buan
Hanne Buan

Summary

This thesis explores salmon welfare in vessel operations, which is a new area within marine system design. Vessel operations that involve salmon have become an essential part of limiting sea lice levels in Norwegian aquaculture, despite economic and biological losses attained from treatment mortality, reduced growth and higher economic feed conversion ratio. Salmon lice have developed a resistance towards traditional medicines, and there has been a shift from medicinal to non-medicinal methods of delousing, which mainly consist of thermal and mechanical treatments.

In order to identify the risks for salmon encountering vessel operations, a preliminary hazard analysis has been conducted. The analysis points out weaknesses within current procedures and suggests risk reducing measures for salmon. Based on data from literature and ongoing research, a simulation model has been developed in Simulink to investigate welfare oriented strategies in salmon farming. The model contains predictions for growth and natural mortality, and also treatment mortality that is based on stochastic models for salmon health, and the response of salmon to treatments. Salmon populations of a thousand fish are modelled with a random health status with a uniform distribution in the interval 1–100%. Reported data from two localities in Norway has been implemented into the model, and after calibration of mortality, baseline productions from both sites were established. Finally, a case study has been conducted with larger smolt and a varying number of lice treatments and starving days, and net benefits are found with a cost benefit analysis.

The established simulation model combines technology with biology and enables to quantify losses from vessel operations, including mortality, weight loss from starvation, increased production time and effects from repeated handling. By combining the case study with a cost benefit analysis, these losses are assembled and compared to the baseline productions. Based on the analysis of the simulated results, some of the strategies are found more efficient and present profitable ways to prevent premature death of thousands of salmon. There is uncertainty connected to modelling health response to treatments, but still, this approach shows how stochastic modelling can be useful in research involving salmon health and economics.

Sammendrag

Denne oppgaven ser nærmere på laksevelferd i fartøyoperasjoner, som er et nytt område innen marin systemdesign. Fartøyoperasjoner som involverer laks har blitt en vesentlig del av å begrense lusenivåene i norsk havbruk, til tross for økonomiske og biologiske tap oppnådd fra behandlingsdødelighet, redusert vekst og høyere økonomisk fôrfaktor. Lakselusa har utviklet en motstand mot tradisjonelle medisiner. Dermed har det skjedd et skifte fra medisinske til ikke-medisinske metoder for avlusing, som hovedsakelig består av termiske og mekaniske behandlinger.

For å identifisere risikoen for laks i møte med fartøysoperasjoner, er det gjennomført en grovanalyse. Analysen peker på svakheter ved gjeldende prosedyrer og foreslår risikoreduserende tiltak for laks. Basert på data fra litteratur og pågående forskning er det utviklet en simuleringsmodell i Simulink for å undersøke velferdsorienterte strategier i lakseoppdrett. Modellen predikerer vekst og naturlig dødelighet, samt en behandlingsdødelighet som er basert på stokastiske modeller for laksens helse, og responsen til laks på behandlinger. Laksepopulasjoner på tusen fisk er modellert med helsestatus, som er en tilfeldig variabel med en uniform fordeling i intervallet 1–100%. Rapporterte data fra to lokaliteter i Norge er implementert i modellen, og etter kalibrering av dødelighet er basisproduksjoner fra begge steder etablert. Til slutt er det gjennomført en casestudie med større smolt og et varierende antall lusebehandlinger og sultedager, og netto nytteverdi er funnet med en nytte-kostnadsanalyse.

Den etablerte simuleringsmodellen kombinerte teknologi med biologi og gjorde det mulig å kvantifisere tap fra fartøysoperasjoner, inkludert dødelighet, vekttap fra sulting, økt produksjonstid og effekter fra gjentatt håndtering. Ved å kombinere en casestudie med en nytte-kostnadsanalyse ble verdien av disse tapene sammenstilt og sammenlignet med basisproduksjonene. Basert på analysen av de simulerte resultatene ble noen av strategiene funnet mer effektive, og presenterte dermed en lønnsom måte å forhindre laksedød på i løpet av produksjonen. Det er usikkerhet knyttet til modelleringen av helserespons, men likevel viser denne tilnærmingen hvordan stokastisk modellering kan være nyttig i forskning som involverer laksens helse og økonomi.

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Abbreviations

ADG = Average daily weight gain
BFCR = Biological feed conversion ratio
CBA = Cost benefit analysis
CMS = Cardiomyopathy syndrome
EFCR = Economical feed conversion ratio
EGI = Ewos growth index
FCR = Feed conversion ratio
GAM = Generalised additive model
GWE = Gutted weight equivalents
HOG = Head on gutted
HSMI = Hearth and skeletal muscle inflammation
IPN = Infectious pancreatic necrosis
IMR = Institute of Marine Research
LABWI = Laboratory-based welfare indicator
MAB = Maximum allowed biomass
MNOK = Million NOK
OWI = Operational welfare indicator
NDF = Norwegian Directorate of Fisheries
NFSA = Norwegian Food Safety Authority
NVI = Norwegian Veterinary Institute
PD = Pancreas disease
PFF = Precision fish farming
PHA = Preliminary hazard analysis
RAS = Recirculating aquaculture system
RGI = Relative growth index
SGR = Salmon growth rate
WI = Welfare indicator
WFE = Whole fish equivalents

Chapter 1

Introduction

Background

Five decades ago, years of trial and error started the path of aquaculture in Norway, which soon became the largest producer of Atlantic salmon in the world. On an international level, salmon farmed in Norway is a quality product in high demand, and some of the success factors have been environmental conditions, farmer competence and market development (Reitan, 2018). Annual production has surpassed 1,350,000 tons (SSB, 2020), and large volumes are exported to the European Union (EU) and Asia. To meet the world's increasing food demand in a sustainable way, further expansion of the industry is predicted and desirable.

During the growth phase in sea cages, salmon are exposed to lice and diseases, and measures to prevent these issues are needed. Moreover, salmon lice have shown a reduced susceptibility towards traditional medicinal treatments, and resistance to several medicines has been developed (Hjeltnes et al., 2019). In response to this, there has been a rapid growth of non-medicinal treatments, and new lice treatment technologies are in development. Also, some salmon farmers have branched out to exposed areas and face new challenges as a consequence of harsher weather conditions.

In recent years salmon supply growth has stagnated, and according to Mowi (2019), "...the industry has reached a production level where biological boundaries are being pushed". In 2017, the government introduced a traffic light system spanning across thirteen geographical regions, aiming to regulate industry growth due to challenges with salmon lice. As a result, growth permits are determined by lice levels on wild salmon, and if conditions are unsatisfactory, sites within the region must reduce their current production.

Problem description

Many ships are designed to solely deal with goods, such as containers, cars or oil and gas. In aquaculture, vessels manage living animals in water filled tanks and piping systems. Thus, in addition to performing a given task, the welfare of the fish must be protected. Otherwise, injuries and mortality within the population will occur, which raise both financial and ethical concerns.

Growth and development within in salmon industry lead to new forms of production. Testing of emerging technologies and procedures occur at the same time as industry actors initiate large scale production. According to Sommerset et al. (2020), the salmon industry does not provide satisfactory documentation of the impact of new technologies on fish welfare, which is an unwanted trend. In 2019, the Norwegian Food Safety Authority (NFSA) announced that thermal lice treatments would be banned within two years unless new knowledge indicates that the method can be used responsibly. Given that almost 60 % of non-medicinal treatments are thermal, and that increasingly more treatments are mechanical and involve intensive handling of fish, these methods require further investigation.

In recent years, average mortality during the sea phase has been close to 15%, which is an improvement compared to the condition in the early 2000s (NVI, 2020). In 2011, the NFSA stated that it is possible to minimize mortality rates if breeders possess the right knowledge, make good choices and have healthy environmental conditions. Since 2015, the reduction in mortality rates has stagnated, and to improve the health situation for farmed salmon in Norway, people within the salmon industry need to take action and increase their initiative.

With the desire to improve fish welfare and reduce mortality rates within the aquaculture industry, this thesis investigates boat operations that are hazardous to fish. Experts believe it is possible to achieve a healthier average mortality rate of 5%. There are already localities that perform at this level, but in general, the average mortality is too high. In order to achieve a further decline, actors in the industry must find conditions that are harmful to the fish, and develop new technology and find procedures that safeguard the health of the fish.

Related Work

The challenges related to salmon encounters with vessel operations are currently being investigated from several angles, and both industry, equipment manufacturers and research communities attempt to analyse and understand the causalities of mortality and poor welfare in salmon farming. The research project Fishwell published the handbook ”Welfare Indicators for farmed Atlantic salmon” which provides tools for assessing fish welfare. Further, the Norwegian Food Safety Authority (NSFA), which has the administrative responsibility to make sure that salmon are treated in accordance to the Animal Welfare Act, initiated a study which found that 38.5% of salmon mortality originates in handling and other stresses at the site (NFSA, 2011).

A core topic in this thesis is when technology encounters biology, and how salmon responds to emerging technologies and existing procedures. SINTEF Ocean has developed and tested Sensorfisk (”sensor fish”), a technical device that logs physical behaviour and compares mechanical loads on fish from different delousing systems. In the future, it is expected that the framework in Precision fish farming (PFF) will improve production and enable individual fish observation. Although research shows potential for improvements in the production of salmon, there is still much work that remains to achieve a satisfactory health situation. An information gap is observed on multiple levels making it difficult to document progress.

Thesis objectives

The aim of this thesis is to investigate challenges that arise when salmon encounters vessel operations. To address potential hazards and consequences of welfare critical vessel operations, a preliminary hazard analysis will be conducted, including risk reducing measures to preserve the salmon. In this study, a simulation model of the salmon production cycle will be developed, which combines technology and biology to monitor populations closely. A stochastic model will construct the health status of salmon. Through simulation of a cage environment at selected localities, different treatment and smolt strategies will be revised in a case study. The results from the simulations will be combined with a cost-benefit analysis, and net benefits will be estimated for the case studies. The goal is to find welfare oriented strategies profitable for farmers.

Report structure

In Chapter 2, I present an introduction to salmon farming and explain how vessel operations that involve salmon are conducted and elaborate mortality within the salmon industry. Chapter 3 reviews literature in the field to provide an overview of current knowledge and highlight problem areas that can be further investigated in my thesis. Further, Chapter 4 describes the approach used to solve the problem, which commences with a risk analysis for salmon health in vessel operations, followed by an introduction to the simulation model and the case studies used in the cost benefit analysis. The established model is described in Chapter 5, while the results from the case study are presented in Chapter 6. The methodology and results are discussed in Chapter 7, before key finding are presented in Chapter 8.

Chapter 2

Salmon Welfare in Vessel Operations

This chapter presents the theoretical framework for the thesis, with the intention that readers will understand the fundamental parts of salmon farming. The production cycle and components of modern fish farms are explained, followed by the welfare needs of salmon. There is an uncertainty in the causes of mortality in salmon farming, and the last sections focus on vessel operations that pose a threat to farmed salmon.

2.1 Introduction to Salmon Farming

2.1.1 Production Cycle of Salmon

The production cycle of Atlantic salmon takes about three years, from fertilizing eggs to ongrowing in sea cages, and finally harvest and slaughtering. Throughout this period, fish are exposed to different environments and are under surveillance at all times. In aquaculture, land based facilities are used until the fish is ready to encounter seawater. The cycle starts at hatcheries, where eggs are fertilised and incubated. Further growth continues in freshwater cages, and by the time juvenile salmon develops into smolt, biological changes in the fish prepare it for a life in seawater. Before smoltification and transfer to sea cages, the fish are vaccinated, and by this time the fish is about 100–150 g (Mowi, 2019).

Wellboats are used for transportation of live fish, and there are different procedures to bring smolt from the tanks onshore to sea cages. If the set fish facility is far from shore, trucks are required to move the fish to the coast, and eventually, the fish are transferred to wellboats by pump systems. More convenient are coastal facilities, and with the latest equipment, smolt can be moved directly from cages into the wellboat by pipe systems at the facility. By arrival at the production site, the fish get unloaded into net cages. As the fish continues to develop and grow, grading of the population might become essential. In that case, wellboats can move fish between cages and even sites.

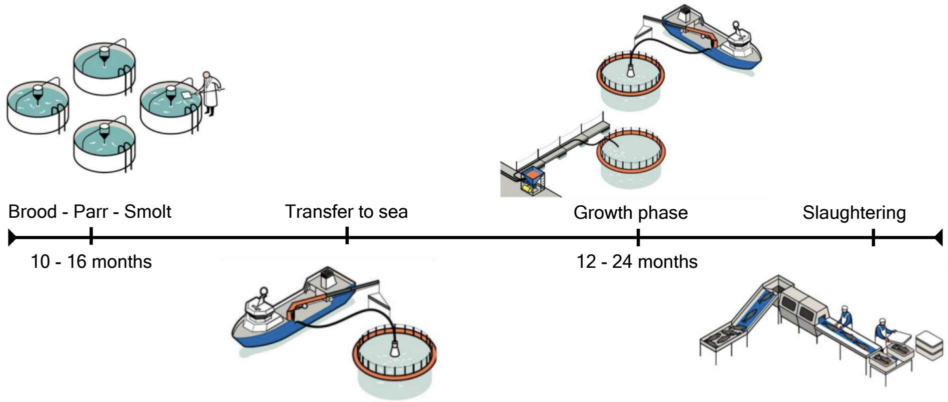

Figure 2.1: Production cycle of Atlantic salmon, illustrations from Mowi (2019)

As illustrated in Figure 2.1, growth in sea cages lasts for about 12–24 months, and during this phase, the fish reach an average weight of 4–5 kg (Mowi, 2019). Salmon growth rates are mainly dependent on seawater temperatures, which have seasonal variations as well as differences between regions but also feeding, light conditions and water quality are essential (SalMar, 2020). When the fish is ready for harvest, it is transported to slaughterhouses ashore. Optionally, fish is handled by a slaughter boat at the site and brought to a processing facility afterwards. During the growth phase, cleaning and maintenance of equipment are parts of the regular operation, and service vessels equipped with cranes, underwater vehicles, robot washers and of course people, perform such procedures.

2.1.2 Modern Fish Farming

Salmon farming takes place along large parts of the Norwegian coast, in sheltered coastal areas or at places exposed to heavier environmental loads. The most usual cage concept in Norway is flexible sea cages. They have beneficial hydrodynamic attributes, and there are typically 8–16 separate cages in a locality (Føre et al., 2018). In floating fish farms, several components are put together to make the production efficient, and in general include cages, system mooring and a feed barge. The cages have reliable anchoring and measures such as bird nets to prevent fish from escaping. Various vessels are necessary for operations at the site. Workboats and service vessels are equipped with cranes and storage, while feed boats deliver feed regularly (Lader, 2019).

The Norwegian Directorate of Fisheries (NDF) has decided that fish farms cannot exceed the maximum allowable biomass (MAB) of the locality, which is specified in the licenses linked to the locality and is based on the sustainability of the area. Thus, the layout of a locality depends on the MAB, weather conditions and the topography at the site, and is designed according to NS 9415[1]. The standard size of a permit is 780 tons per license, except for localities in Troms and Finnmark where the permits are 945 tons (NDF, 2017).

As a result of economies of scale, both farms and cages have increased in size. According to Føre et al. (2018), floating cages in Norway often have a diameter of 60 meters and contain about 40,000 m^3 of water. Besides, each cage can keep a maximum of 200,000 salmon and have a fish density of 25 kg/m^3 (Akvakulturdriftsforskriften § 47 a). The crew operating a site usually consist of 5–10 people and can have the responsibility for millions of salmon (Føre et al., 2018). Sea cages are also exposed to a coastal environment, and when moving localities to more exposed areas, it implicates the ability to monitor and operate salmon populations. Despite the challenges farmers experience when operating in coastal areas, open sea cages are preferred as they are cost effective and easy to manage.

2.1.3 Salmon Welfare Needs

Welfare addresses both physical and mental health status and Stien et al. (2013) define animal welfare as ”the quality of life as perceived by the animal itself”. Welfare needs for salmon are categorised into resources, environment, health and behaviour. The welfare needs are listed in Figure 2.2 and the degree of fulfilment of these affects the welfare status of fish (Mellor et al., 2009). Moreover, some welfare needs are essential for survival, like respiration and nutrition, while others are necessary in the long run to not decrease fish welfare (Noble et al., 2018).

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[1] Norwegian Standard 9415: Requirements for site survey, risk analyses, design, dimensioning, production, installation and operation

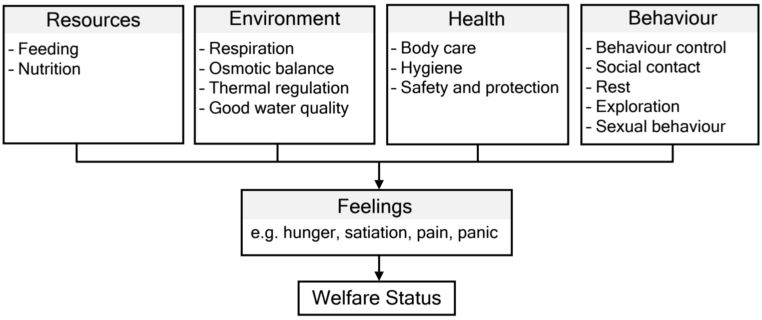


Figure 2.2: Welfare needs of salmon presented as resources, environment, health and behaviour, adapted from Noble et al. (2018)

2.2 Welfare Critical Vessel Operations

In aquaculture, vessel operations represent a central part of the production, including transport of live salmon, staff and feed, delousing of salmon and maintenance of cages to mention some. These operations utilise service vessels, wellboats and newly developed lice treatment vessels. Some vessel operations involve salmon, and if so, they are considered welfare critical to the fish and the crew must prevent salmon escapes and take fish welfare into account. In the following, welfare critical vessel operations are explained to highlight operations where fish welfare is threatened.

In order to prepare fish before handling, feeding is terminated for a period. According to Holan et al. (2017), starving time depends on sea temperature, but is usually 3–4 days, and up to a week in the winter. The purpose of fasting is to empty the gut and reduce metabolism, which results in reduced rates of carbon dioxide (CO_2) and ammonia (NH_3) produced by the fish (Lines and Spence, 2012). Fasting enhances the ability of salmon to tolerate stress from subsequent procedures (Mørkøre et al., 2008), and before slaughter fasting is done for hygienic and quality reasons. Despite this, there are uncertainties of how fasting may achieve the desired effects without compromising fish welfare (Sommerset et al., 2020).

2.2.1 Live Salmon Transport

Wellboats are mainly used for the transport of live fish and includes operations as the transfer of smolt to production sites, relocation of fish between cages and sites, and finally, transport to slaughterhouses. As mentioned, slaughter boats can stun and bleed fish at sea and thus avoid the final live transport, but this technology is not particularly widespread. Besides, transport requires other operations than transport itself, such as crowding of fish in the cage and loading and unloading of fish by pumps. Given these points, fish are repeatedly handled in transport operations, and even if wellboats are designed to load, transport and unload fish, transport may cause numerous physiological reactions (Erikson et al., 1997).

During sea transport, the well may have open valves and seawater circulates through the system. Otherwise, if the system is closed, internal systems must provide good water quality without new water supply. In particular, carbon dioxide (CO_2) and ammonia (NH_3) must be dealt with, which occur naturally due to the fish's metabolism, and are toxic to fish (Rosten, 2010). An advantage of closed systems is that diseases from the surrounding water are not transmitted to fish inside the well, and vice versa. A consequence of infectious diseases is that more fish are required to be transported in closed systems, to prevent further contagion (Hjeltnes et al., 2008). As open systems pose a risk for transmitting diseases, the NFSA has decided that from 2021, all wellboats must be capable of disinfecting transport water (NFSA, 2019).

2.2.2 Lice Treatments

Salmon lice are the biggest problem in aquaculture (Holan et al., 2017; Hjeltnes et al., 2019), and treatments of lice will be the main topic discussed further in this section. Current regulations prevent high levels of lice, and farmers must initiate delousing procedures if the average lice level exceeds 0.5 adult female lice per fish. In periods critical for wild salmon, the treatment limit drops to 0.2 adult female lice per fish. If the lice burden is below that limit, fish welfare is not considerably affected (Hjeltnes et al., 2019).

Measures against lice are either preventative or active. Preventative measures intend to keep the lice away from the fish and comprise cleaner fish, lice skirts, closed and semi closed cages and land based facilities. On the other hand, active measures attempt to remove lice from the fish by different methods, which are either medicinal or non-medicinal. Table 2.1 and 2.2 illustrate how often active delousing measures are used from 2014–2019, and it has been a distinct shift from medicinal to non-medicinal methods.

Table 2.1: The number of prescriptions given for categories of active ingredients used in lice treatment from 2014–2019, (VetReg, 2020)

Active ingedient	2014	2015	2016	2017	2018	2019
Azamethiphos	752	621	262	59	39	82
Pyrethroids	1,049	664	280	82	56	73
Emamectin benzoate	481	523	612	351	371	424
Flubenzurones	195	202	173	81	40	42
Hydrogen peroxide	1,021	1,284	629	214	96	77
Total medicinal	3,498	3,294	1,956	787	602	698

Table 2.2: The number of non-medicinal treatments reported to the NFSA, from 2014–2019. A treatment is a week where a locality has conducted a non-medicinal treatment against salmon lice, (Sommerset et al., 2020)

Category	2014	2015	2016	2017	2018	2019
Thermal	3	36	685	1,247	1,355	1,451
Mechanical	38	34	331	279	471	734
Freshwater	1	28	88	96	104	172
Other	136	103	75	51	72	89
Total non-medicinal	178	201	1,179	1,673	2,002	2,446

Medicinal Treatments

Throughout the production cycle, fish are exposed to different challenges that might require medicinal treatments. According to Noble et al. (2018), the welfare issues depend on the way the medicine is managed, and bath treatments, in-feed treatments and injections are available methods. Emamectin benzoate is added to feed, which is better known as ”Slice” and is usually given to newly released salmon or in cold temperatures, to prevent excessive handling against lice in vulnerable periods. Injections are rarely used but are an option if the fish have received an infectious pathogen.

In recent years, salmon lice have shown a reduced susceptibility towards medicinal treatments, and resistance to several medicines has been developed (Hjeltnes et al., 2019). In light of this, there has been a rapid growth of non-medicinal treatments, and new technologies are in development. The shift from using medicines to not doing so has completely changed the way salmon lice is dealt with, and not to mention how frequent salmon are handled in non-medicinal lice treatments.

Non-Medicinal Treatments

Non-medicinal treatments are generally classified into thermal, mechanical and freshwater treatments. These treatments have in common that they require handling of the fish – first by crowding and pumping followed by a treatment, before transfer back to the cage. In order to have a lasting effect, lice must be collected and removed after delousing; otherwise, there is a high risk of re-infection (Gismervik et al., 2017). However, there are other methods in development, such as lasers, which may become more significant in the future (Noble et al., 2018).

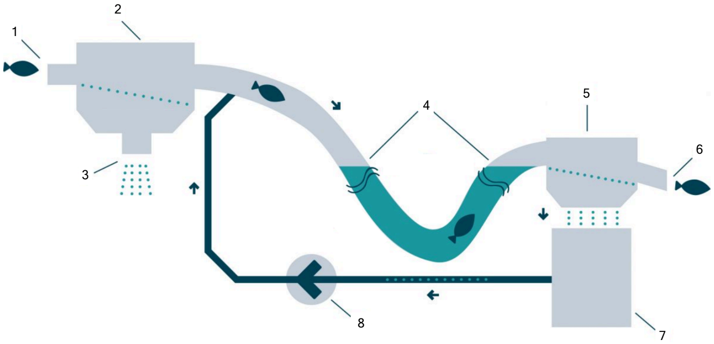


Figure 2.3: Principle presentation of Thermolicer. 1: fish enters after pumping; 2: filter out seawater, 3: release seawater; 4: thermal treatment; 5: filter out treatment water; 6: fish exit; 7: recirculate treatment water; 8: pumping of treatment water (Steinsvik, 2020).

Thermal

Thermal treatments constituted 59% of non-medicinal treatments in 2019 (Hjeltnes et al., 2019), and there were twice as many thermal treatments than mechanical. The method utilises temperature adjusted seawater, usually, in the range between 28–34 °C, and is effective against moving lice, not those that are attached to the fish. There exist two commercial tools of thermal treatment; Optilicer and Thermolicer. Optilicer uses an open bath with temperate seawater where fish are distributed with impellers before the heated water is filtered out and the fish returns to the cage. Figure 2.3 illustrates Thermolicer, which usually takes place in a container on a treatment barge, and is extensively equipped to move fish through pipes with temperate water. Besides, a filter that removes detached lice.

Mechanical

Mechanical delousing has become more apparent in recent years, and from 2017 to 2019, the mechanical treatments increased drastically by 263% (279–734 reported treatments). Such treatments physically remove lice from the fish, by either low pressure washing or brushing of the fish, or a combination of both which is prevalent in SkaMik treatments. Other commercial methods are FLS and Hydrolicer. FLS is developed by Flatsetsund Engineering AS (abbreviated FLS) and uses ejector pumps as the fish is washed with seawater. Likewise, Hydrolicer washes fish by low pressure, but in this case, the fish is turned backwards with the tail first. Table 2.3 summarises the procedures in the commercial thermal and mechanical lice treatments.

Table 2.3: List of procedures in thermal and mechanical lice treatments. Optilicer and Thermolicer are thermal, while FLS, Hydrolicer and Skamik are mechanical.

Thermal		**Mechanical**		
Optilicer	*Thermolicer*	*FLS*	*Hydrolicer*	*Skamik*
Transfer by impeller pump	Transfer by vacuum pump	Transfer by ejector pump	Transfer by ejector pump	Transfer by vacuum pump
Dewatering	Dewatering	Seawater flushing x2	Fish turned backwards	Seawater flushing
Heated seawater bath	Pipes with heated seawater	Dewatering	Seawater flushing	Brushing
Dewatering	Dewatering		Dewatering	Dewatering

Freshwater

Another practice that has emerged in recent years is freshwater treatments. This method utilises freshwater to remove lice and other parasites, and the fish are treated in wellboats filled with freshwater. The procedure usually lasts for 4–8 hours before the fish are pumped back to the cage again. This disrupts the osmotic balance of the lice, and causes paralysis and eventually death. To avoid lice from becoming resistant to freshwater treatments, these treatments should not be used more than twice a year and should only be used in rotation with other treatment methods (NFSA, 2017).

2.2.3 Live Salmon Transfer

The majority of the mentioned operations require movement of the salmon between sea cages and vessels, and the following explains how such operations are carried out when the fish are placed in cages. As mentioned, salmon are starved for some days before such operations, and prior to the vessel arrives, people at the locality prepare the cage by removing equipment that limits access. Figure 2.4 illustrates a floating net cage, which is typically aligned with other cages at the site.

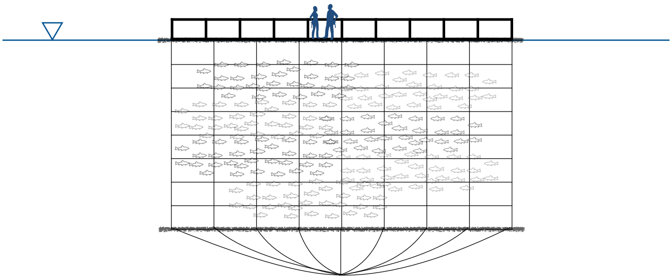


Figure 2.4: Floating net cage used for salmon breeding

A bottom ring or another weight system is placed beneath the cage to keep the net expanded underwater. The first procedure is to elevate the bottom ring. If the cage is equipped with winches, these can be used directly without involving boats and much workforce. Føre et al. (2018) encouraged the use of winches, as this allows agile crowding and can easily be included in an automated process. Otherwise, service vessels with cranes are common practice. In either case, the raising must be done gradually in order to distribute forces and not harm the fish inside the cage. As the bottom ring raises, excessive net and ropes are hauled in, and Figure 2.5 illustrates the cage at this stage.

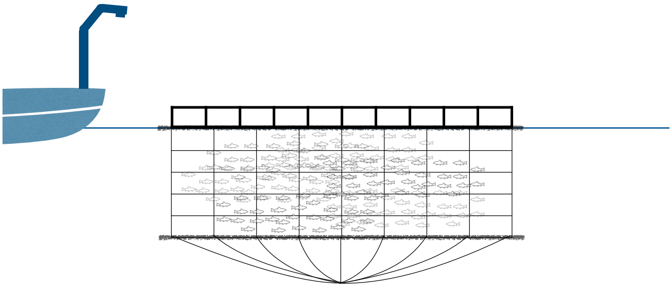


Figure 2.5: Net cage after elevating the bottom ring

At this time, a wellboat or a delousing vessel arrive to perform the given operation, and the vessel must carefully manoeuvre between the other cages at the facility and also avoid mooring lines underneath the surface. Further, the vessel ties up to the cage so that sea currents drift the boat towards the cage and not away from it. Consequently, the fish are prevented from being clamped in the following crowding and pumping.

Crowding

Crowding of the fish is necessary to pump the fish efficiently afterwards. In sea cages, crowding occurs before most vessel operations. However, crowding also initiates before transport of smolt to sea cages and before slaughtering, in case the fish are placed in waiting cages by the slaughterhouse. Although, the principles of crowding are similar, and sea cages are mainly crowded in two ways, either by crowding of the net cage or by inserting another net inside the net cage to crowd a smaller population, where the latter is illustrated in Figure 2.6. If the entire cage is to be emptied, the first method applies, given that the vessel has enough space for the fish. Further, crowding of sea cages often require cranes to haul in nets and ropes, and assistance from service boats may be necessary.

Pumping

After crowding, the fish are collected using pumps, and this is usually done with vacuum pumps. The end of the pump pipe is placed inside the cage and loads fish into tanks on the boat. The number of pipes varies between vessels. As the fish move inside the vessel, it is time to perform the determined operation, varying from lice treatments and shipments to other cages, sites and slaughterhouses. If the fish is going back to the same cage, it gets pumped back inside the cage, and the procedures mentioned above are performed in reversed order.

Pumps are utilised to transfer fish between systems, and for both juvenile and adult salmon, the most common type is vacuum pumps. However, some vessels are equipped with impeller pumps, and then fish is moved with mechanical impellers installed in the water flow. Advantages with impeller pumps are large capacities and that they provide a steady flow of fish. Otherwise, ejector pumps are a third option, which pumps fish by using high water pressure. Research has found that in terms of acceleration, ejector pumps exert less physical impact than impeller pumps (Erikson, 2018).

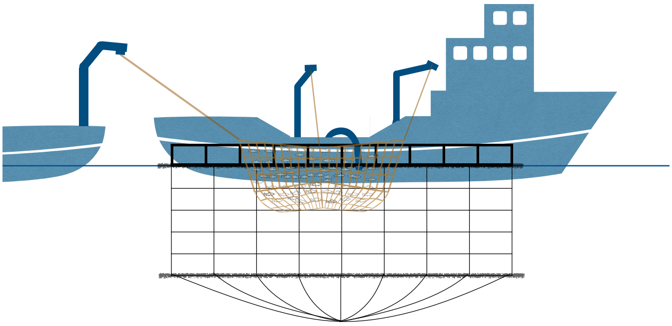


Figure 2.6: Crowding by inserting a second net and pumping of fish

Vacuum pumps consist of a pipe with a pump chamber in the middle. The pump chamber alternates between negative (vacuum) and positive pressure, where fish is pumped from its current location and into the pump chamber, and then pushed further into the system. The pipe whereas the fish is transported should be of a suitable diameter, and pressure guidelines for adult fish are from 0.3–0.7 bar in vacuum and from 1.5–2.0 bar when the fish move away from the pump chamber. For smolt, there is a restriction that water velocity inside pipes should be below 2.3 m/s. In general, this velocity must be higher than the swimming speed of fish, as salmon tend to swim against the current. At the same time not too high, as there is a risk for the fish to get harmed (Noble et al., 2018).

Grading

Grading or sorting of fish is conducted to split the population. For instance, when fish is moved between cages, or before vessel operations. Grading may be performed with grading machines or by net panels installed into a sweep net. When a sweep net is lifted, smaller fish are able to swim through holes in the net panel and remain in the cage, while the bigger fish can be moved (Noble et al., 2018). Also, it is useful before harvest, as a selection of the bigger fish can optimize profits. Removal of the larger and more dominant fish is beneficial for smaller fish, as it allows them to develop more quickly afterwards.

Harvest

Harvest is the final operation at sea where fish are involved, and this section focuses on the procedures before slaughter. There are several ways to end the production cycle of salmon, and some involve more handling than others. Table 2.4 lists the sub-operations for welfare critical vessel operations, including two methods for harvesting fish. In either case, the fish are crowded, followed by pumping into a vessel. The traditional way is to use wellboats, and transport the live fish ashore, either to temporarily waiting cages before slaughter or directly to the slaughterhouses. Otherwise, slaughter boats have become an available and competitive option. These boats have equipment that stuns and bleed fish by the production site before transport, and thereby reduces the number of handling operations while the fish are alive.

Table 2.4: List of operations with sub-operations. Two methods for harvesting fish; I is the traditional way with live transport to waiting cages before slaughter onshore, and II represents immediate slaughter by vessels that stun and bleed by the cage followed by transport and processing.

Smolt transport	**Delousing**	**Grading**	**Harvest I**	**Harvest II**
Crowding	Crowding	Crowding	Crowding	Crowding
Pumping	Pumping	Pumping	Pumping	Pumping
Shipment	Lice treatment	Shipment	Shipment	
Unload fish	Unload fish	Unload fish	Unload fish	
			Crowding	
			Pumping	

2.2.4 Other Operations

Other vessel operations cover those not involving fish directly, for example, transport of feed, equipment and crew to the locality and maintenance and cleaning of the cages. In the same way, as waves affect fish, propellers on vessels stress the fish. This is especially true for bow thrusters, as they are directed towards the cages. For this reason, propellers are turned off when boats are moored, and dynamic positioning systems are not widely used nearby aquaculture farms (Ellefsen, 2014).

Growth of organisms on the net cage is another problem that requires actions. If net cages have high concentrations of biofouling, water quality is impaired, the resistance of the cage increases and the growth of organisms may attract cleaner fish whose purpose is to eat salmon lice. According to Noble et al. (2018), nets are cleaned weekly in periods when exposed to high levels of fouling. For cleaning operations, robot washers and service vessels may be utilised, and rotating discs remove fouling by high pressure water jets. To maintain good water quality, cleaning of nets are necessary, but the procedure may affect fish welfare due to physical injuries, stress and toxic chemicals (Noble et al., 2018). At times fish have been observed actively avoiding the debris that is washed off the net, and Bloecher et al. (2018) found organisms in the debris with active stinging cells which may cause harm to the gills of fish.

2.3 Mortality in Salmon Farming

Mortality in fish farming is an indicator of fish welfare, and an indirect measure of fish health. According to the NFSA (2020), the health situation in Norwegian aquaculture is not satisfactory. There is reasonable control of bacterial diseases but still challenges with viral diseases and injuries associated with the production. Since early 2000s, the industry has managed to reduce average mortality from above 20% to about 15%. After 2015, the reduction in mortality rates have stagnated, and Table 2.5 shows the development in average and median mortality as well as the number of salmon that were lost in production from 2015–2019.

Table 2.5: Reported mortality in Norway from 2015–2019. Average and median mortality rates, and losses of salmon that have been transferred to sea, specified for mortality, discards and ”other”, in millions, (NDF; NVI).

	2015	**2016**	**2017**	**2018**	**2019**
Average mortality (%)	14.2	16.2	15.5	14.7	16.2
Median mortality (%)	12.3	15.7	15.9	15.1	13.5
Losses	48.3	53.3	52.3	53.0	59.3
Mortality	41.3	44.8	45.8	46.2	52.8
Discards	4.4	3.6	3.2	3.5	3.9
Other	2.5	3.2	3.3	4.8	2.4

Mortality rates are based on commercial productions completed in the given year, while losses include data for all salmon transferred to the sea, including ongrowing, broodstock, fish from research and development licenses and more. Discards are fish of poor quality which gets segregated during slaughter, and ”other” may include mortality episodes due to lice treatment and other handling, but also fish that are killed due to disease control. Although mortality rates are relatively stable, a clear increase in lost individuals is seen. In 2019, the industry reported a total loss of 59.3 million salmon, compared to 53.0 million the previous year. In addition, the median mortality rate was 2.7 percentage points lower than the average, which indicates particularly high mortality at some locations. This can be explained by the occurrence of toxic algae in Northern Norway which killed an estimate of 8 million salmon (Sommerset et al., 2020).

Cleaner fish

The aquaculture industry experiences high mortality and welfare challenges in farmed fish and cleaner fish. In addition to active lice treatments, cleaner fish is a preventative measure that provides continuous delousing as salmon lice nourish them. An advantage with cleaner fish is that handling of salmon is avoided and the measure is also considered efficient. However, the welfare of cleaner fish is questionable, and according to Sommerset et al. (2020), the main challenges are high mortality, consequences from handling and bacterial diseases.

In 2019, 49.1 million cleaner fish were placed in Norwegian cages, and a study conducted by the NFSA found that during a production cycle, 42% of all cleaner fish died. The results revealed that the industry lacks knowledge of when and why cleaner fish dies and indicate that routines covering the welfare of cleaner fish are missing. The Animal Welfare Act applies equally to all fish in aquaculture, also lumpfish and species of wrasse which are two of the most used species of cleaner fish. Nevertheless, there is a long way until fish in general are treated as individuals with their own welfare needs – and welfare of cleaner fish is a separate issue that needs more attention.

2.3.1 Causes of Mortality

Research from the Norwegian Veterinary Institute (NVI) have found that except the parasite salmon lice, viral diseases have the greatest effect on fish health (Hjeltnes et al., 2019). It is primarily pancreas disease (PD) and infectious salmon anaemia (ISA) that characterize the disease picture. The number of ISA outbreaks have been relatively stable, and outbreaks of PD are reduced in recent years, but the occurrences are doubled since 2009 (NFSA, 2020). In addition, there are several unrecorded diseases that cause poor health and welfare for farmed fish. This includes heart and skeletal muscle inflammation (HSMI) and cardiomyopathy syndrome (CMS), also called heart failure.

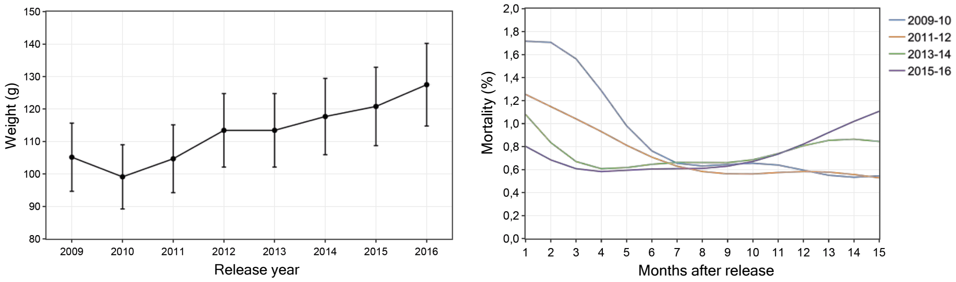
The NFSA (2011) categorizes the causes of mortality into three groups, which are conditions linked to set fish facilities (38%), infections in the sea (23.5%) and other conditions at the locality (38.5%), which includes handling. As a precaution against diseases, all salmon are vaccinated before transfer to sea. Despite this, the use of antibiotics in Norwegian aquaculture is very low (Government, 2019). Nevertheless, outbreaks occur and pose a threat to fish welfare. To avoid further transmission, the NFSA is authorized to intervene with measures which include slaughter, destruction or movement of fish.

2.3.2 Mortality in Operations

Smolt release

The smolt release phase is associated with considerable risk. The fish are repeatedly handled and moved to a new environment in sea cages. According to Iversen et al. (2005), live fish transport in wellboats can have a useful recovery function between other handling operations such as crowding and pumping. However, for the fish to become calm during transport, conditions need to facilitate a safe journey, which is affected by the water quality, transport duration and weather conditions. In case of bad weather during transport, the stress hormone cortisol does not return to resting levels, and the fish is already stressed before the unloading, which increases the mortality rate after release (Iversen et al., 2005).

According to Iversen et al. (2005), disease outbreaks are more apparent in the months after release, and consequently, mortality rates are higher in this period. Further, salmon are anadromous fish, meaning that their gills adapt to both freshwater and seawater. By arrival at the production site at sea, smolt are released into a brand new environment of seawater. Small fish are sensitive to changes in salinity, and if smoltification is incomplete at this time, they risk dying from dehydration (Noble et al., 2018). Figure 2.7 shows that smolt size increased by 30% from 2009–2016, and during the same period there was a considerable reduction in mortality rates in the first six months after release.



(a) Smolt size development from 2009–2016

(b) Mortality after sea transfer from 2009–2016

Figure 2.7: Released smolt size and mortality after transfer from 2009–2016. (**a**): Initial weight of salmon when released to sea cages. (**b**): Monthly mortality the first 15 months after transfer to sea cages, in four time periods from 2009–2016. Productions that were split, stopped or harvested before 15 months were excluded in these estimates, (Glover K et al., 2018).

Salmon handling

Mortality due to lice treatments and other types of handling raises concerns for salmon welfare. Moreover, the current procedures and technology can be harmful to the fish (Noble et al., 2018). Injuries from handling may be fatal, and when salmon encounters vessel operations, dead fish can be found in the vessel and the sea cage afterwards. During and after handling procedures, the fish becomes stressed, which appears as an increased level of the stress hormone cortisol, and fleeing behaviour. As a result, stressed individuals collide into pipe walls and other fish, and collisions involving teeth, sharp edges or bends will, in general, be harmful to fish.

As of 2018, non-medicinal delousing accounted for over half of the reported incidents to the NFSA. Both mechanical and thermal treatments include some of the same hazards, like crowding, pumping and transport through pipes. Besides, mechanical treatments have at least one more hazard such as brushing and washing, while thermal delousing involves temperate water. After thermal treatments, high mortality rates are observed, as shown in Figure 2.8, and suggests that temperate water is more detrimental to salmon than both mechanical and chemical bath treatments (Stien et al., 2019).

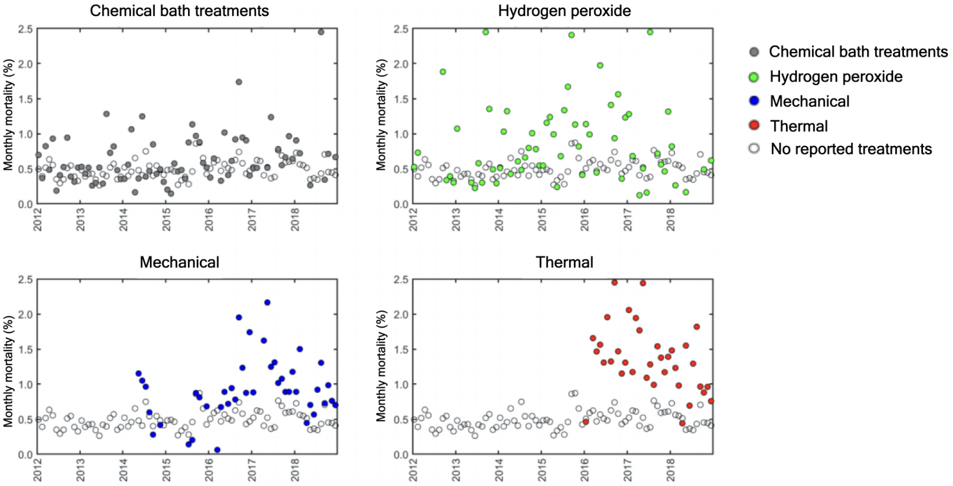


Figure 2.8: Comparison of monthly mortality rates at sites that reported delousing (coloured circles) and sites with no reported treatments. Include chemical bath, hydrogen peroxide, mechanical and thermal treatments in the period 2012–2019. Figure is translated and legends are inserted, (Stien et al., 2019)

A study from 2019 conducted by the Institute of Marine Research (IMR) and the NVI found that salmon shows painful behaviour in water temperatures above 28 °C (Sommerset et al., 2020), and in 2019 the NFSA forbade all thermal treatments with temperatures above 34 °C. Observations of faster swimming, collisions with walls, intensive splashing and head shaking indicate discomfort. If the industry fails to document the welfare of the fish during and after thermal treatments, treatments with water temperatures above 28 °C will be banned within two years.

Handling of fish in sea cages often include both crowding and pumping of fish through pipes. Common problems during these procedures are injuries on gills, eyes and snout, loss of mucus and secondary infections. As both crowding and pumping are associated with other handling procedures, such as grading or lice treatments, this leads to adverse repeated stress of fish (Roth et al., 2012). Even if repeated handling may not be fatal right away, wounds from handling may serve as the indirect cause of death. Secondary infections and winter ulcers are typically a challenge in colder water temperatures, and wounds are painful for salmon pain and reduce the quality of the meat.

According to Noble et al. (2018), eyes and snout have receptors so that fish feel pain when these body parts are damaged. Other challenges during crowding are lack of oxygen and situations where the fish get jammed due to restricted mobility. Crowding stresses salmon, and increased levels of cortisol (Erikson et al., 2016) demonstrate this, and if the crowding becomes too long or forceful, the fish will be harmed, regardless of the following operation.

For pump operations, there is a risk associated with collisions in the pipe, with sharp corners and other irregularities, even with other fish. In impeller pumps, damage usually occurs as fish pass the rotating impellers which push the fish in another direction. Even if pump pipes restrict swimming behaviour, larger fish achieves more momentum, and therefore have a greater risk of encountering the impeller than smaller fish (Roth, 2016). In cases when the pump stops or during long transits, hazards may occur from deteriorated water quality and overcrowding in the pipe. Vacuum pumps, which are the most common pump type, may have a double chamber setup, and this often results in turbulent flow through the pipes. Salmon tend to swim against the current, and as the turbulent flow might be slower than the swimming speed, this can potentially exhaust the fish (Lines and Spence, 2012).

Harvest

Progressive handling before slaughter is crucial in terms of fish welfare and meat quality (Gatica et al., 2010). Research on harvest procedures with wellboats has found that the maximum observed stress levels increase with more handling operations before slaughter (Gatica et al., 2010; Merkin et al., 2010). Further, studies on Atlantic salmon, have found a clear link between stressed fish and shorter pre-rigour time (Iversen et al., 2005; Merkin et al., 2010), which make processing more difficult and reduce the shelf time of the product. Hence, harvest procedures should avoid prolonged and frequent handling of the fish, which emphasize the use of slaughter boats. Otherwise, waiting cages outside the slaughterhouse are crucial as they allow the fish to calm down before slaughter. Additionally, losses related to discards amounted 3.9 million salmon in 2019 (NVI, 2020). Discards are costly to lose as they have been through the whole production, and if less fish are downgraded at slaughter, salmon farming would be more sustainable.

Chapter 3

Literature Study

This chapter presents relevant literature and ongoing projects that deal with salmon encounters with vessel operations. The purpose is to explain how scientists, the NFSA and site operators take different approaches to the problem of interest, and not to mention that together they make a significant contribution in how to better understand the response of the fish and increased mortality after interactions with vessels.

3.1 Survival of Fish

The NFSA has administrative responsibility to make sure that salmon are treated in accordance with the Animal Welfare Act, and initiated ”Project Survival of Fish” to review mortality of farmed salmon in Central Norway. The study involves 61 localities, with a total release of 65.5 million salmon in 2009. 10.6 million, or 16.1% died in the period between release to slaughter. The NFSA (2011) categorizes the causes of mortality into three groups, which are set fish facilities, infections in the sea and other conditions at the locality, which includes handling.

Figure 3.1 shows the distribution between the three categories, and there is a remarkable part of farmed fish that dies due to conditions at site and handling (38.5%). Together with causes associated with the set fish facility, which in general is poor smolt quality, the two groups constitute over 75%. Poor smolt quality is fish that does not tolerate the transmission to sea cages and dies shortly after release. The NFSA (2011) criticizes the industry for not focusing more on these two groups, as they received less attention than infections at the time this study took place.

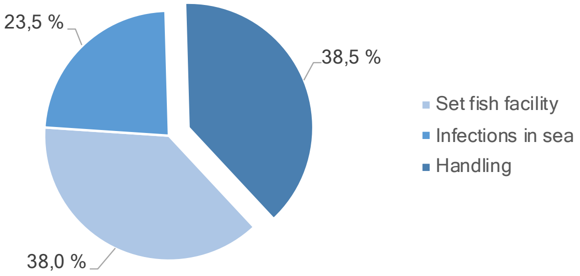
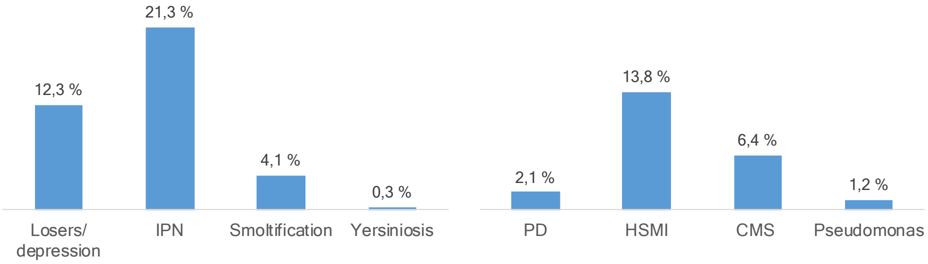


Figure 3.1: Mortality related to set fish facility, infections in sea and handling

Each category is then divided into specific causes, which are presented in Figure 3.2. Mortality from the set fish facility is mainly caused by IPN and ”losers”. Losers are fish that are easy to recognize by their stunted growth and in general poor appearance, and should be taken out of production as soon as possible (Noble et al., 2018). The most critical infections from the sea are HSMI and CMS. Figure 3.2(c) presents fish mortality from other conditions at the locality and handling accounts for 12.4%, while 17.3% are due to accidents. 6.4% are from wounds, and according to (Noble et al., 2018) wounds from handling can make an entrance for new infections, which may turn out to be deadly or at least create a serious welfare issue for salmon. Lice or low water temperatures are factors that hinder the healing of wounds.

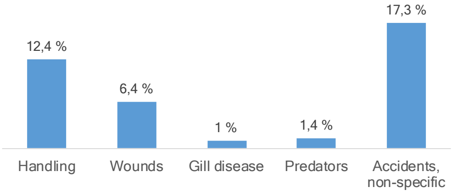
The NFSA (2011) found significant variations in the survival of fish. By distinguishing between fish farms, survival rates were from 35.6–96.6%. Based on results from the survey, the NFSA (2011) concluded that mortality rates could diminish if breeders possess the right knowledge, make good choices and have healthy environmental conditions. Further, the results from this project are an essential contribution to raising awareness of where the industry should focus on reducing losses. A direct consequence of this will be improved fish health and fish welfare for farmed fish. The NFSA is evident that the aquaculture industry is responsible for reducing the mortality of farmed salmon.

Pettersen et al. (2016) developed a stochastic model to simulate the spread of pancreas disease (PD) and studied how profitable various harvest strategies were. Like salmon lice and other infections, the viral disease PD demands measures when first being discovered and is associated with economic losses. They combined the results from different scenarios



(a) Set fish facility

(b) Infections in sea



(c) Handling and other conditions at the locality

Figure 3.2: Causes of mortality based on 65.5 million salmon released in Central Norway in 2009, and are sorted by set fish facilities, infections in sea, and handling and other conditions at the locality.

with a cost benefit analysis, and the idea was to evaluate harvest strategies over time by estimation of net benefits.

3.2 Welfare Indicators

Noble et al. (2018) published the handbook *Welfare Indicators for farmed Atlantic salmon*, which provides guidelines for assessing fish welfare in aquaculture systems, operations and in new technology. The handbook defines a set of animal based WIs, which are observations and measurements of how the welfare needs of the fish are met. Some WIs consider groups of fish, like mortality rate, appetite and growth, while others are for individuals, such as scale loss, sea lice and smoltification stage. A separate part defines environment based WIs, which mainly focus on the water quality surrounding the fish.

Mortality rates are commonly used as a group based WI, as abnormally high mortality rates implicate poor fish welfare. To better understand why fish dies or to describe the health status of fish, it is useful to look at other WIs than mortality, such as physical injuries and blood parameters. Some WIs require special equipment and are referred to as laboratory-based welfare indicators (LABWI). By sampling, it is possible to measure cortisol, which indicates how stressed the fish is. In the handbook, WIs are linked to welfare needs, both animal based (See Appendix G.1) and environmental based (See Appendix F.1). Noble et al. (2018) explain how the WIs can be used, what critical values that exist and how they may be interpreted to routines.

A consequence of lice being less vulnerable to medicinal treatments is the rapid growth of new delousing technologies, and in particular thermal and mechanical treatments that both involve repeated handling of fish. To measure and document welfare in a scientific way, Noble et al. (2018) generated a set of operational welfare indicators (OWI). Also, a complete list of the OWIs and LABWIs that are useful in different operations is included in Appendix G.2, and a similar for the environment based OWIs in Appendix F.2. Besides the removal of lice, treatments must safeguards fish welfare. In terms of emerging technologies and new farming routines, scientific research might be missing and then the handbook serves as a great tool for assessing welfare (Noble et al., 2018).

3.3 Quantification of Mechanical Loads

This section demonstrates how technology can quantify physical loads on salmon inflicted by equipment in vessel operations, such as the components in lice treatment units or transfer operations in general. SINTEF Ocean has developed and tested a technical device named Sensorfisk (”sensor fish”), which is a barrel-shaped capsule, equipped with sensors that log physical behaviour as shown in Figure 3.3.

Figure 3.3: Capsule and instrumentation of a Sensorfisk, (SINTEF Ocean, 2019)

Two units of 3 and 6 kg log motion-related data and one of 6 kg records collisions by a pressure sensitive mat. The lightest is also smaller in size; thus, the sensor fish capture the differences in stresses for salmon of varying size and illustrate effects in systems designed for fish of a particular size. The motivation for creating this tool was to establish a method that could modify systems where fish are handled, and make them more gentle to fish (Caharija et al., 2019).

The units were sent through different delousing systems to gather data and observe the behaviour of the capsules, and an overview of the systems is given in Table 3.1. Of particular interest were observations of pressure, collisions and residence time in the different parts of the system. When the position of the unit is known, it is possible to retrieve location specific loads, such as acceleration, velocity, pressure and temperature, and thus physical conditions in the system can be addressed.

Table 3.1: Overview of lice treatments specifying pump type, treatment and design. Thermal include Optilicer and Thermolicer, and FLS, Hydrolicer I and II and SkaMik are mechanical, (Lie, 2019).

	Optilicer	Thermolicer	FLS	HL I	HL II	SkaMik
Pump						
Vacuum/pressure	x	x				x
Ejector			x	x		
Impeller					x	
Lice treatment						
Low pressure washing			x	x	x	x
Tempered water	x	x				
Brushing						x
Design						
Contact with impeller	x					
Removal of water	x	x	x		x	x
Partly and completely water filled pipes	x	x	x	x	x	x
Pipe bends over 90 °C	x	x				x
Pumping height	∼10 m	∼4 m	∼5.5 m	∼6 m	∼5 m	<1 m

According to Caharija et al. (2019), vacuum/pressure pumps expose units to the highest pressure gradients (from 0.55–1.3 bar), and at times the capsule got stuck in the pump chamber, exposing it to several cycles with vacuum and pressure. Likewise, units got trapped in impeller pumps, which in general inflicted high g-forces on the sensor fish. For ejector pumps, some trials failed, as the pump was not able to move the capsule, and consequently, the unit stalled inside the pipe. Stalling in ejector pumps can be solved by installing another pump, as similar systems with such configuration performed well. Moreover, impacts from collisions were observed on several occasions, and especially around main equipment such as pumps, pressure washers, branched pipes, as well as edges and irregularities in the systems.

In the long run, results from this project may contribute to meeting the NFSA's requirements for documentation of technology and procedures. However, at this time the sensor fish is only able to quantify mechanical loads, and there is yet to be established links between measurements from a sensor fish and the biological response of salmon. Still, some participants from the project modified their systems after feedback from the trials.

3.4 Precision Fish Farming

It is expected that the framework in Precision Fish Farming (PFF) will improve production and enable individual fish observation, and when applying PFF to operations farmers or computers will make decisions based on knowledge, instead of experience (Føre et al., 2018). As a single farm may consist of millions of fish, there are obvious problems with individual monitoring through direct observation. Although submerged cameras are placed for monitoring reasons in most cages, Føre et al. (2018) intend to utilise software, computer vision algorithms and technology to enable remote monitoring, and thereby give farmer's insight into biological processes that were not possible before.

Føre et al. (2018) drew parallels to Precision Livestock Farming where sensors and information technology have been used in decades to automate the production and mentioned automated milking rows for cows and cameras to monitor real time positions. However, salmon farming is more complicated as it involves far more animals, located in an underwater environment. Besides, feeding is only provided by farmers and operations are conducted on whole cages, instead of individuals. Figure 3.4 illustrates an echogram during a crowding operation, where a sonar registered sound waves from fish. The echogram is suitable for some purposes, but each monitoring technology has pros and cons (Føre et al., 2018), and thus sensor types must be selected based on the situation.

Further, Føre et al. (2018) presented four applications of PFF in salmon farming, which include automation of biomass monitoring, feeding strategies, monitoring of lice levels and crowding control during delousing operations. These are all areas represent central parts of salmon farming, and can be improved in terms of efficiency and by reducing harm to fish. Today, lice counting is time-consuming as people do this manually, and also fish is repeatedly handled in the process. Crowding operations are critical for fish welfare, and with PFF, it can be possible to monitor salmon and alert farmers when something is wrong.

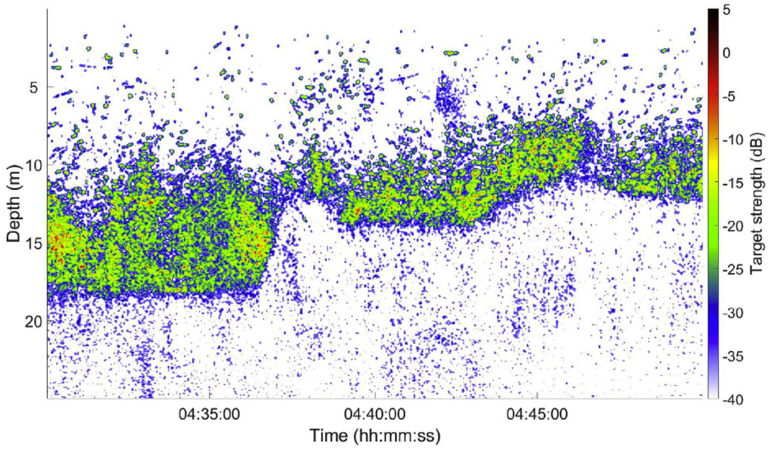


Figure 3.4: Echogram describing the vertical swimming behaviour of salmon when the net bottom is raised from 18 to 11 meter (at 04:37:00) during crowding, (Føre et al., 2018)

3.5 Bridging Technology and Biology in Design

The biological nature of salmon is pressured in aquaculture, and in particular during vessel operations. Technical solutions that involve animals are challenging to develop, and often require insight from several disciplines. According to H. Farzaneh (2020), cooperation between engineers and biologists can reduce the knowledge gap and develop new and innovative ideas, and in her study, she challenged students with the following question: ”Which aspects of a given technical system could be improved by bio inspired design?”

Bio inspired design or biomimetics uses elements from nature, which have evolved through the process of natural selection, to solve technical problems. In the study, biologists and engineers were paired. As engineers and biologists are used to different terminology, problem solving and information in general, H. Farzaneh (2020) developed BioId Support, which provides information and analysis techniques that people from both engineering and biology disciplines can follow. H. Farzaneh (2020) found that pairs with an engineer and a biologist can transfer more analogies into solutions than pairs with the same education when provided BioId Support.

3.6 Status Quo: Farming Procedures

To get an overview of salmon encounters with vessel operations and trends in the industry, Erik A. Næstvold was contacted. Erik currently works at Optimeering Aqua, and has experience as a delousing specialist and holds a Master of Science in Marine Technology. He explained that there still are uncertainties about treatment related mortality, and that unrecorded deaths might be an additional challenge. Although, small adjustments to procedures and equipment setup have demonstrated positive effects for salmon, and this section focus on observed trends in salmon farming which are promising for the existing challenges with fish welfare.

As mentioned, crowding and pumping together represent significant threats to fish welfare, and to avoid complications during these operations are crucial to keeping mortality rates down. Multiple factors are contributing to a well-structured crowding and pumping setup, including crowding time, pump height, pressure gradients, absolute pressure, velocity, pipe dimensions and a seamless design to avoid impact injuries to mention some. Besides, effective pumping is desirable to shorten the crowding time, which is expressed by the pump capacity in tons per hour. However, a balanced relation between these properties is needed to succeed.

The size and amount of fish constrain operations, but at times compromises are made due to the absence of better solutions. When fish are transferred from a sea cage and into a wellboat or treatment vessel, space restrictions might not allow the entire salmon population to be transferred at the same time. Given that, a part of the population remains crowded for an extended period. Situations of prolonged crowding are undesirable, and overcrowding may occur. If so, the operation must be cancelled right away, as overcrowding might lead to mass mortality or at least reduced welfare among the crowded fish.

Næstvold also provided insight about changes in pump technology and lice treatments. Vacuum pumps present the most robust technology and are as mentioned, the most used technology, especially for smaller fish. He also explained that impeller pumps are becoming less popular, and this is due to high mortality rates for fish above 3 kg. In contrast, ejector pumps have a rising trend and have the best potential to ensure good welfare while the pump efficiency is kept high. However, ejector pumps depend more on external factors as waves, so if the performance is poor, high mortality may occur. Besides, for the two competing thermal treatments, Thermolicer is, to some extent, being replaced by Optilicer. Also, temperatures are reduced to 30 °C, which is good for fish welfare but has less effect against salmon lice.

3.7 Concluding the Literature Study

This literature study describes several angles of salmon encounters with vessel operations and highlights the need for combining technology with biology when analysing aquaculture systems. H. Farzaneh captured the importance of supporting tools for teams with different backgrounds, and something similar can be helpful when uniting engineers with biologists in aquaculture. The NFSA wants to improve fish health and welfare and found it necessary to map mortality causes to reduce salmon mortality. Besides, to measure welfare, other welfare indicators need attention, and both mortality and salmon health status should be considered.

The future of aquaculture may involve individual monitoring, and a big step forward would be to only treat the fish that require treatment. Then again, to achieve the competence required for PFF, scientists must develop intelligent systems as described by Føre et al. (2018). Pettersen et al. (2016) introduced the economic aspect of decisions and used a bio-economic model to evaluate harvest strategies. This indicates that it is still possible to simulate the behaviour of salmon health before the IT systems described by Føre et al. (2018) are in place. The variation in the chosen literature demonstrates the complexity of the problem, and therefore this study will serve as a source of inspiration and guidance.

Chapter 4

Methodology

The challenge with mortality in salmon farming can no longer be avoided. In the following chapter, I outline a preliminary hazard analysis (PHA) to get a better understanding of hazards for salmon during vessel operations. With the trend of increased handling and more frequent vessel operations, it is necessary to find procedures that take fish welfare into account. I start with establishing risk reducing measures for hazardous events in different vessel critical operations. I proceed by introducing a discrete event simulation model of a cage environment and present the different farming strategies used in the model. Finally, I present a cost benefit analysis used for evaluation of farming strategies.

4.1 Problem Description

Currently, the use of non-medicinal lice treatments is one of the main reasons for mortality and other welfare challenges in salmon farming. To further reduce mortality, we need to identify the procedures and equipment that are too harmful to the fish. Vessel operations often require multiple sub-operations, like crowding, pumping and a delouser, which lead to repeated stress and make it complicated to target the real hazards for animal welfare. There is uncertainty related to mortality in aquaculture, but if statistics from previous years continue in the same direction, losses will pass 60 million salmon in 2020 (NVI, 2020).

Mortality in the salmon farming industry has stabilised around 15% (NVI, 2020). Salmon also experience a wide range of welfare challenges, despite the Animal Welfare Act stating that all fish must have living environments and handling procedures that ensure good welfare throughout the life cycle. Farmers strive to achieve this, but still, 1,392 welfare related incidents were reported to the NFSA in 2019 (Sommerset et al., 2020). Figure 4.1 shows that 60% was from non-medicinal treatments, and handling accounted for 6%. Additionally, 240 incidents are classified as unexplained mortality.

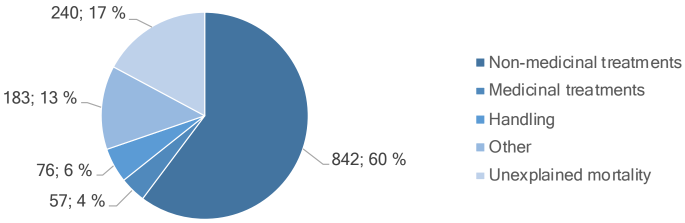


Figure 4.1: Welfare related incidents that were reported to the NFSA in 2019. The total number of reports were 1,392, (Sommerset et al., 2020)

These numbers indicate that the industry has not been able to develop and utilise technology that takes salmon welfare into account. If salmon production expands further, stakeholders in the industry must establish procedures and present new technology that provide safe growing environments for the fish. To get a complete understanding of the risk situation in salmon farming and elaborate on hazards for salmon, I have conducted a preliminary hazard analysis. The focus of the study is how salmon are affected by vessel operations, which contributes to understanding why vessel operations are dangerous for the fish.

4.2 Preliminary Hazard Analysis

A preliminary hazard analysis is useful to outline hazards systematically and is a risk analysis based on military techniques (Rausand, 2011). In the following, a PHA is used to review hazards for salmon in different vessel operations and eventually assess the risk. Popov et al. (2016) defines risk as ”the combination of the likelihood of the occurrence of harm and the severity of that harm”. The purpose of the analysis is to find situations that are harmful to fish and see if there is room for improvement.

Welfare critical vessel operations are analysed by identifying harmful consequences and challenges are addressed. Finally, risk reducing measures are found to improve routines and equipment. To evaluate the risk of various incidents includes finding potential injuries and circumstances contributing to the risk situation. In addition to increased mortality, different welfare indicators such as scale loss and behaviour are included in the analysis, which shows how operations threaten salmon welfare, and ultimately the fish's quality of life.

The analysis begins with identifying hazardous events that may occur during vessel operations and then establishes links between these events and the underlying causes, also called the triggering events. Further, the likelihood and the consequences of that cause are specified. Moreover, breeders have varying strategies for operations, including smolt release, lice treatments and harvest. In the PHA, hazardous events are based on a selection of ways to perform vessel operations. It should also be noted that I have assumed traditional net cages in the analysis, but certain events are relevant for other cages as well.

4.2.1 Categories for Consequence and Likelihood

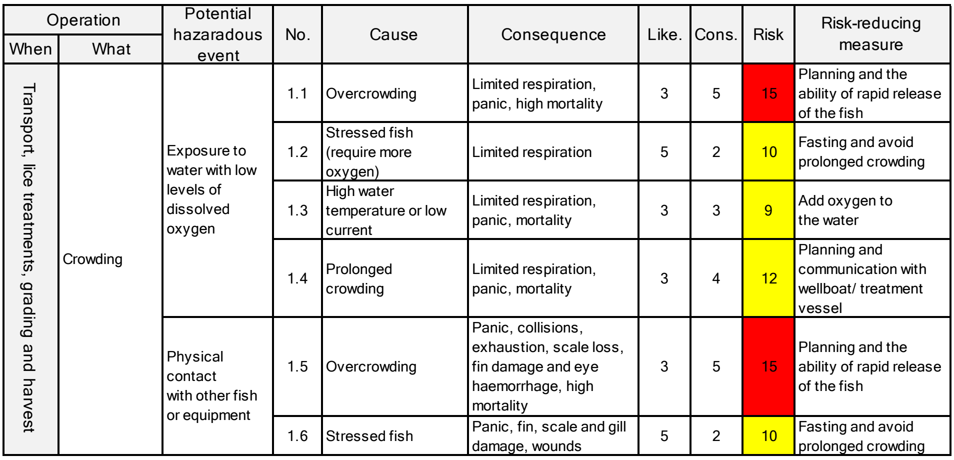
To quantify risk for salmon in vessel operations, likelihood and consequences are classified into the five categories listed in Table 4.1. Consequences are ranked by the extent of harm to the fish; from minor injuries to a severe increase in mortality rate. While likelihoods are based on how likely the triggering events are. The analysis targets harm from vessel operations that involve fish, either directly or indirectly. Hence, mortality and welfare challenges from other circumstances, such as diseases and lice counting, will not be considered in this section. Finally, a general method to evaluate risk is established, which in this case is a shared understanding of the risks we are willing to take. In the analysis, risk is divided into three types: unacceptable, tolerable and acceptable risk, which later are coloured red, yellow and green respectively.

Table 4.1: Categories for consequences and likelihood ranked from 1–5. Increase in mortality rate is given in percentage points.

Category	Consequence	Likelihood
5	Severe increase in mortality rate (≥ 2.5)	Almost certain
4	Significant increase in mortality rate (≥ 1.0)	Likely
3	Fish mortality	Possible
2	Serious fish injuries	Unlikely
1	Minor fish injuries	Rare

4.2.2 Structure of the PHA

In order to outline a representative sample, the PHA is structured into different welfare critical operations. The example of crowding is illustrated in Figure 4.2, and crowding usually takes place before pumping of fish into vessels. For the complete PHA, see Appendix A. The PHA is mainly based on the handbook by Noble et al. (2018), which indicates the welfare indicators that are threatened during different operations (see Appendix F.2 and G.2). For some events, research was limited, and then I have focused on published papers and current theories. For instance, studies with Sensorfisk in different pump environments have made quantifiable data available. However, it remains to be seen whether these results are applicable for real fish with other characteristics (Caharija et al., 2019).

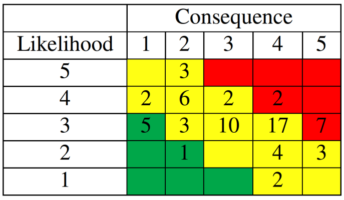


Operation		Potential hazaradous event	No.	Cause	Consequence	Like.	Cons.	Risk	Risk-reducing measure
When	What								
Transport, lice treatments, grading and harvest	Crowding	Exposure to water with low levels of dissolved oxygen	1.1	Overcrowding	Limited respiration, panic, high mortality	3	5	15	Planning and the ability of rapid release of the fish
			1.2	Stressed fish (require more oxygen)	Limited respiration	5	2	10	Fasting and avoid prolonged crowding
			1.3	High water temperature or low current	Limited respiration, panic, mortality	3	3	9	Add oxygen to the water
			1.4	Prolonged crowding	Limited respiration, panic, mortality	3	4	12	Planning and communication with wellboat/ treatment vessel
		Physical contact with other fish or equipment	1.5	Overcrowding	Panic, collisions, exhaustion, scale loss, fin damage and eye haemorrhage, high mortality	3	5	15	Planning and the ability of rapid release of the fish
			1.6	Stressed fish	Panic, fin, scale and gill damage, wounds	5	2	10	Fasting and avoid prolonged crowding

Figure 4.2: Structure of the PHA

4.2.3 Risk Situation for Farmed Salmon

The PHA reveals weaknesses with current procedures and contributes with insight for further technology development by suggesting risk reducing measures for salmon. Each event is placed in the risk matrix in Figure 4.3 and the cell figure represents the number of events with the given likelihood and consequence. The risk matrix indicates that nine events are in the unacceptable area and that most events are in the tolerable region. Nonetheless, one must consider the risks and evaluate if the operations safeguard the fish's health, or whether they should be improved. From the PHA, challenges are observed in several operations, specifically during crowding, smolt release and thermal lice treatments.



	Consequence				
Likelihood	1	2	3	4	5
5	🟨	🟨 3	🟥	🟥	🟥
4	🟨 2	🟨 6	🟨 2	🟥 2	🟥
3	🟩 5	🟨 3	🟨 10	🟨 17	🟥 7
2	🟩	🟩 1	🟨	🟨 4	🟨 3
1	🟩	🟩	🟩	🟨 2	🟨

Figure 4.3: Risk matrix with results from the PHA for farmed salmon.

It is also essential to consider the long-term effects of handling. Wounds and other types of skin damage increase the probability of secondary infections, although the damage might seem harmless initially. Besides, in the wintertime, there is a greater risk of developing winter ulcers, and wounds that do not heal as good in colder temperatures. Procedures that result in skin damage make the fish more prone to secondary infections and increase the risk of getting other diseases. The risk of obtaining secondary infections emphasize the importance of fish health before operations, and fish with preexisting wounds and infections should not undergo handling operations, as they may not tolerate the treatment.

An aspect that the PHA misses is the repeated handling which occurs during boat operations. The process of transferring fish from a net cage onboard a vessel is both time consuming for the crew and demanding for the fish, and crowding has proved to be a critical operation. If a fish is injured or has reduced health at this stage, it will be less fit to handle stress in the subsequent procedures. Repeated handling is also relevant when considering all operations that the fish encounters during the production cycle. In terms of boat operations, this starts with smolt release and ends with harvest and slaughtering. Still, it remains uncertain how repeated handling in vessel operations affect the fish, which I choose to study closer.

This thesis explores a new area within marine engineering, and the preliminary work in the PHA is essential. Based on the risk analysis, I want to continue with challenges that involve repeated delousing operations and investigate both economic consequences and health effects on salmon from vessel operations. For this reason, I decide to move forward with a simulation model to produce new insight into the topic of salmon encounters with vessel operations.

4.3 Simulating the Salmon Production Cycle

A discrete event simulation model of the production cycle is developed, and consequences from vessel operations are considered. The simulation model includes the variables and parameters mentioned in Figure 4.4 and is constructed to follow the production from smolt release to slaughter. With a generic model, various farming strategies can be tested in the same model by adapting the input. The purpose of the model is to quantify side effects of vessel operations, which include treatment mortality, reduced health status and biomass loss from starving. Moreover, results from the model are applied in a cost benefit analysis (CBA), in order to estimate net benefits and determine whether strategies with better welfare are profitable for farmers.

The developed model simulates a production at a given location and can test different farming strategies. The aim is to be able to predict the outcomes of vessel operations before they are realised. Fish populations are modelled with a given quantity and stochastic health status. These populations are released into a modelled sea cage environment at the same time, where growth and natural mortality is estimated daily. Further, the outcome from vessel operations is determined based on the fish's health and body mass, starving days, treatment type and the environmental condition at the site. Historical sea temperatures are obtained from BarentsWatch and implemented in the model. Hence, the modelled environment provides an accurate weather representation, including seasonal variations.

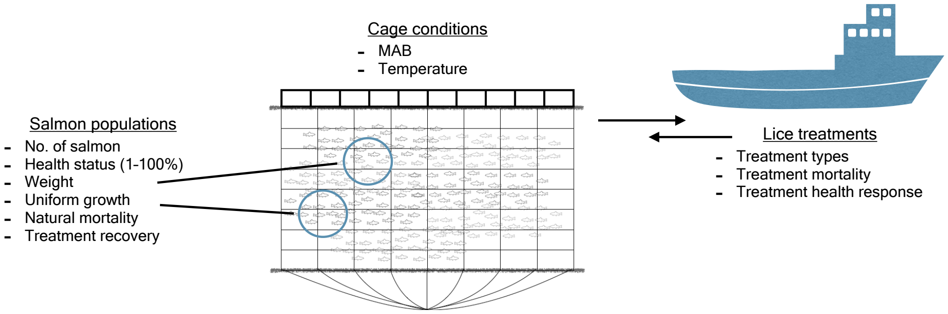


Figure 4.4: System description of the established simulation model

4.3.1 Case Studies

For the simulation model to be of value, a case study of different farming strategies are conducted. Farming strategies can vary a lot depending on the whereabouts of the locality, but does in the following consist of the combination of lice treatments, smolt size and starvation days before vessel operations (Table 4.2). Thus, three parameters can be changed to form scenarios different from a baseline scenario.

Table 4.2: Overview of strategies applied in the case study

Scenario	Description
Baseline	No changes in reported farming strategy
T	Number of lice treatments
S	Smolt size in grams
D	Starving days

In order to establish baseline productions, managers of ten different sites were contacted. The sites were selected through BarentsWatch, as they had complete reports of temperatures and mainly used mechanical delousers. The requested information included production mortality, treatment strategies and transportation distance to the set fish facility. However, it turned out to be challenging to receive the information of interest. Due to lack of data, transport operations were disregarded, and it was decided to focus on effects from reported lice treatments on BarentsWatch and effects from feed withdrawal.

Despite the issue with data collection, project manager R. Mathisen from Nordlaks Oppdrett provided the requested data for a locality in Troms. The locality referred to is Elgen, and is located within a yellow marked production area, which indicates no immediate change in future production permits. To study another site that is more prone to salmon lice and administers more treatments, Juvika B is also selected. Juvika B lies within a red production area, and authorities may restrict further production unless the locality can point to low lice levels on wild salmon. In the baseline productions, assumptions for smolt release and sea cages are made based on specifications obtained from BarentsWatch, augmented with the received data from R. Mathisen. An overview of the baseline productions at Elgen and Juvika B is presented in Table 4.3.

Elgen belongs to the production area Andøya to Senja, and the last production started in the summer of 2018 with harvest in late 2019. The smolt release took place from June 15th to August 7th, where 392,691 smolt with an average weight of 125 grams were released from June 15th–18th, while 600,691 smolt with an average weight of 64 grams were released between the 6th and 7th of August. From a total of 993,382 salmon, 73.304 died during production. The locality has a MAB of 3.120 tons, and it is assumed that six cages with a circumference of 120 meters are used. In the model, smolt from the second release are simulated, and 166,000 salmon are released into the cage in early August 2018, and harvested in week 50, 2019.

Juvika B is located in Nordfjord in the north of Vestland county and belongs to the production area Nordhordaland to Stadt. The site is chosen due to frequent mechanical lice treatments and consistent reporting of both treatments and sea temperatures. Juvika B has a MAB of 5,460 tons, and it is assumed that six cages with a circumference of 157 meters are used and that 180,000 smolt of 60 grams are released into each cage. The reports from BarentsWatch begin in the autumn of 2018 and end in spring 2020. In the baseline production, small smolt are used so that they receive all reported treatments before a harvest weight of 6 kg is reached. MAB per cage is based on Norwegian volume restrictions for farmed salmon in cages with depths of 20 meters, (NFSA and NDF, 2010).

Table 4.3: Overview of the baseline productions Elgen and Juvika B

	Elgen	**Juvika B**
MAB for locality	3,120 tons	5,460 tons
No. of cages	6	6
Cage circumference	120 m	157 m
MAB per cage	573 tons	981 tons
No. of salmon per cage	166,000	180,000
Smolt size	64 g	60 g
Lice treatments	2	7
Starving days	3	3
Reported mortality	7.4%[a]	16%[b]
Production start	week 32 2018	week 38 2018
Time of harvest	week 50 2019	week 11 2020

[a] Production mortality reported by R. Mathisen, Nordlaks Oppdrett

[b] Median mortality in Sogn and Fjordane in 2019 (NVI, 2020)

Management strategies and scenarios

With adjustments in treatments, smolt size and starving days, three case studies are derived. In case 1 and 2, I want to investigate ways of avoiding lice treatments either by making treatments unnecessary or by releasing larger smolt to shorten the production time. The first case attempts to find the savings with fewer treatments, and thus the price site managers should be willing to pay to avoid one or more treatments. It is assumed that treatment mortality decreases, while harvest weight increases. To clarify, released funds can be used in a preventative manner, for example, by investments in lice skirts or other measures that do not require excessive handling of salmon. Alternatively, in periods with repeated treatments, which suggest that one delousing operation was unable to reduce lice levels sufficiently, farmers could instead purchase a more efficient delouser and possibly avoid the second treatment.

Another way to avoid lice treatments is to use larger smolt and thereby shorten the time to reach a given harvest weight. In the second case, different smolt sizes are tested while the harvest weights at both Elgen and Juvika B are kept constant. After testing the simulation model with various smolt sizes, the weights that reduce treatments are shown in Table 4.4. Finally, multiple scenarios are tested in the third case, with 1–6 days of feed withdrawal before vessel operations, and a range of delousing operations with 0–2 operations at Elgen and 0–7. By simulating body mass and mortality, operators can keep track of standing biomass and not exceed MAB, and this makes it feasible to predict slaughter weight and production time.

Table 4.4: Overview of strategies applied in the case study at Elgen and Juvika B

	Case 1		**Case 2**		**Case 3**	
Locality	**Elgen**	**Juvika B**	**Elgen**	**Juvika B**	**Elgen**	**Juvika B**
Treatments	1	6, 5	-	-	0–2	0–7
Smolt size	-	-	130, 200	70, 100, 170, 225	-	-
Starving days	-	-	-	-	1–6	1–6

4.3.2 Cost benefit Analysis

The results from the simulated scenarios are used in a cost benefit analysis (CBA), and net benefits are estimated compared with the baseline scenarios. CBA is a method used for evaluating decisions, where, for instance, the benefits of taking action is compared against the associated costs (Kenton, 2020). As a result, this thesis combines a CBA with the case study to illustrate the economic effects of choices that affect lice treatment operations. The analysis covers the farmers' role in the value chain, from smolt release and until slaughter, and considers how various strategies for delousing, smolt weight and starvation period affect their end product.

The production costs of Atlantic salmon continue to rise, and increased feed costs and costs for monitoring, prevention and treatment of lice are some of the reasons (Iversen et al., 2019). The development of production costs from 2001–2018 is shown in Figure 4.5 and the nominal value has more than doubled since 2005. Feed costs still account for about 50% of the production costs and have the biggest increase in NOK per kg. Even if the cost rise has declined in recent years, expenses should be evaluated to make production more profitable.

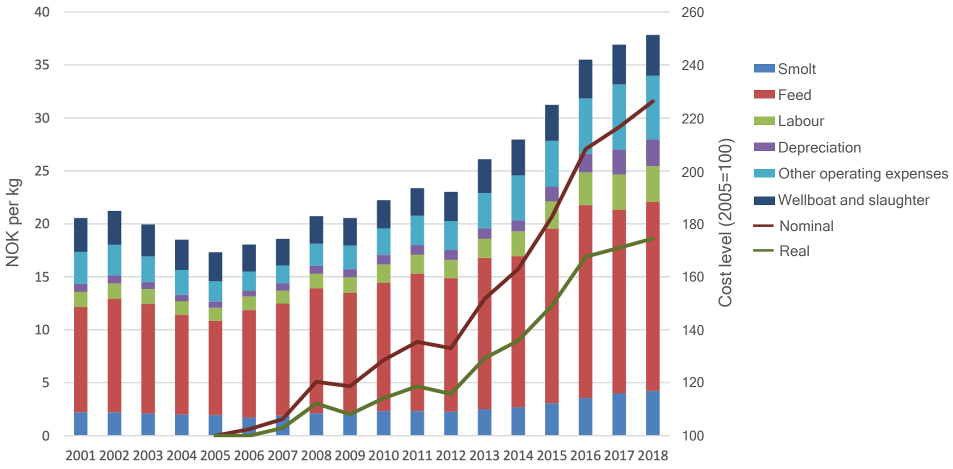


Figure 4.5: Cost development since 2005, with the nominal price per kilo for processed fish from 2001–2018, translated from Iversen et al. (2019) with data from Kontali Analyse and SSB.

According to Iversen et al. (2019), costs for control, prevention and treatment of lice amount to 4 NOK per kg slaughtered salmon, which is a fourfold increase over the last decade. With the same model, it is estimated that the whole industry pays more than 5 billion a year due to salmon lice, even if the effects of lost biomass growth are excluded. Further, Rødseth (2016) states that the indirect costs from lost biomass are grossly underestimated. By looking at changed feed factors from 2012 to 2015 and national feed consumption in 2015, Rødseth (2016) estimated that the industry missed 100,000 tonnes slaughtered salmon in 2015, or 10% of Norwegian production in 2015.

Biomass loss from mortality and starvation increases the economic feed conversion ratio (EFCR) of salmon, which is the amount of feed used per kg slaughtered fish. There is also a biological feed conversion ratio (BFCR), which is the amount of feed per kg fish produced, and according to Skretting, the largest producer of feed for farmed fish in the world, salmon need 1.15 kg of feed to gain 1 kg. A low FCR indicates efficient food production, and the BFCR has decreased by 15–20% over the past decades (FHL, 2009), while the EFCR continues to rise. Pettersen (2016) found that the average weight of dead fish went from about 900 grams to almost 1800 grams in salmon generations harvested from 2008–2014, and this partly explains why the EFCR increases. Besides, a study by Einen et al. (1998) found that only a few days of starvation cause a weight reduction, and this is further explained in Section 5.2.2.

Income estimate

Each run or scenario results in a number of harvested salmon with an average weight, and by multiplication harvested biomass is found. Most of the salmon from Norway is sold head on, gutted (HOG) to customers in the EU for further processing (Olafsdottir et al., 2019). Live weight is converted to HOG by dividing by a conversion factor of 1.2. Further, HOG is denoted as gutted weight equivalents (GWE).

Since the salmon price fluctuates between seasons, and also from year to year, an index for salmon prices is used, and sales prices are obtained from the NASDAQ Salmon Index. The NASDAQ Salmon Index reflects the sales price of fresh salmon to exporters and provides spot prices for salmon from 1-9 kg (GWE). Because of a highly volatile price in the last year, income is estimated based on the average sales price, from week 39 2017 to week 38 2020. Also, according to Mathisen (2014), the sales price to breeders is 1.45 NOK lower than indicated by the NASDAQ index, due to sales and administration costs in addition to freight and terminal costs. Thus, resulting prices range from 43.02 NOK for 1–2 kg salmon to 60.80 NOK for 5–6 kg.

In addition to income from harvested salmon, the lost potential income from mortality is estimated throughout the production. Pettersen et al. (2016) looked at the possibility of selling salmon below 1 kg (GWE), but after contacting production managers from the largest firms in Norway, they found it unlikely. None of the baseline productions have harvest weights below 1 kg, but potential income from lost salmon initiates when the gutted weight passes 1 kg.

Cost estimate: production

Production costs are assumed to increase proportionally with the standing biomass. Table 4.5 presents production costs for both round and live weight, where round weight is the same as whole fish equivalents (WFE). In the model, live weight costs are applied throughout the production cycle. This representation does not capture effects from various production strategies. However, for lost biomass growth and changes in the EFCR, this representation is considered sufficient. Besides, the smolt cost is treated separately in the following section.

Table 4.5: Average reported costs per kg produced salmon, excluding smolt cost. The conversion factor from live weight to round weight after starvation and bleeding is 1.067. Costs are based on average numbers per company in Norway for 2018, (NDF, 2020).

	Round weight - 1 (NOK)	**Live weight - 1.067 (NOK)**
Feed per kg	14.15	13.26
Insurance cost per kg	0.15	0.14
Labour cost per kg	2.80	2.62
Depreciation per kg	2.19	2.05
Other operating expenses	7.24	6.79
Net financial cost per kg	0.12	0.11
Production cost excl. smolt per kg	26.65	24.97
Slaughter cost incl. transport per kg	3.79	3.55
Sum cost excl. smolt per kg	30.44	28.52

Cost estimate: smolt

Historically, the smolt costs have more than doubled since 2006. The cost increase is associated with changes in smolt production, with a transition to larger smolt and more investments in recirculating aquaculture systems (RAS) which replace flow through systems (Iversen et al., 2018). Further, with larger smolt and lower harvest weights, the smolt cost represents a larger share of the costs. Cost of smolt is also available in per kg produced salmon, and is 3.44 NOK per kg (WFE) (NDF, 2020). However, it is more accurate to specify the unit cost for smolt, and this is supported by varying costs for different smolt weights, as illustrated in Table 4.6. Besides, since I only found costs and not selling prices, it is assumed that the farmers can produce smolt. In the cost estimates, smolt is purchased at the beginning of the production.

Table 4.6: Estimated cost per smolt in NOK for three weights, 95–100, 200, and 500 grams, (Iversen et al., 2018), including a smolt cost per kg live weight based on a harvest weight of 5 kg.

	95–100 g (NOK)	**250 g (NOK)**	**500 g (NOK)**
Roe	1.50	1.50	1.50
Feed	1.50	3.30	6.90
Labour	2.00	3.20	5.20
Vaccine (incl. admin)	2.25	2.25	2.25
Energy	0.40	0.90	2.00
Other operating expenses	1.75	2.85	5.25
Depreciation	1.20	2.20	3.00
Interest rates	0.60	1.20	1.60
Transport to locality	0.30	0.50	0.80
Estimated cost per smolt	11.50	17.90	28.50
Smolt cost per kg	2.3	3.58	5.7

To estimate the cost of a smolt size between those listed in Table 4.6, linear interpolating is used. The formula in Equation 4.1 is then completed with costs and weights of the neighbouring sizes to find the unknown cost.

$$c = \frac{c_2 - c_1}{w_2 - w_1}(w - w_1) + c_1 \tag{4.1}$$

For smolt smaller than 95 grams, the estimate in Equation 4.2 is used (Stephansen, 2015), where c is smolt cost and w_s is smolt weight in grams. The formula is adapted to meet the price of 95–100 g smolt in Tab. 4.6. However, the smolt costs are from 2018, so there is a chance that they are underestimated. If so, the estimated cost will be lower than the real ones.

$$\mathrm{c} = 6 + 0.04 \cdot w_s \cdot 1.375 \tag{4.2}$$

With attention to mortality during the cycle, economic losses are calculated based on the lost biomass, and include feed, labour and other operating expenses, in addition to smolt cost and a income loss, which is deducted for the slaughter cost. In contrast, production costs for harvested salmon incorporate the total amount of 24.07 NOK per kg, while the slaughter cost is subtracted from the income.

Chapter 5

Simulation Model

In the following chapter, I describe how the modelled cage environment in Figure 5.1 is developed. While the economics was explained in the previous sections, this chapter focuses on the biology of the modelled salmon and the external conditions that affect it. The modelled growth and growth loss from starving are based on existing literature. In contrast, the biological characteristics of health status and salmon mortality are based on my assumptions regarding the salmon, which are supported by ongoing research when it comes to natural mortality.

The established model is constructed to simulate the production from smolt release to harvest, and includes encounters between the salmon and vessel operations. The model is created in Simulink, which is an add-on to MATLAB. Moreover, the simulation model is ran from MATLAB, and after the simulation the results are post processed further in MATLAB to prepare the cost benefit analysis. The reported data from the localities Elgen and Juvika B were implemented by separate scripts in MATLAB, and the main script for Juvika B, is included in Appendix B.1.

Salmon populations of a thousand fish are released into a cyclic loop, where the fish is fed daily in the ”Growth” block. Growth is estimated based on the current sea temperature. It is a discrete event model, so only generated events will cause state transitions. The usual growth loop is interrupted when the fish have reached harvest weight, maximum allowable biomass, or if it is time for a prescheduled delousing operation. Before treatments, a fasting period entails which negatively affect salmon growth. Moreover, the treatments are modelled to harm the salmon, and either directly by increased mortality, or indirectly by reduced health.

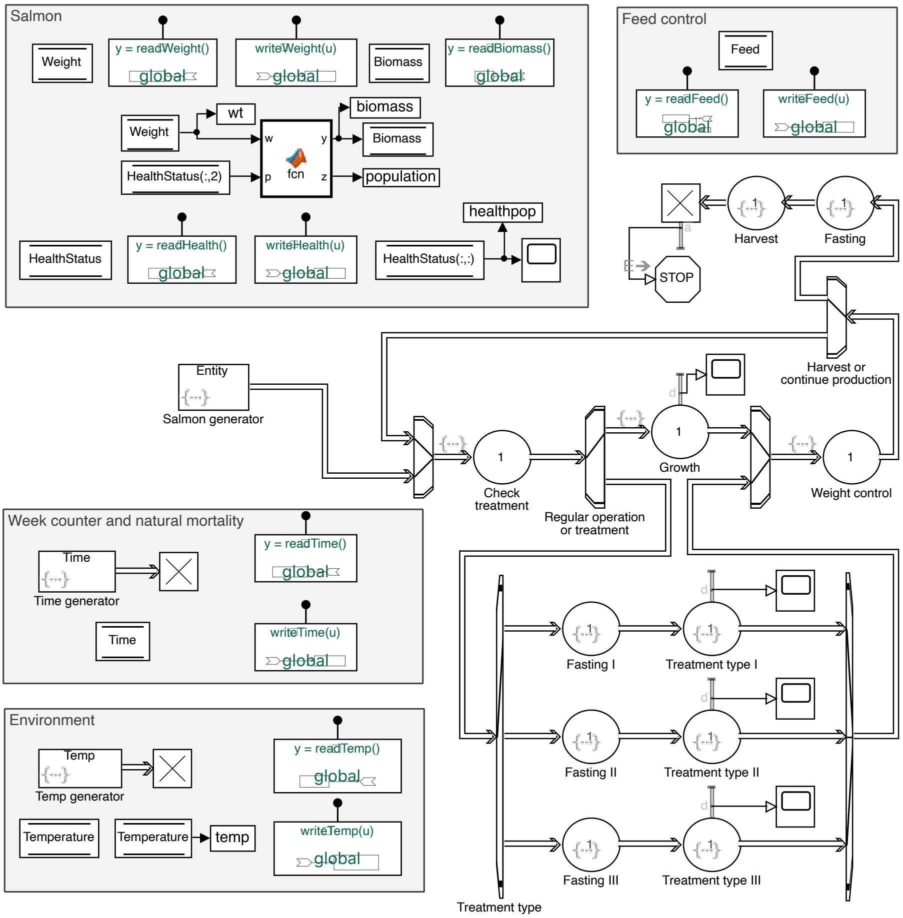


Figure 5.1: Established simulation model in Simulink

5.1 Modelled Environment

In aquaculture, the salmon are usually kept in sea cages for about 1.5 years before harvest (Pettersen et al., 2016), which leads to seasonal variations, as well as regional differences in the environment. According to Mowi (2019), salmon farming is optimal in temperatures from 8–14 °C, and growth and effects from feed withdrawal are both affected by sea temperatures. Generally, higher temperatures lead to better growth, but also diseases become more prevalent when the temperature rises. In the modelled baseline scenarios, historical sea temperatures are collected from BarentsWatch and updated daily. As a result, the model includes variations in growth and starvation, and also varying outcomes from lice treatments. The following sections present in detail how the temperature affects the mentioned conditions.

5.2 Modelled Salmon Population

The entire salmon stock is modelled with an initial weight, being the weight of the smolt, and the amount of fish. Moreover, the stock is divided into smaller populations of a thousand fish, and each population has an individual health status that is generated before the simulation. The health status of each population is an independent random variable with a uniform distribution from 1 to 100%. In the model, the health status is affected by delousing operations, and the impact depends on current health status, treatment type and sea temperature. Throughout the production, the fish size increases, while the fish amount decreases except for periods with feed withdrawal, where a weight loss is modelled. Weight gain is a function of current salmon size and the ambient sea temperature, while modelled salmon mortality is explained separately in Section 5.3.

5.2.1 Salmon Growth

The growth rate of salmon is size dependent and strongly affected by factors like temperature, access to feed and day length (Thorarensen and Farrell, 2011). There are several ways to predict salmon growth, and some of the most common models include specific growth rate (SGR), thermal growth coefficient (TGC), the Ewos growth index (EGI), and average daily weight gain (ADG). Aunsmo et al. (2014) validated these four models by comparing them with 827 real groups of Atlantic salmon and found the EGI to be the most robust method for fish of various size being exposed to different abiotic factors like temperature and light. In contrast, SGR biased towards small fish when the cage consisted of varying sized fish (Aunsmo et al., 2014). However, the scenarios used in the case study utilise smolt of equal sizes, and thus the SGR metod is assumed appropriate and is applied in the model.

SGR decreases with increasing fish weight and is strongly affected by sea temperature.

An increase in temperature generally boosts the appetite of fish and consequently SGR increases, but only to a given optimum, where after this point SGR diminish (Thorarensen and Farrell, 2011). SGR is calculated as in Equation 5.1, where w_1 and w_2 are salmon weights at time t_1 and t_2, respectively.

$$\text{SGR} = 100 \cdot \frac{ln(w_2) - ln(w_1)}{t_2 - t_1} \tag{5.1}$$

Thus, with established SGR values, growth estimates are feasible with the formula in Equation 5.2.

$$w_2 = w_1 \cdot e^{\text{SGR} \cdot (t_2 - t_1)/100} \tag{5.2}$$

Forsberg (1995) derived an expression for daily SGR which excludes the time domain, see Equation 5.3. This model is limited for temperatures between 4 and 14 °C and body mass from 50 g to 3 kg. Figure 5.2 presents the SGR curves for three temperatures, 4, 10, and 14 °C, and demonstrates the mentioned relationships between SGR, size and temperature.

$$\text{SGR} = 0.97 \cdot T^{0.97} \cdot w^{-0.34} \tag{5.3}$$

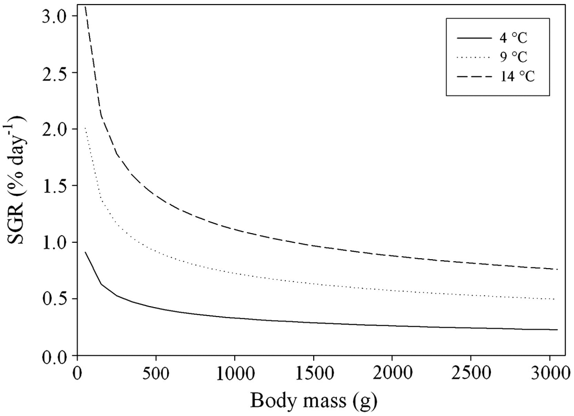


Figure 5.2: Specific growth rates (SGR) of Atlantic salmon at 4, 10 and 14 °C, (Forsberg, 1995)

In order to predict growth rates for fish above 3 kg, the model utilises a relative growth index (RGI) table for Atlantic salmon, which presents SGR based on daily growth estimates for a given weight and sea temperature. The RGI table is valid for fish sizes in the range between 35 g and 13 kg and temperatures from 2–15 °C, and was obtained after correspondence with Næstvold (2020). As a result, the daily growth of salmon is estimated by the following formula:

$$w_2 = w_1 \cdot \frac{\mathrm{SGR}(w_1, T)}{100}, \tag{5.4}$$

where SGR = $f(w_1, T)$, and is retrieved from the RGI table in Appendix C. The script utilised in Simulink for modelled growth is attached in Appendix B.2.

5.2.2 Reduction in Biomass from Feed Withdrawal

Starving is practised before handling operations in order to reduce fish metabolism and to empty the gut. According to Mørkøre et al. (2008), feed withdrawal leads to lower harvest weight but does not cause a remarkable weight loss. However, a study on starvation before slaughter found effects from starving versus feeding fish for 0, 3, 7, 14, 30, 58 and 86 days, and the case of 86 days found that starvation led to an 11.3% weight loss, while the control group had an increase of 26.3% (Einen et al., 1998). From the study by Einen et al. (1998), Mørkøre (2008) derived the graph in Figure 5.3, which is also expressed by Equation 5.5.

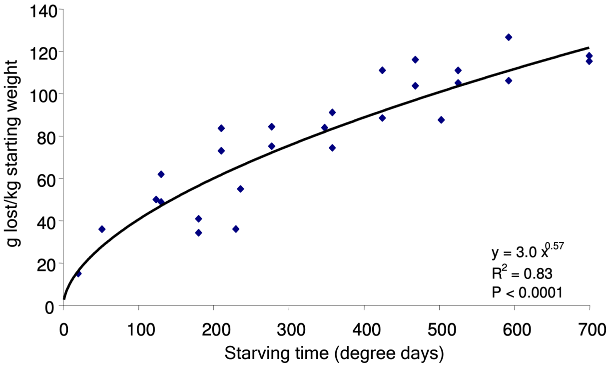


Figure 5.3: Weight loss in g/kg starting weight for Atlantic salmon, (Mørkøre, 2008)

Both studies indicate that starvation reduces body weight and that only some days of feed withdrawal lead to a significant weight reduction. In the simulation model, a fasting period entails before delousing operations and harvest, and the weight loss is estimated by Equation 5.5. Estimates of EFCR are also included in all simulations to measure the feed utilization, and based on the assumption that salmon need 1.15 kg feed to gain 1 kg, the best possible EFCR would be 1.15 with no mortality and no starving days.

$$\frac{\text{g loss}}{\text{kg starting weight}} = 3 \cdot (\text{starving days} \cdot \text{sea temperature})^{0.57} \tag{5.5}$$

5.3 Prediction of Salmon Mortality

Scientists aim to find standardized models for mortality in salmon farming Tvete (2020), but given the complexity of this, I have created a simplified approach. As a result, mortality is divided into two main components, one that covers natural causes like diseases and low smolt quality, and mortality from delousing operations. Mortality from natural causes is evenly distributed over the populations, while mortality from lice treatments depends on fish health status, treatment type and sea temperature.

5.3.1 Natural Causes

A background mortality is established based on ongoing research from the Norwegian Computing Center, which was presented by Ingunn F. Tvete at the conference ”Havbruk 2020”. The study is based on data from Grieg Rogaland, Lerøy and Bremnes, and Tvete (2020) has developed a generalised additive model (GAM) for mortality. The GAM function contains non-linear expressions, given by splines functions and multiple input variables. After corresponding with Tvete, she shared their preliminary predictions of mortality. The received data applies to the first 500 days after release, for a theoretical normal state with a temperature of 10 °C, 30 psu salinity and no lice treatments or PD (see Appendix D).

The populations will act according to the predicted mortality, so the amount of fish decreases throughout the production. With the model from Tvete (2020), 13.5% died after 500 days, as illustrated in Figure 5.4. However, some productions have lower overall mortality rates, so for this reason, natural mortality is customized for the baseline productions. By multiplying the daily loss with a factor c, the background mortality is tuned to a reasonable level that matches the reported mortality rates at the selected sites, and c=0.4 at Elgen whereas at Juvika B, c=0.6.

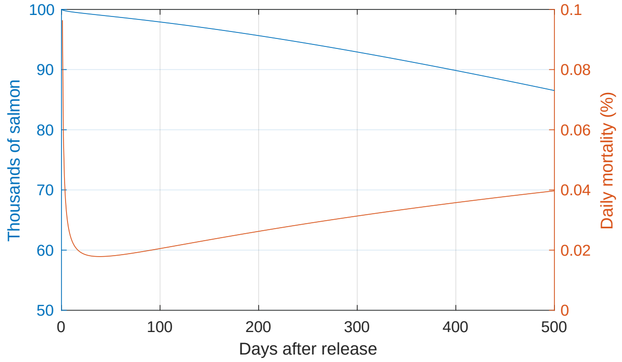


Figure 5.4: Simulated mortality with a release of 100,000 salmon, given a temperature of 10 °C, salinity of 30 psu, and no lice treatments or PD, based on predictions from Tvete (2020).

5.3.2 Mortality and Recovery from Delousing Operations

Treatment mortality can occur either directly to individuals or indirectly by reduced health status. Indirect deaths happen when the health status of a population reach 0%. The response from delousing operations is modelled by differentiating on salmon health status. Health is categorized into five groups, as shown in Table 5.1, and presents x_i and y_i for each group, which indicates how different groups respond to treatments. The parameter α denotes the severity of the harm caused by the treatment, while β describes the fish's ability to recover after treatments. Also, α and β are equal for all populations, but α depends on treatment type and the present sea temperature.

Table 5.1: Health response and recovery for populations of salmon, divided by health status

Health status	Group no.	x_i	y_i	Treatment response	Health recovery
81–100	1	1	1	$\mathrm{x}_1\alpha$	$\mathrm{y}_1\beta$
61–80	2	1.2	0.9	$\mathrm{x}_2\alpha$	$\mathrm{y}_2\beta$
41–60	3	1.4	0.8	$\mathrm{x}_3\alpha$	$\mathrm{y}_3\beta$
21–40	4	1.6	0.7	$\mathrm{x}_4\alpha$	$\mathrm{y}_4\beta$
1–20	5	1.8	0.6	$\mathrm{x}_5\alpha$	$\mathrm{y}_5\beta$

The treatment response and health recovery from Tab. 5.1 must be viewed together with the following equations, where q is the number of salmon and h is the health status.

$$q_2 = q_1 \cdot (1 - x_i\alpha) \tag{5.6}$$

$$h_2 = h_1 - x_i\alpha \cdot 1000 \tag{5.7}$$

$$h_2 = h_1 + y_i\beta \cdot 1000 \tag{5.8}$$

For the subscripts, 1 denotes the state before the treatment, while 2 is the resulting state after the treatment. In the model, Equation 5.6 and 5.7 are performed to all populations right after delousing operations. In contrast, recovery after treatments is modelled two weeks later, which is done according to Equation 5.8 (see Appendix B.3 and B.4). Besides, populations can never obtain health over 100%. Given these points, populations with poor health in the first place will handle treatments worse, as they are modelled with higher values of x_i and lower of y_i.

Table 5.2: Parameters used for simulating response after lice treatments: α_1=0.0005, α_2=β=0.0007, α_3=0.0009 and α_4=0.0011.

Temperature (°C)	Treatment 1	Treatment 2	Treatment 3
4–7	α_3	α_1	α_1
7–10	α_3	α_3	α_1
10–13	α_2	α_3	α_2
13–16	α_4	α_2	α_2

Three lice treatments are chosen, and the harm caused to salmon is expressed in four α values, 4 being the most severe. The assumptions for placement of the parameters in Table 5.2 are based on reported mortality from 2015–2017, despite treatment 3, which had data all the way from 2012 (Glover K et al., 2018). Mortality was given as an increase in %-points for the same temperatures as in Tab. 5.2 and the mean value is used to estimate expected values for treatment mortality. Then expected mortality is used to determine the placements for the four α parameters (See Appendix E). Finally, α values are tuned to match reported mortality at the selected localities, and equal treatment parameters are set at both locations.

Chapter 6

Salmon Encounters with Delousing Operations

The established model has been tested for two chosen localities, Elgen and Juvika B, which are located in the counties of Troms and Vestland, respectively. The model is based on the previous production cycles at these localities, and the baseline scenarios utilised the reported management strategies at these localities, as described in Chapter 4. The baseline production at Juvika B had seven delousing operations and was used to demonstrate the modelled effects from repeated handling of salmon. After the baseline scenarios were established, a variety of scenarios were tested in a case study. Meanwhile, the simulations results were used in a cost benefit analysis to estimate the net benefit of different management strategies.

6.1 Establishing Baseline Scenarios

Baseline scenarios were established based on the management strategies in Section 4.3.1, with sea temperatures and treatment regimens retrieved from BarentsWatch. Salmon populations of one thousand fish have a modelled health based on a uniform distribution from 1–100%. The health status of each population is affected throughout the production by delousing operations. Through testing of the model in the following sections, each run renewed the initial health status, making it a realization of the stochastic process. In contrast, the case study (Sect. 6.2) is dependant on a reproducible output. To achieve this, a single run is selected from each locality for further use.

6.1.1 Locality: Elgen

The simulated results from five realisations at Elgen are shown in Table 6.1. Due to historical temperatures and the same smolt size, all runs had a harvest weight of 3.46 kg, resulting in a gutted weight below 3 kg. The mean number of harvested salmon was 153,668 per cycle, with an average produced biomass of 532 tons (WFE). Run 1 had results that were close to these average values, which also best represented the reported values at the real production at Elgen. Thus, run 1 was selected for further research and is referred to as the baseline scenario at Elgen. This involves that the initial health status for the 166 populations released at Elgen, was stored corresponding to the generated input.

Table 6.1: Five realizations of the production cycle at Elgen

Run	Harvest weight	No. harvested	Biomass (WFE)	EFCR	Mortality
1 (baseline)	3.46 kg	153,290	531 tons	1.23	7.7%
2	3.46 kg	155,173	537 tons	1.22	6.5%
3	3.46 kg	156,110	540 tons	1.22	6.0%
4	3.46 kg	151,414	524 tons	1.24	8.8%
5	3.46 kg	152,352	527 tons	1.23	8.2%

The development of salmon weight and quantity are presented in Figure 6.1. With a production time of almost 73 weeks, a maximum weight of 3.5 kg was reached. Further, the harvest weight was reduced to 3.46 kg due to three starvation days before all vessel operations, including harvest. The baseline scenario obtained an average dead fish weight of 1.20 kg and an EFCR of 1.23. In addition, the production mortality was 7.7%, and mortality from treatments amounted to 1.9%, while the remaining deaths were due to natural causes. The mortality peaks in Fig. 6.1 indicates the two delousing operations.

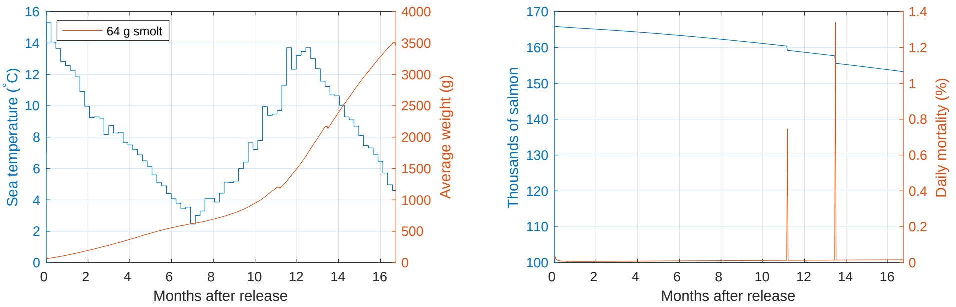


Figure 6.1: Sea temperature, salmon weight, population and daily mortality throughout the baseline production cycle at Elgen

6.1.2 Locality: Juvika B

The results from Juvika B are presented in Table 6.2. All runs had a harvest weight of 5.91 kg, which resulted in a gutted weight just below 5 kg. The mean number of harvested salmon was 150,450 per cycle, with an average produced biomass of 889 tons (WFE). Run 4 was most alike the average values, and at the same time close to the reported mortality of 16%. For this reason, run 4 was chosen for further investigation in the case study, and the health of the 180 populations released at Juvika B was stored (see Fig. 6.3 t_1).

Table 6.2: Five realizations of the production cycle at Juvika B

Run	Harvest weight	No. harvested	Biomass (WFE)	EFCR	Mortality
1	5.91 kg	148,786	879 tons	1.43	17.3%
2	5.91 kg	153,321	906 tons	1.40	14.8%
3	5.91 kg	149,750	885 tons	1.42	16.8%
4 (baseline)	5.91 kg	150,641	890 tons	1.41	16.3%
5	5.91 kg	149,751	885 tons	1.42	16.8%

In the baseline scenario, the seven delousing operations over the course of 80 weeks resulted in a mortality of 16.3%. Natural mortality accounted for 9.6%, which means that out of the 29,359 salmon that died, about 60% died from natural causes. Delousing operations triggered a reduction of health, and also a direct mortality which alone added up to an average of 172 salmon per delousing operation. The development of salmon weight and quantity is shown in Figure 6.2. All delousing operations occurred after 12 production months, which resulted in an average dead fish weight of 2.58 kg and an EFCR of 1.41. Additionally, lice treatments led to losses in produced biomass and peaks in daily mortality.

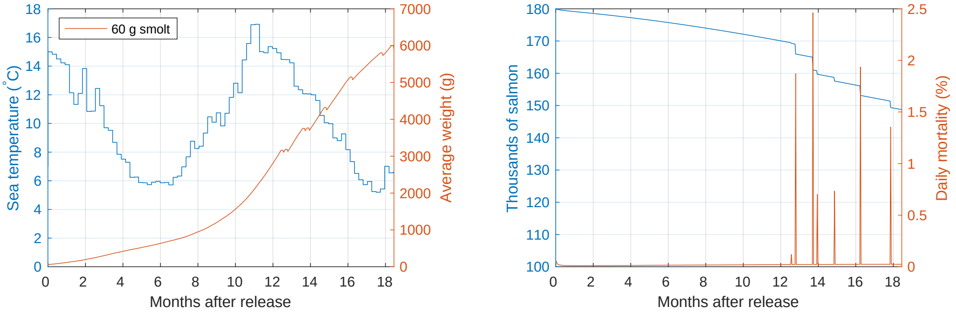


Figure 6.2: Sea temperature, salmon weight, population and daily mortality throughout the baseline production cycle at Juvika B

6.1.3 Repeated Handling of Salmon

To demonstrate how delousing operations affected salmon health at Juvika B, the health distribution is given at six points in Figure 6.3. A total of 180 populations were released with individual health statuses, being an independent random variable with a uniform distribution in the interval 1–100%. The initial health distribution for the baseline production is shown at time t_1. After seven delousing operations 14 populations had a health status below 1%. Twelve populations reached 0% health and died due to poor health before delousing operations. From the fourth treatment and until harvest, the number of populations with 0% health went from 8 to 12. This indicates that the first four treatments had a worse effect on salmon health per treatment than the last three treatments.

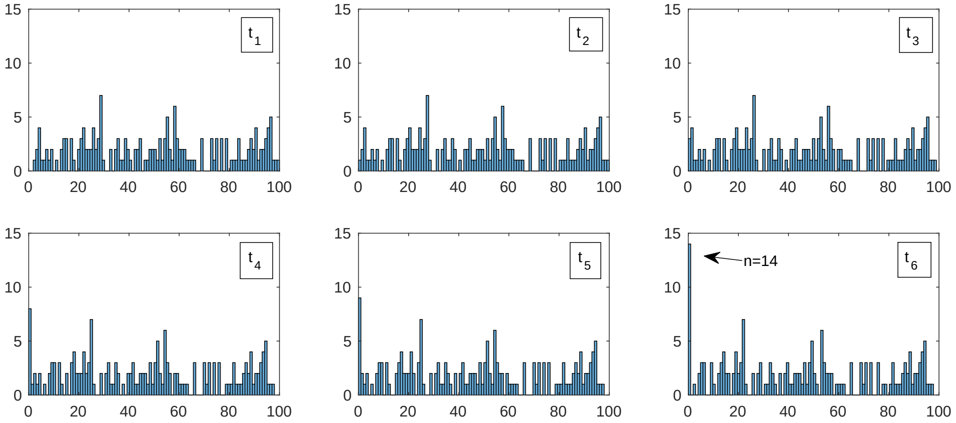
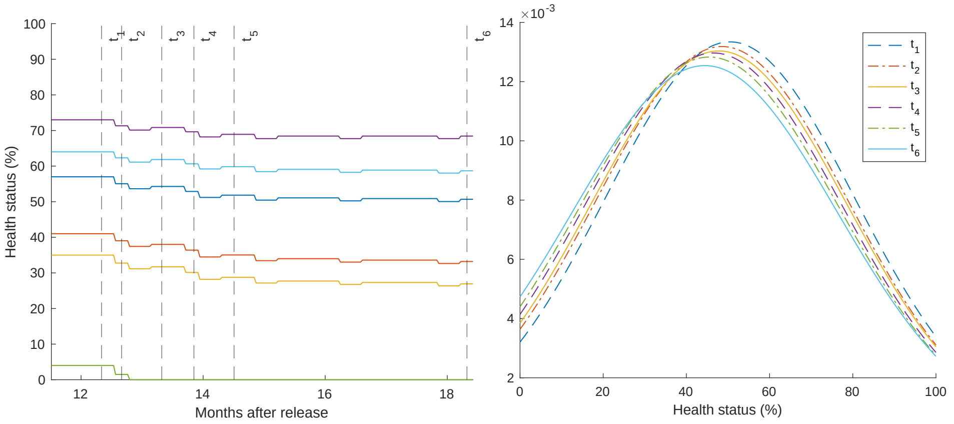


Figure 6.3: Illustration of health status distributions for the 180 populations released at Juvika B at six points: smolt release , after treatment 1–4, and at harvest. x-axis = health status, y-axis = number of salmon populations.

The production at Juvika had two cases where treatments were performed at intervals of one week. These cases occurred between treatment 1 and 2, and 3 and 4. As shown in Figure 6.4(a), the populations did not recover after the first and third treatment. This is illustrated by a drop in health two times in a row, before the populations recovered after a treatment break of two weeks. The displayed population with the lowest initial health reached 0% health and died after the second delousing operation. With attention to the whole cage, the health statuses were fitted to a Gaussian distribution and are given at six times in Figure 6.4(b). The mean health went from 51.1 to 46.0% during the baseline production, and populations with an initial health status of less than or equal to 8% did not survive until the end of the production.

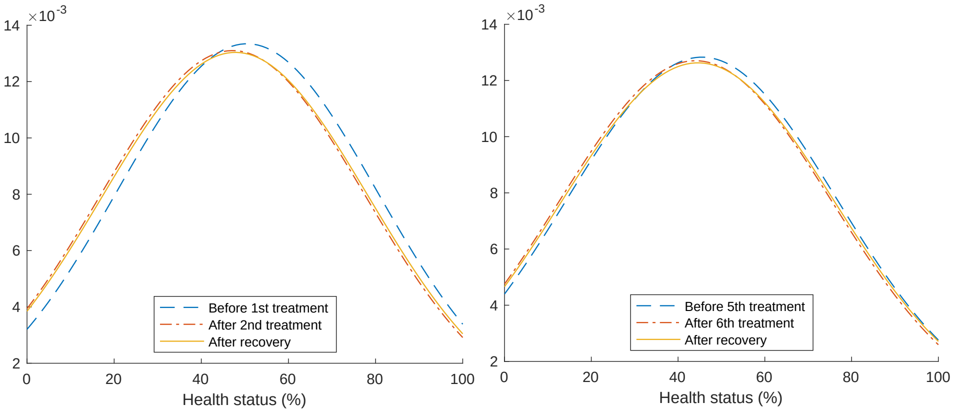


(a) Health development of six populations

(b) Gaussian distribution of health status

Figure 6.4: Development of salmon health at Juvika B. Six random salmon populations are shown in **(a)**, while **(b)** shows the Gaussian health distribution within the cage at six times: smolt release , after treatment 1–4, and at harvest.

To capture the modelled health response to repeated delousing operations, a comparison between the two sets of consecutive treatments in Figure 6.5 was made. The first and second treatment occurred within two weeks, and the mean health went from 51.1 to 48.6% right after the last treatment. For the fifth and sixth treatment, a period of six weeks separated them, and the mean health went from 47.5–46.2%. When the salmon were given time to recover between treatments, the reduction in health went down by nearly 50%.



(a) 1 week for recovery between treatments

(b) 6 weeks for recovery between treatments

Figure 6.5: Comparison of Gaussian health distribution before and after delousing with time and without time for recovery between treatments. Development after the first and second treatment **(a)** and after the fifth and sixth treatment **(b)** at Juvika B.

6.2 Case Study of Management Strategies

Through simulation of cage environments at selected localities, different treatment and smolt strategies have been revised. All cases were introduced in Section 4.3.1 and have been tested in the same simulation model. Each simulation initiated at the same time as the baseline scenarios, which implies that the same temperature series were used in all scenarios, at both localities. The results obtained from the simulations were finally evaluated with a cost benefit analysis, where the net benefit was estimated for different management strategies.

6.2.1 Case 1: Reduction in Treatments

Case 1: Locality Elgen

The production at Elgen had only two delousing operations in total, ten weeks apart. The simulated results without the second treatment are shown in Table 6.3. By avoiding a treatment gutted weight went up by 3.7 % and production mortality was reduced from 7.7 % to 6.4 %, leading to 2,032 more salmon. Scenario T1 also improved the EFCR down to 1.20 which is a consequence of lower treatment mortality.

Table 6.3: Simulated results at Elgen with reduction of one lice treatment

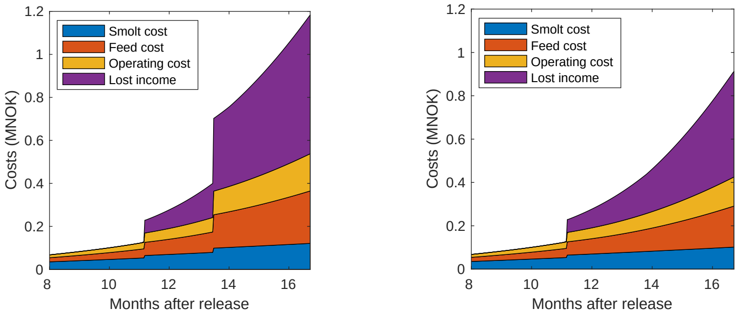
Scenario	GWE	No. harvested	EFCR	Mortality	Treatments
T2 (baseline)	2.88 kg	153,290	1.23	7.7%	2
T1	2.99 kg	155,322	1.20	6.4%	1

The results from the cost benefit analysis are presented in Table 6.4. In scenario T1, produced biomass increased with 5.2 %, which again negatively affected the production cost. However, increased revenue and lower mortality costs lead to a net benefit of 0.61 MNOK, with one less delousing operation. In addition comes the benefit from the cost of the delousing operation.

Table 6.4: Net benefit per cage at Elgen with reduction of one lice treatment

	T2 (baseline)	**T1**
Biomass (GWT)	442	465
Marginal revenue	-	1.13
Marginal production cost	-	-0.79
Marginal mortality cost	-	0.27
Net benefit (MNOK)	-	0.61

Accumulated costs linked to mortality are shown in Figure 6.6, and the distribution is given from 8 months after release to harvest. The sudden increases in costs represent mortality costs from delousing operations. The modelled salmon reached a GWE of 1 kg, corresponding to a live weight of 1.2 kg, just before the first treatment, and initiated lost income from fish that could have been harvested and sold. With one less treatment, mortality costs are reduced with 0.27 MNOK. Further, mortality costs increased throughout the production due to mortality from natural causes.



(a) Loss for baseline scenario

(b) Loss with one less treatment

Figure 6.6: Accumulated mortality costs at Elgen based on the scenarios used in the CBA, divided into smolt, feed and operating cost, and lost income.

Case 1: Location Juvika B

The production at Juvika B had a total of seven delousing operations, where two of the treatments were reported one week after another treatment. By avoiding one or two of the successive operations, a more extensive spread was obtained between the treatments. The simulated results are shown in Table 6.5. By avoiding the sixth treatment in scenario T6, GWE went up 3.9 %, and in scenario T5 where the second treatment was removed as well, GWE increased by 8.2 %. Both case scenarios had reduced mortality rates, resulting in

1,044 and 3,972 more salmon, and lower EFCR.

Table 6.5: Simulated results at Juvika B with reduction of one and two lice treatments

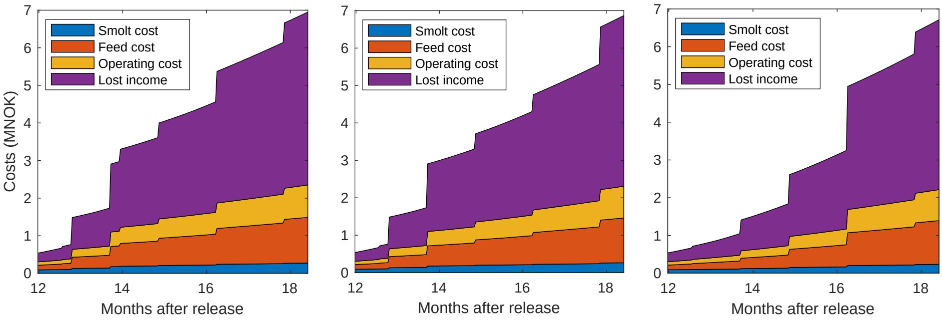
Scenario	GWE	No. harvested	EFCR	Mortality	Treatments
T7 (baseline)	4.923 kg	150,641	1.41	16.3%	7
T6	5.11 kg	151,685	1.39	15.7%	6
T5	5.33 kg	154.613	1.36	14.1%	5

The results from the CBA are presented in Table 6.6. With lower mortality and higher GWE for both case scenarios, produced biomass increased accordingly. Besides, a GWE above 5 kg led to an increase of 1.81 NOK per kg sold. The net benefit was 2.32 MNOK with one less treatment, and 3.72 MNOK in scenario T5. In terms of avoiding a second treatment an additional 1.75 MNOK were released. In addition comes the benefit from the cost of the delousing operations.

Table 6.6: Net benefit per cage at Juvika B with reduction of one and two lice treatments

	T7 (baseline)	T6	T5
Biomass (GWT)	742	776	824
Marginal revenue	-	3.41	6.32
Marginal prod. cost	-	-1.17	-2.84
Marginal mortality cost	-	0.08	0.24
Net benefit (MNOK)	-	2.32	3.72

Accumulated costs linked to mortality are shown in Figure 6.7, and the distribution is given from 12 months after release to harvest. After 12 months, the fish was about 2.8 kg and was then treated 7 to 5 times before harvest. Further, mortality costs increased throughout the production due to mortality from natural causes. In scenario T5, mortality cost was reduced with 0.24 MNOK per cage, while T6 had a reduction of 0.08 MNOK. The same scenarios had an increase in average dead fish weight, from 2.58 kg in the baseline scenario to 2.85 kg and 2.64 kg, respectively. Although mortality was reduced in both scenarios, the decline in mortality costs was limited due to higher average weights of the fish lost in production.



(a) Loss for baseline scenario **(b)** Loss with one less treatment **(c)** Loss with two less treatments

Figure 6.7: Accumulated mortality costs at Juvika B based on the scenarios used in the CBA, divided into smolt, feed and operating cost, and lost income.

6.2.2 Case 2: Release Larger Smolt

Case 2: Location Elgen

The smolt released in the simulation of Elgen was only 64 grams. In the real production, there was another release with smolt almost twice as big, and therefore 130 grams smolt were tested in scenario S130. To avoid one lice treatment, various smolt sizes were tested. With smolt of 200 grams, the salmon obtained the given harvest weight before the second treatment. The simulated results with different smolt sizes are shown in Table 6.7. Both case scenarios had reduced mortality rates, resulting in 1,506 and 4,416 more salmon per cycle. Despite this, scenario S130 had the greatest EFCR, but also a higher average weight of the dead fish. The average dead fish weight varied between the scenarios, from 1.20 kg in the baseline scenario to 1.42 kg in S130 and 1.32 kg in S200.

Table 6.7: Simulated results at Elgen with smolt of 64, 130 and 200 grams

Scenario	No. harvested	EFCR	Mortality	Treatments	Production days
S64 (baseline)	153,290	1.23	7.7%	2	508
S130	154,796	1.25	6.7%	2	445
S200	157,706	1.21	5.0%	1	408

The results from the CBA are presented in Table 6.8. Both case scenarios had a slight increase in produced biomass, which led to higher revenues. However, larger smolt is more expensive to buy and overall scenario S130, and S200 ended with a negative net benefit of about 0.6 MNOK. By extending the production, it was also studied how the scenarios performed with a higher harvest weight, as the simulations did not fully utilise the MAB for the cage. The MAB was 573 tons and allowed a GWE above 3 kg, and then the sales price went up 6.52 NOK per kg. Then scenario S200^{a} had both treatments as well, and consequently, mortality went up. Even if these scenarios had higher mortality from the prolonged production, the most profitable was the baseline scenario which obtained a net benefit of 3.29 MNOK, to the cost of 413 salmon and 17 days longer production.

Table 6.8: Net benefits per cage at Elgen with smolt of 64, 130 and 200 grams

	S64 (baseline)	**S130**	**S200**	**S64^{a}**	**S130^{a}**	**S200^{a}**
Biomass (GWT)	442	445	450	465	468	470
Marginal revenue	-	0.15	0.40	4.18	4.34	4.49
Marginal prod. cost	-	-0.10	-0.27	-0.78	-0.88	-0.97
Marginal smolt cost	-	-0.52	-1.03	-	-0.52	-0.99
Marginal mortality cost	-	-0.11	0.29	-0.11	-0.17	-0.34
Net benefit (MNOK)	-	-0.58	-0.61	3.29	2.77	2.19

[a] Harvest weights are changed from 3.5–3.7 kg to obtain a GWE over 3 kg

Case 2: Location Juvika B

The production at Juvika was simulated with smolt of 60 grams, and four scenarios were tested with a gradual increase in smolt weight. The simulated results with various smolt sizes are shown in Table 6.9. All scenarios with larger smolt and fewer treatments, needed less production days to reach the harvest weight of 6 kg. Also, mortality went down with less treatments and shorter production time, and 14,326 more salmon survived in scenario S225, which had the lowest mortality of 8.4 %. Scenario S225 was able to avoid five treatments, and shortened the cycle with over 4.5 months.

Table 6.9: Simulated results at Juvika B with smolt of 60, 70, 100, 170 and 225 grams

Scenario	**No. harvested**	**EFCR**	**Mortality**	**Treatments**	**Production days**
S60 (baseline)	150,641	1.41	16.3%	7	560
S70	152,560	1.39	15.2%	6	537
S100	156,059	1.37	13.3%	5	494
S170	158,816	1.37	11.8%	4	449
S225	164,967	1.28	8.4%	2	417

The results from the CBA are presented in Table 6.10. All case scenarios produced more biomass than the baseline scenario, and revenues and production costs increased accordingly. Even if larger smolt resulted in higher smolt costs, the reduction in mortality costs was able to compensate for the difference. Scenario S225 had a net benefit of 3.71 MNOK, and would still perform better than the baseline scenario with a smolt cost of 37 NOK per smolt, compared to the 16.8 NOK used in the model. Scenario S170 achieved a lower net benefit than S100, which was due to a higher average weight of the fish lost in production combined with higher smolt and production costs.

Table 6.10: Net benefits per cage at Juvika B with smolt of 60, 70, 100, 170 and 225 grams

	S60 (baseline)	**S70**	**S100**	**S170**	**S225**
Biomass (GWT)	742	752	770	782	808
Marginal revenue	-	0.61	1.64	2.37	3.94
Marginal prod. cost	-	-0.35	-0.95	-1.37	-2.29
Marginal smolt cost	-	-0.10	-0.39	-0.90	-1.37
Marginal mortality cost	-	0.54	1.23	1.22	3.43
Net benefit (MNOK)	-	0.70	1.53	1.32	3.71

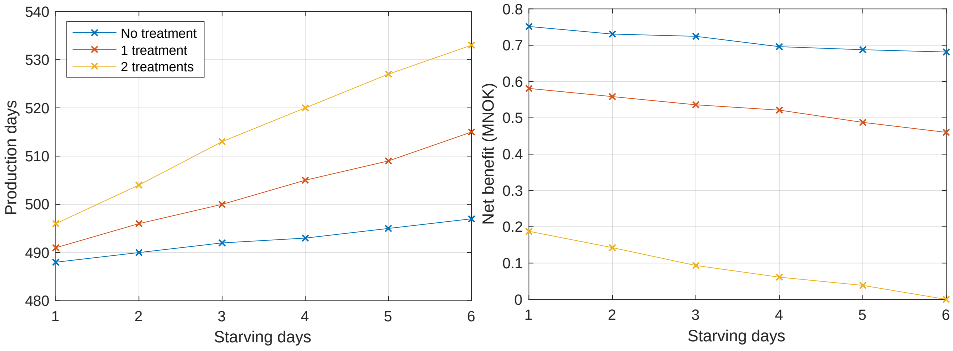
6.2.3 Case 3: Starvation Before Vessel Operations

In the final case, combinations of treatments and number of starving days were tested. In Figure 6.8 and 6.9, all scenarios are represented by an x-mark, and are sorted by number of treatments. A baseline scenario with no lice treatments was selected for both localities, and thus salmon were only starved before harvest.

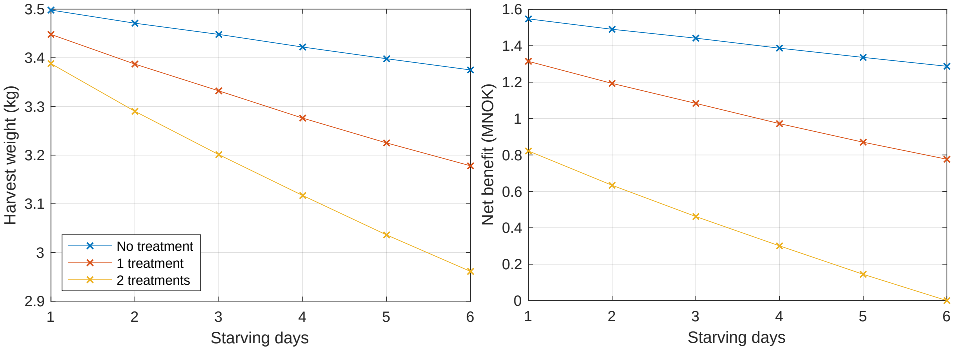
Case 3: Location Elgen

The case consisted of two parts. In the first part, the harvest weight was fixed to 3.5 kg, with a varying number of production days. In part two, the same combinations of treatments and starving days were tested with a constant production time of 16 months, with varying harvest weights. The production at Elgen had two lice treatments, and net benefits are compared to scenario T2/D6, with two treatments and six starving days.

The results from the CBA are presented in Figure 6.8. All scenarios performed better with fewer treatments and fewer days of feed withdrawal. In Fig. 6.8 (a) and (b), 45 days and 0.75 MNOK in net benefit separated scenario T0/D1 with scenario T2/D6. In general, more delousing operations increased treatment mortality, while a longer production caused more natural mortality. With a fixed production time of 16 months, variations in harvest weights and net benefits are shown in Fig. 6.8 (c) and (d), and 0.54 kg and 1.55 MNOK in net benefit separated scenario T0/D1 with the scenario T2/D6. Also, the EFCR was 1.18 in scenario T0/D1 compared to 1.40 in scenario T2/D7. Despite different harvest weights, all scenarios obtained a gutted weight of 2–3 kg and thus revenues are based on the same sales price.



(a) Production days to reach w=3.5kg **(b)** Net benefit in MNOK



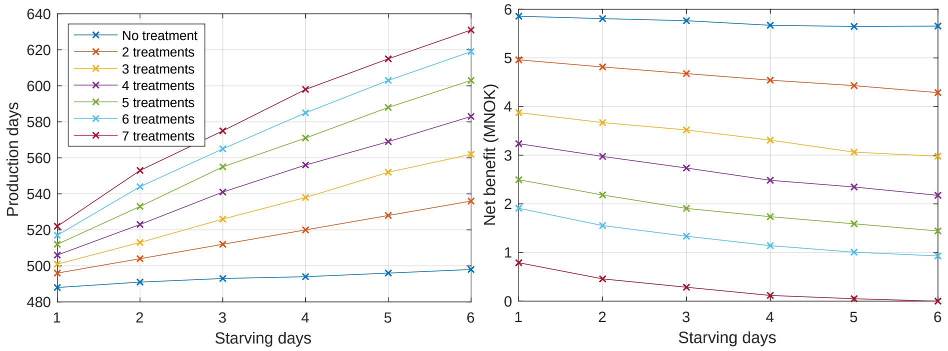
(c) Harvest weight after t=16 months **(d)** Net benefit in MNOK

Figure 6.8: Harvest weights and production days with 1–6 starvation days before delousing and harvest at Elgen. Fixed time in **(a)** is 16 months, and in **(b)** the constant harvest weight is 3.5 kg.

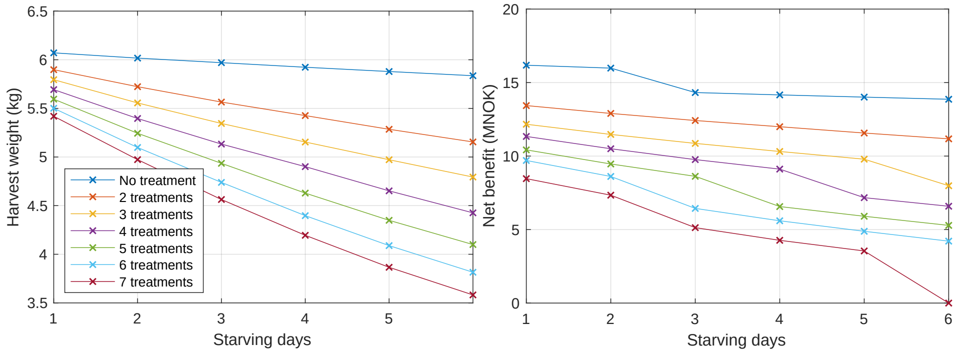
Case 3: Location Juvika B

The results from the CBA are presented in Figure 6.9. With a harvest weight of 6.1 kg, scenario T0/D1 had a net benefit of 5.86 MNOK and shortened the production with 143 days (>4.5 months), compared to scenario T7/D6 (Fig. 6.9(a) and (b)). Besides, the EFCR was 1.19 and 1.40 for these remotest scenarios. Although some scenarios had similar duration, different numbers of delousing operations had great impact on profitability. For example, by comparing scenario T7/D2 with T5/D3, scenario T7/D2 took two less days. However, scenario T5/D3 had a net benefit that was 1.45 MNOK higher than scenario T7/D2.

With a production time of 17 months, variations in harvest weights and net benefits are shown in Fig. 6.8(c) and (d). Scenario T0/D1 had a net benefit of 16.18 MNOK per cage, and the fish were 0.54 kg heavier at harvest compared to scenario T7/D6. Irregularities in net benefits are results of varying harvest weights and thereby price category for the GWE. Scenario T7/D6 was the only one with a gutted weight below 3 kg, which resulted in a sales price of 50.43 NOK per kg. In contrast, scenario T0 with one or two starving days, had a gutted weight above 5 kg and a sales price of 60.80 NOK per kg.



(a) Production days to reach w=6.1 kg **(b)** Net benefit in MNOK



(c) Harvest weight after t=17 months **(d)** Net benefit in MNOK

Figure 6.9: Harvest weights and production days with 1–6 starvation days before delousing and harvest at Juvika B. Fixed time in **(a)** is 17 months, and in **(b)** the constant harvest weight is 6.1 kg.

Chapter 7

Discussion

This chapter presents a discussion of the methods used, which were described in Chapter 4 and 5, and also the results from the case study that were presented in Chapter 6.

7.1 Methodology

Stochastic modelling is useful in research involving salmon health and economics, considering that biological systems include variation and uncertainty. Pettersen et al. (2015) and Aunsmo et al. (2010) studied harvest strategies for a PD infected area, and with veterinary expertise, they managed to implement new ideas for how management strategies could be evaluated. However, it must be noted that simulation models are based on the assumptions we make and will not reflect reality perfectly. Still, this model enables simulation of various farming strategies, and profitability can be assessed objectively. Further, the model can be adjusted to comply with other farms, and include other treatments against salmon lice. This would ultimately make the model useful in many situations and improve its ability to provide decision support.

Cost benefit estimates

The CBA was based on a setup used by Pettersen et al. (2016) and was adapted to be a decision support tool for welfare oriented farming strategies. The cost estimates were obtained from reported data from the industry (NDF, 2020; Iversen et al., 2018), while harvested salmon were priced based on the average sales price from the NASDAQ Salmon

Index (from week 39 2017 to week 38 2020), minus the export cost. The gutted weight was found by dividing the harvest weight by a conversion factor of 1.2 and was used to find the right price category from 1-9 kg.

Due to large fluctuations in salmon price, a price index was used. However, for small salmon with a gutted weight below 3 kg, there was a massive benefit associated with obtaining a higher weight and thereby price category, as shown in Figure 6.9 (d). The effect of increased weight may not be as rigid outside of the model, but since the price index is divided into weight intervals of 1 kg, this assumption was used in the model.

The production costs increased proportionally with kg salmon produced, while a unit cost applied to different sizes of smolt. The retrieved costs were based on national reports and did not include variations in production. As a result, expensive productions with more lice treatments and disease control will have underestimated production costs and vice versa. For productions of different length, the cost of longer productions was embedded in increased production costs. Given this, the model has limited value for comparing deviating productions and should confine to evaluate farming strategies at a given locality.

One of the goals with the model was to include losses that derived from vessel operations, and to quantify them. The mortality cost was estimated daily based on how many fish that died and their current weight, and due to natural causes the morality cost increased for each day. A sunk cost was attained from feed, operations and smolt, while an income loss was based on potential income for fish (GWE>1kg), minus the slaughter cost. However, since mortality from vessel operations, both due to 0% health and treatment mortality, was modelled right after the delousing operations, mortality costs from lice treatments can be found by studying the sudden increases in accumulated mortality costs (Fig. 6.6 and 6.7).

Another unwanted effect from delousing operations was increased economic feed conversion ratio. This happened due to a combination of mortality, starving days, and also longer production time if the harvest weight was fixed. However, it should be noted that the EFCR at Juvika B was extra high because of lice treatments that where scheduled late in the production cycle. Thus, salmon that died during productions at Juvika B had in general, very high average weights.

Modelled salmon populations

Salmon populations of a thousand fish were modelled with individual health statuses, being an independent random variable with a uniform distribution in the interval 1–100%. The idea behind this representation was to quantify salmon health and be able to measure a health response after delousing operations. Although, the model could have provided more nuanced numbers with less fish per population. In order to develop this approach further, different intervals could be tested with the same distribution, or other stochastic distributions could be modelled and compared. Moreover, it would be desirable with data that describes the condition of the smolt at release, in addition to a measurable health response after delousing operations. Given that, the welfare indicators in Noble et al. (2018) could be a good starting point.

Further, growth was estimated daily based on an RGI table obtained from Næstvold. The origin of the SGR values in the table are uncertain, and they may be intended for a specific area. Still, the RGI table provided a detailed description of the growth rate for all sizes and temperatures observed in the simulated scenarios. Before vessel operations, feed withdrawal caused a reduction in salmon weight and was modelled according to a formula by Mørkøre (2008). The method was only based on starvation and did not consider the strain from vessel operations. According to Noble et al. (2018), stress from vessel operations can cause a reduced appetite for the fish. Thus, the modelled effects from starvation are assumed to be conservative.

Prediction of salmon mortality

There are large variations of production mortality in Norway, some sites report rates below 5 %, while others are far beyond that with productions where almost all the fish go to waste. As a result, it was challenging to model salmon mortality, and the established method is based on ongoing research by Tvete (2020) and literature describing treatment mortality (Glover K et al., 2018; Bleie and Skrudland, 2014). Mortality was divided into two main components, one that covered natural causes like diseases and low smolt quality, and mortality from delousing operations, which either occurred directly to individuals or indirectly to populations by reduced health status. Treatment mortality and health reduction were associated with three delousing operations, and the treatments were anonymised in order not to present a method better or worse than the competitors.

Both baseline scenarios were modelled with production mortality close to documented values, and salmon populations from both localities responded equally to treatments, with the same values for α_{1-4} and β, where α was the severity of the harm caused by the treatment, and β the fish's ability to recover after treatments. However, the background mortality from natural causes had to be tuned separately for the sites. In other words, I was unable to make a generalised model for mortality, but the model still provides an environment that allows testing of different farming strategies.

The modelled mortality occurred right after delousing operations, while in reality, indirect mortality would happen over time. Tvete (2020) tries to develop the delayed response to treatments and diseases, but since there is still great uncertainty associated with these predictions, this part was simplified. The results of a delayed response would be increased mortality costs and higher EFCR, and also a more realistic daily mortality. However, the immediate response captures the essence of how fish are affected, and the modelled response is assumed to be sufficient in this context.

7.2 Evaluation of Results

The results from the simulation model demonstrate that vessel operations cause substantial losses and that welfare-oriented farming strategies can be economically efficient and at the same time prevent premature death of thousands of salmon. With more physical treatments against salmon lice, treatment mortality and restrained growth is a challenge. Vessel operations require starvation of fish, and productions with more delousing operations have additional periods with feed withdrawal.

For the results in case 1, avoidance of treatments will ultimately improve production efficiency. By avoiding delousing operations, treatment mortality is reduced, and the harvest weights increase. However, the focus of this case was to study the released funds with these strategies, as there are alternative methods of dealing with lice. Released funds from net benefits could be spent on measures preventing salmon lice and thereby avoid excessive vessel operations. According to Noble et al. (2018), laser treatments which use camera vision to continuously shoot lice, present an attractive option as they do not require starving or handling inside a delousing vessel. Although the producer of this system has reported that cages with their systems have not caused salmon harm by wounds or mortality, this treatment is in development like many other, and site operators face challenging choices when it comes to keeping lice levels low. With repeated operations, a more efficient treatment could replace the second treatment in order to avoid losses associated with another delousing operation. It is questionable that repeated operations occur, and it suggests that the first treatment either failed or was not able to reduce the lice level enough.

It is not straightforward to compare growth performance between fish of various size or between localities, but the results from case 3, demonstrate that additional treatments and starving days directly reduce production margins. More vessel operations, and thus starving days, lead to a higher EFCR, which indicates an inefficient utilization of the feed. The production time also increases, and so does mortality rates. When considering the proportion of feed costs in salmon farming, which accounts for about 50% (Iversen et al., 2018), effects from feed withdrawal are considerable. Vessel operations ultimately reduce production efficiency and represent a threat to animal welfare in aquaculture, and therefore the number of boat operations should be kept to a minimum.

Chapter 8

Conclusion

This research aimed to identify the challenges that arise when salmon encounters vessel operations. To organise hazards for salmon in these operations, A PHA was conducted. The PHA revealed weaknesses with current procedures and suggested risk reducing measures for salmon. Some farming procedures are still based on old traditional methods, like crowding and manual lice counting, which expose the fish to more hazards than what may be necessary. The focus on technology development must continue to provide better conditions for the fish and thereby facilitate safe and efficient production.

A stochastic model proved useful for simulating the health response of salmon in delousing operations. The model included biological features of salmon, such as growth and health status. With a generic model, different management strategies could be tested in the same model. While a simulation of salmon health limits a generalisation of the results, this approach provides new insight into salmon welfare in aquaculture.

The results indicate that vessel operations cause substantial losses and if possible, should be avoided to spare the salmon. Based on a cost benefit analysis of the simulated results, some of the welfare oriented farming strategies were found profitable. Economic and biological losses attained from delousing operations are substantial, and origins from treatment mortality, reduced growth and higher EFCR. As mentioned in the literature study, there is a demand for combining disciplines when analysing aquaculture systems. The established simulation model applies biological insight into a technological framework and can assist salmon producers as a decision support tool to find more sustainable farming strategies.

For future research I recommend to expand the model to include response from other vessel operations, in particular transport operations. This was attempted, but due to limited literature on the topic and lack of reported data, a modelled response would be based on unsupported assumptions and was therefore not incorporated.

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Appendix

A Preliminary Hazard Analysis

Operation		Potential hazaradous event	No.	Cause	Consequence	Like.	Cons.	Risk	Risk-reducing measure
When	What								
Transport, lice treatments, grading and harvest	Crowding	Exposure to water with low levels of dissolved oxygen	1.1	Overcrowding	Limited respiration, panic, high mortality	3	5	15	Planning and the ability of rapid release of the fish
			1.2	Stressed fish (require more oxygen)	Limited respiration	5	2	10	Fasting and avoid prolonged crowding
			1.3	High water temperature or low current	Limited respiration, panic, mortality	3	3	9	Add oxygen to the water
			1.4	Prolonged crowding	Limited respiration, panic, mortality	3	4	12	Planning and communication with wellboat/ treatment vessel
		Physical contact with other fish or equipment	1.5	Overcrowding	Panic, collisions, exhaustion, scale loss, fin damage and eye haemorrhage, high mortality	3	5	15	Planning and the ability of rapid release of the fish
			1.6	Stressed fish	Panic, fin, scale and gill damage, wounds	5	2	10	Fasting and avoid prolonged crowding
Transport, lice treatment, grading and harvest	Pumping (general)	Detoriated water quality	2.1	Long transits	Limited respiration, reduced appetite, gill beat rate, mortality	3	3	9	Reduce fish metabolism by sufficient fasting and balanced water ciculation
			2.2	Pump stops	Limited respiration, reduced appetite, gill beat rate, mortality	3	4	12	Ensure that the pump is empty before planned breaks, technical maintenance
			2.3	High fish density	Limited respiration, reduced appetite, gill beat rate, mortality	3	3	9	Monitor water quality according to actual fish density in pipes
		Collisions in pipe	2.4	Irregularities like sharp edges and bends in the pipe	Impact injuries, fin, scale and gill damage, wounds, mortality	3	4	12	Lower pump velocity/pressure and avoid irregularities in pump design
			2.5	High fish density	Impact injuries, fin, scale and gill damage, wounds	4	2	8	Lower pump velocity/pressure and avoid high fish densities
			2.6	High pump speed	Impact injuries, fin, scale and gill damage, wounds, mortality	3	4	12	Reduce pump speed

Transport, lice treatment, harvest, grad	Pumping (vacuum/ pressure)	Fish being trapped in the pump system	3.1	Too low pump speed	Limited respiration, exhausted fish, reduced appetite, mortality	3	3	9	Pump speed must be above the swimming speed of the fish
			3.2	Fish stuck in pump chamber for several rounds of vacuum/ pressure	Impact injuries, fin, scale and gill damage, wounds, mortality	3	3	9	Avoid irregularities in pump inlet/outlet
			3.3	Slaughter line is full and stops intake of fish	Shorter pre-rigor time, gill beat rate, mortality	3	3	9	Communication between slaughter line and waiting cage
		Pump acceleration	3.4	Fish damaged by large pressure gradiets	Uncertain	3	1	3	Observation from Sensorfisk, but uncertain how this affect real fish
Lice treatments	Pumping (impeller)	Impeller blades	4.1	Fish stuck in impeller	Impact injuries, fin, scale and gill damage, wounds, mortality	3	4	12	Avoid large fish in these pumps as they tend to get stuck more often
			4.2	Fish damaged by impeller	Impact injuries, fin, scale and gill damage, wounds, mortality	4	3	12	Make sure that the impeller is dimensioned for the given fish size
		Pump acceleration	4.3	Fish damaged by high g-forces	Uncertain	3	1	3	Observation from Sensorfisk, but uncertain how this affect real fish
Lice treatments	Pumping (ejector)	Fish stalles by ejector module	5.1	Turbulence from ejector pump	Fin and gill damage, wounds	3	1	3	Install additional ejector pumps to even out the load and avoid bubbles and cavitation
		Fish stalles in the pipe	5.2	Uneven radial water pressure (theory from SINTEF's Sensorfisk project)	Fin and gill damage, wounds	3	1	3	Pump setup that ensures even water flow
			5.3	Systems with internal water circulation block the suction (theory from SINTEF's Sensorfisk project	Fin and gill damage, wounds	3	1	3	Pump setup that ensures even water flow
Transfer to sea cages, moving fish to other cages or sites and ha	Transport	Wellboat motions at sea	6.1	Bad weather during transport (e.g. waves and wind)	Does not allow fish to rest between loading/unloading, motion sickness, increased mortality	3	4	12	Planning
			6.2	Transport to exposed production site	Does not allow fish to rest between loading/unloading, motion sickness, increased mortality	3	4	12	Strict operational limits for weather
		Detoriated water quality in well	6.3	High fish density	Limited respiration, reduced appetite, mortality	1	4	4	Follow fish density guidelines
			6.4	Stressed fish (require more oxygen)	Limited respiration	4	2	8	Reduce fish metabolism by sufficient fasting and balanced water ciculation.
			6.5	Closed vents and insufficient oxygen level	Limited respiration, reduced appetite, panic, high mortality	2	5	10	Reduce fish metabolism by fasting and add oxygen to the well
			6.6	Closed vents and insufficient aerating of toxic gases	Limited respiration, reduced appetite, high mortality	2	5	10	Fasting to empty intestine
			6.7	Closed vents and gas supersaturation	Limited respiration, reduced appetite, mortality	2	4	8	Monitor water quality
			6.8	Open vents and bad water circulation	Limited respiration, reduced appetite, panic, mortality	2	4	8	Monitor water quality and use equipment to improve the quality of the water

vest		Disease outbreak	6.9	Infections in water and open vents to the well	Pass infections to farmed stock, high mortality	3	5	15	Close vents to the well, regulate water quality with internal systems
			6.10	Infections among smolt - braught from hatchery, and open vents to the well	High mortality, pass infections to wild stock	3	5	15	Close vents to the well, better quality control of smolt at the hatchery
Moving fish to other cages or sites, lice treatments and harvest	Grading	Exposure to water with low levels of dissolved oxygen	7.1	Overcrowding	Limited respiration, panic, high mortality	3	5	15	Planning and the ability of rapid release of the fish
			7.2	Stressed fish (require more oxygen)	Limited respiration	5	2	10	Fasting and avoid prolonged crowding
			7.3	High water temperature or low current	Limited respiration, panic, mortality	3	3	9	Add oxygen to the water
			7.4	Prolonged crowding	Limited respiration, panic, mortality	3	4	12	Planning and communication with wellboat/ treatment vessel
		Withdrawal of water (grading machine)	7.5	High or low temperatures and when humidity is low	More harmful under such conditions, limited respiration	4	2	8	Avoid dewatering under these conditions
			7.6	Fish kept too long without water	Stress, limited respiration, mortality	2	4	8	Minimize time out of water. Max 15 seconds according to RSPCA welfare standards
		Physical contact with sorting net, grading machine or other fish	7.7	Fish nearing the size of the gaps in the Flexi-Panel and get stuck	Reduced appetite, panic, exhaustion, mortality	4	3	12	Fasting and avoid prolonged crowding
			7.8	Irregularities like sharp edges and bends in the grading machine	Impact injuries, fin damage, gill damage and wounds	3	4	12	Avoid protruding edges, sharp edges, rough surfaces, dry surfaces and abrupt changes of direction
			7.9	High fish density	Impact injuries, fin damage, gill damage and wounds	4	2	8	Lower pump velocity/pressure and avoid high fish densities
			7.10	High pump speed	Impact injuries, fin, scale and gill damage, wounds, mortality	3	3	9	Reduce pump speed
Transfer to sea cages	Smolt release	Salinity at site	8.1	Stock not fully smoltificated	High mortality due to dehydration	2	5	10	Introduce a post-smolt phase in a sheltered location
		Wounds and skin damage	8.2	Skin damage from freshwater stage	Secondary infections (e.g. ulcers) and diseases, mortality	4	4	16	Avoid smolt release at low temperatures (5℃)
			8.3	Skin damage from handling during transfer to sea cages	Secondary infections (e.g. ulcers) and diseases, mortality	4	4	16	Avoid smolt release at low temperatures (5℃)
		Damage from seawater flushing and turbulence (e.g. FLS and Hydrolicer)	9.1	Setup failure	Bleeding from gills and scale loss, mortality	3	4	12	Correct adjustment of the equipment, evaluate general health status before treatment
			9.2	System does not fit the fish size	Bleeding from gills and scale loss, mortality	3	4	12	Correct proportions of the system, evaluate general health status before treatment
		Damage from soft brushes and seawater flushing (e.g. SkaMik)	9.3	Setup failure	Bleeding from gills and scale loss, mortality	3	4	12	Correct adjustment of the equipment, evaluate general health status before treatment
			9.4	System does not fit the fish size	Bleeding from gills and scale loss, mortality	3	4	12	Correct adjustment of the equipment, evaluate general health status before treatment

	Lice treatments	Kept in tanks or pipes with temperature adjusted seawater (e.g. Thermolicer and Optilicer)	9.5	Water temperature just below 28 ℃	Panic, head shaking, mortality	3	4	12	Avoid thermal treatment when ambient temperature is low, ensure correct treatment temperature
			9.6	Water temperature between 28-34 ℃ (above 34 ℃ is already prohibited)	Panic, head shaking, collisions with tank wall, brain, eye and skin haemorrhaging, high mortality	3	5	15	Currently being phased out by The Norwegian Food Safety Authority due to poor animal welfare in temperatures above 28 ℃
			9.7	Prolonged treatment time	Panic, head shaking, collisions with tank wall, brain, eye and skin haemorrhaging, high mortality	3	5	15	Strictly monitor treatment time
			9.8	Poor water quality due to high ammonia and turbidity values	Ammonia is toxic to fish, reduced appetite, mortality	3	4	12	Fasting to empty intestine
			9.9	Poor water quality due to low levels of oxygen	Limited respiration, panic, mortality	3	3	9	Fasting to reduce metabolism, monitor/regulate oxygen levels
Grading machines and lice treatments	Dewatering	Fish get stuck between bars	10.1	Bad dimensioning of bars according to fish size	Injuries and wounds, mortality	3	3	9	Adjust dimensions to fish size, in particular for fish < 1 kg
		Collisions	10.2	Irregularities like sharp edges and bends in the system	Impact injuries, fin, scale and gill damage, wounds, mortality	3	4	12	(Water) velocity and pipe angels adjusted to fish flow. Avoid irregularities in design
			10.3	High fish density	Impact injuries, fin, scale and gill damage, wounds	4	2	8	Avoid high fish densities
			10.4	High velocity	Impact injuries, fin, scale and gill damage, wounds, mortality	3	4	12	Reduce velocity
		Withdrawal of water	10.5	High or low temperatures and when humidity is low	More harmful under such conditions, limited respiration	4	2	8	Avoid dewatering under these conditions
			10.6	Fish kept too long without water	Stress, limited respiration, mortality	2	4	8	Minimize time out of water. Max 15 seconds according to RSPCA welfare standards
Cleaning and replacement of old net	Cleaning of net cage (with fish)	Contact with harmful substances	11.1	Harmful organisms with active stinging cells in debris	Gill irritation	2	2	4	Look for fish that actively avoid debris water
			11.2	Residues of harmful substances in water	Effects from toxic chemicals	3	2	6	Safe and effective use of chemicals
		Physical contact with other fish or equipment	11.3	Problems with the cleaning tool or procedure	Damage to eyes, scale loss, snout damage and damage to fins	3	2	6	Equipment maintenance, staff training and standard operating protocols
			11.4	Water stream from high pressure water jets	Panic, collisions, skin damage	4	1	4	Staff training and standard operating protocols
	Net change	Physical contact with other fish or equipment	12.1	Fish are driven to excessive escape or avoidance behaviour	Panic, collisions, skin damage	3	2	6	Staff training and standard operating protocols
Maintenance and supply	Local boat traffic and underwater activity	Noise, waves and disturbance in sea	13.1	Jet streams from thrusters	Panic, skin damage	4	1	4	Avoid dynamic positioning thrusters - likely to force jet streams directly on net cages
			13.2	Detonations	Panic, damage to swim bladder and mortality, but great uncertainties to the damage threshold	1	4	4	Detonations cause harm even if they occur several kilometers away

B Selected Scripts from the Model

B.1 RunSimulation.m

```
%Script to prepare, run and process data from simulation model

clear
clc
close all

tic

model = 'SalmonCycle';
open_system(model)

%% Define model constants
salmon_wt    = 60;       %smolt weight in [g]
salmon_n     = 180000;    %number of fish
popsize      = 1000;      %population size

%generate health status of populations
%fish_populations = healthgenerator(salmon_n,popsize);
fish_populations = csvread('fish_popJuv.csv');

harvest_w    = 6000; %g
max_biomass = 981;   %tons

set_param(model, 'StopTime','560*24')

%% Set lice treatments

treatments = xlsread('treatment.xlsx');
starving_d = 3;
starving_h = starving_d*24;

%% Mortality

salmon_mort = xlsread('salmon_mort.xlsx');

%health response
a1 = 0.0005;
a2 = 0.0007;
```

```
a3 = 0.0009;
a4 = 0.0011;

%health recovery
b = 0.0007;

%natural mortality
c = 0.6;

%% Run Simulation
out = sim(model);

toc
%% Plot results from Juvika
%store results from simulation
totbio       = [out.biomass.Time/24 sum(out.biomass.data,2)];
weight       = [out.wt.Time/24 out.wt.Data];
pop          = [out.population.Time/24 out.population.data];
pop(1,2)     = salmon_n;
healthpop    = [out.healthpop.data];
tempout      = [out.temp.Time/24 out.temp.Data];
time_diff    = out.population.Time(2:end)/24;
pop_diff     = pop(2:end,2);
weight_diff = weight(2:end,2);
daily_mort   = abs(diff(pop(:,2)));
mort_acc     = zeros(length(daily_mort),1);
mort_acc(1) = daily_mort(1);

for i = 2:length(daily_mort)
    mort_acc(i) = daily_mort(i)+mort_acc(i-1);
end

cycle_mort = (1-pop(end,2)/salmon_n)*100;
disp(cycle_mort);

eFCR = out.feed.data(end)/(totbio(end,2)-(salmon_n*salmon_wt/10^6));
disp(eFCR)

%% Cost-Benefit Analysis

lost_biomass = sum(daily_mort.*weight_diff/1000);
lost_fish     = sum(daily_mort);
ave_deadwt    = lost_biomass/lost_fish/1.2;
```

```
n_fish  = round(pop(end));
wt_fish = round(weight(end))

gwe_fish = wt_fish/1.2/1000;
gwe = round(wt_fish/1000*n_fish/1.2);

%Cost estimates
smolt_c      = 9.3;   %per 60 g smolt
feed_c       = 13.26; %per kg live fish
prod_c       = 9.41;  %per kg live fish, labour and other operating costs
                      %excl. financial costs and slaughter

salmon_price1 = 50.43; %2-3 kg HOG, NASDAQ average 2017-2020
salmon_price2 = 56.95; %3-4 kg HOG
salmon_price3 = 58.99; %4-5 kg HOG
salmon_price4 = 60.80; %5-6 kg HOG

dead_inc1 = 43.02 - 3.55; %1-2 kg HOG - slaughter cost
dead_inc2 = 50.43 - 3.55; %2-3 kg HOG
dead_inc3 = 56.95 - 3.55; %3-4 kg HOG
dead_inc4 = 58.99 - 3.55; %4-5 kg HOG
dead_inc5 = 60.80 - 3.55; %5-6 kg HOG

cost_s   = zeros(length(daily_mort),1);
cost_f   = zeros(length(daily_mort),1);
cost_p   = zeros(length(daily_mort),1);
lost_inc = zeros(length(daily_mort),1);

cost_s(1) = daily_mort(1) * smolt_c;
cost_f(1) = daily_mort(1) * weight(1,2)/1000 * feed_c;
cost_p(1) = daily_mort(1) * weight(1,2)/1000 * prod_c;
lost_inc(1) = 0;

for i = 2:length(daily_mort)
    cost_s(i)   = cost_s(i-1) + daily_mort(i) * smolt_c;
    cost_f(i)   = cost_f(i-1) + daily_mort(i) * weight(i,2)/1000 * feed_c;
    cost_p(i)   = cost_p(i-1) + daily_mort(i) * weight(i,2)/1000 * prod_c;

    if weight(i,2)/1000/1.2 >= 1 && weight(i,2)/1000/1.2 < 2
    lost_inc(i) = lost_inc(i-1) + daily_mort(i) * weight(i,2)/1000 *...
        dead_inc1;

    elseif weight(i,2)/1000/1.2 >= 2 && weight(i,2)/1000/1.2 < 3
    lost_inc(i) = lost_inc(i-1) + daily_mort(i) * weight(i,2)/1000 *...
```

```
        dead_inc2;

    elseif weight(i,2)/1000/1.2 >= 3 && weight(i,2)/1000/1.2 < 4
    lost_inc(i) = lost_inc(i-1) + daily_mort(i) * weight(i,2)/1000 *...
        dead_inc3;

    elseif weight(i,2)/1000/1.2 >= 4 && weight(i,2)/1000/1.2 < 5
    lost_inc(i) = lost_inc(i-1) + daily_mort(i) * weight(i,2)/1000 *...
        dead_inc4;

    elseif weight(i,2)/1000/1.2 >= 5
    lost_inc(i) = lost_inc(i-1) + daily_mort(i) * weight(i,2)/1000 *...
        dead_inc5;

    else
        lost_inc(i)=lost_inc(i-1);
    end
end

loss = [cost_s cost_f cost_p lost_inc];

%price fish in correct GWE category
if gwe_fish >= 2 && gwe_fish < 3
    turnover = round(gwe*salmon_price1);
elseif gwe_fish >= 3 && gwe_fish < 4
    turnover = round(gwe*salmon_price2);
elseif gwe_fish >= 4 && gwe_fish < 5
    turnover = round(gwe*salmon_price3);
elseif gwe_fish >= 5 && gwe_fish < 6
    turnover = round(gwe*salmon_price4);
end

%include financial cost of 2.3 and slaughter cost of 3.55
prodcost      = round((prod_c+feed_c+2.3+3.55)*n_fish*wt_fish/1000);
smoltcost     = round(smolt_c*n_fish);
mortalitycost = round(sum(loss(end,1:4)));
profit        = turnover -prodcost-smoltcost-mortalitycost;

CBA = [turnover;prodcost;smoltcost;mortalitycost;profit];
disp(CBA)

%% Plot Results

figure('Name','Control Production')
```

```
subplot(1,2,1)
grid on
xticks(0:60.8:608)
set(gca,'XTickLabel',0:2:20)
yyaxis left
plot(tempout(:,1),tempout(:,2));
axis([0 inf 0 18])
ylabel('Sea temperature (^{\circ}C)')
yyaxis right
p1 = plot(weight(:,1),weight(:,2));
legend(p1, '60 g smolt','Location','northwest')
ylabel('Average weight (g)')
xlabel('Months after release')
hold off

subplot(1,2,2)
grid on
xticks(0:60.8:608)
set(gca,'XTickLabel',0:2:20)
yyaxis right
plot(time_diff,daily_mort./pop_diff*100)
ylabel('Daily mortality (%)')
yyaxis left
plot(pop(:,1),pop(:,2)/1000)
ylabel('Thousands of salmon')
xlabel('Months after release')
axis([0 inf 100 inf])

figure('Name','Production loss')
grid on
area(time_diff,loss/10^6)
legend('Smolt cost', 'Feed cost', 'Operating cost', 'Lost income',...
    'Location', 'northwest')
xlabel('Months after release');
xticks(0:60.8:608)
axis([364 inf 0 7])
set(gca,'XTickLabel',0:2:20)
ylabel('Costs (MNOK)')

figure('Name','Health status')
subplot(2,3,1)
histogram(healthpop(:,1,1),100)
axis([0 100 0 15])
```

```
subplot(2,3,2)
histogram(healthpop(:,1,385),100)
axis([0 100 0 15])

subplot(2,3,3)
histogram(healthpop(:,1,405),100)
axis([0 100 0 15])

subplot(2,3,4)
histogram(healthpop(:,1,421),100)
axis([0 100 0 15])

subplot(2,3,5)
histogram(healthpop(:,1,441),100)
axis([0 100 0 15])

subplot(2,3,6)
histogram(healthpop(:,1,end),100)
axis([0 100 0 15])

length = time_diff(end);
disp(length);
```

B.2 Script in ”Growth”

```
%Growth rate estimate
persistent feedtable

coder.extrinsic('xlsread')
if isempty(feedtable)
    feedtable = zeros(21,15);
    feedtable = xlsread('sgrtabell');
end

%Locate current growth rate
temp    = round(readTemp());

if temp >= 15
    colnum = 15;
else
    colnum = temp;
end

weight  = readWeight();         %grams
biomass = sum(readBiomass());   %tons
feed    = readFeed();           %tons

if biomass == 0
    biomass = weight*salmon_n/(10^6);
end

dist          = abs(feedtable(:,1) - weight);
[~, min_loc] = min(dist);

if feedtable(min_loc) > weight
    rownum = min_loc-1;
else
    rownum = min_loc;
end

growthrate = feedtable(rownum, colnum)/100;
weight     = weight + weight*growthrate;
tons_feed  = feed + biomass*growthrate*1.15;

writeWeight(weight);
writeFeed(tons_feed);
```

B.3 Script in ”Check Treatment”

```
persistent count lasttreatment recovery

if isempty(count)
    count          = 1; %treatment number
    lasttreatment = 0; %counts weeks since last treatment
    recovery      = 1;
end

health_pop = readHealth();
week = readTime();

if count <= size(treatments,2) %Check if there are more treatments
    treatment_type = find(treatments(:,count)>0,1); %set treatment
    treatment_week = treatments(treatment_type,count); %set treatment week
else
    treatment_type = inf;
    treatment_week = inf;
end

if treatment_week == week %lice treatment this week
    entity.treatment      = 2;
    entity.treatmentType = treatment_type(1,1);
    count                 = count+1;

elseif isempty(treatment_type) %no treatment in column
    count = count+1; %next column

    if count > size(treatments,2) %finished all treatments
        entity.treatment = 1;
        return

    treatment_type   = find(treatments(:,count)>0, 1); %next treatment
    treatment_week   = treatments(treatment_type,count); %next treatment week

    elseif treatment_week == week % treatment directly
        entity.treatment      = 2;
        entity.treatmentType = treatment_type(1,1);
        count                 = count+1;
    else
        entity.treatment = 1;
    end
```

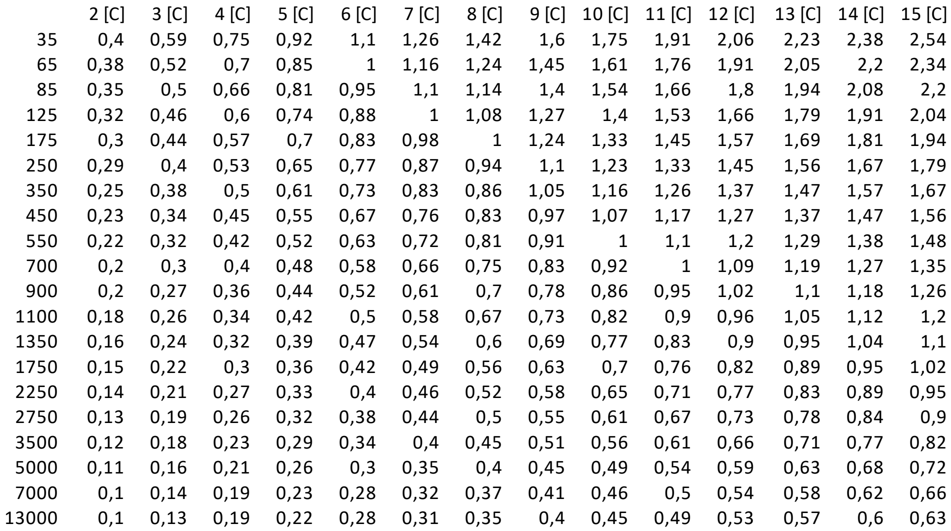
```
else
    entity.treatment = 1;
end

if entity.treatment == 2
    lasttreatment = week;
    recovery = 0;
end

if week-lasttreatment == 2 && recovery == 0

    %health recovery after treatment
    for i = 1:length(health_pop)
        if health_pop(i,1) > 80
            health_pop(i,1) = health_pop(i,1) + b*1000;

        elseif health_pop(i,1) > 60 && health_pop(i,1) <= 80
            health_pop(i,1) = health_pop(i,1) + 0.9*b*1000;

        elseif health_pop(i,1) > 40 && health_pop(i,1) <= 60
            health_pop(i,1) = health_pop(i,1) + 0.8*b*1000;

        elseif health_pop(i,1) > 20 && health_pop(i,1) <= 40
            health_pop(i,1) = health_pop(i,1) + 0.7*b*1000;

        elseif health_pop(i,1) > 0 && health_pop(i,1) <= 20
            health_pop(i,1) = health_pop(i,1) + 0.6*b*1000;
        end

    end
    recovery = 1;
    writeHealth(health_pop);
end
```

B.4 Script in ”Treatment Type 1”

```
health_pop = readHealth();
temp = readTemp();

a = 0;

%Define "a" based on temperature
if temp < 10
    a = a3;
elseif temp >= 10 && temp < 13
    a = a2;
elseif temp >= 13
    a = a4;
end

%Mortality and reduced health from treatment
for i = 1:length(health_pop)

    if health_pop(i,1) > 80
        health_pop(i,1) = health_pop(i,1) - a*1000; %health
        health_pop(i,2) = health_pop(i,2) - health_pop(i,2)*a; %mort

    elseif health_pop(i,1) > 60 && health_pop(i,1) <= 80
        health_pop(i,1) = health_pop(i,1) - a*1.2*1000;
        health_pop(i,2) = health_pop(i,2) - health_pop(i,2)*a*1.2;

    elseif health_pop(i,1) > 40 && health_pop(i,1) <= 60
        health_pop(i,1) = health_pop(i,1) - a*1.4*1000;
        health_pop(i,2) = health_pop(i,2) - health_pop(i,2)*a*1.4;

    elseif health_pop(i,1) > 20 && health_pop(i,1) <= 40
        health_pop(i,1) = health_pop(i,1) - a*1.6*1000;
        health_pop(i,2) = health_pop(i,2) - health_pop(i,2)*a*1.6;

    elseif health_pop(i,1) > 0 && health_pop(i,1) <= 20
        health_pop(i,1) = health_pop(i,1) - a*1.8*1000;
        health_pop(i,2) = health_pop(i,2) - health_pop(i,2)*a*1.8;
    end

    if health_pop(i,1) <= 0
        health_pop(i,1) = 0;
        health_pop(i,2) = 0;
```

```
    end
end

writeHealth(health_pop);
```

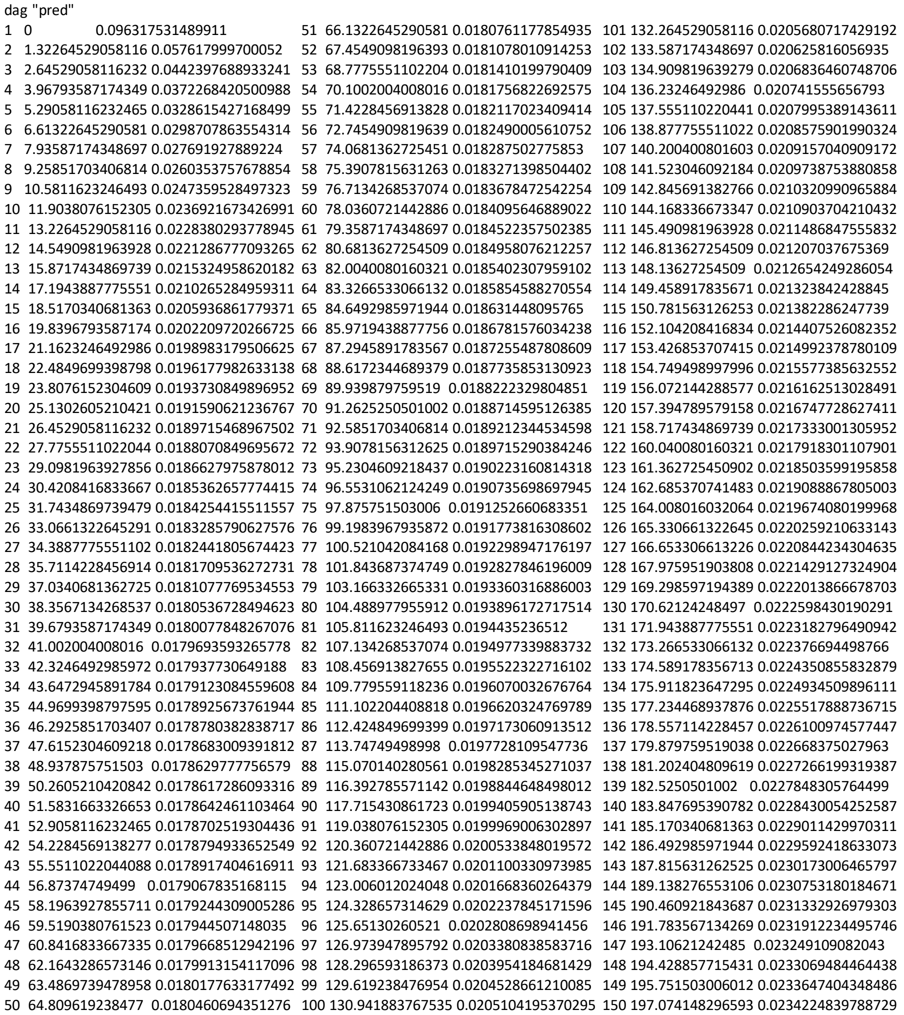
C Relative Growth Index for Atlantic salmon



	2 [C]	3 [C]	4 [C]	5 [C]	6 [C]	7 [C]	8 [C]	9 [C]	10 [C]	11 [C]	12 [C]	13 [C]	14 [C]	15 [C]
35	0,4	0,59	0,75	0,92	1,1	1,26	1,42	1,6	1,75	1,91	2,06	2,23	2,38	2,54
65	0,38	0,52	0,7	0,85	1	1,16	1,24	1,45	1,61	1,76	1,91	2,05	2,2	2,34
85	0,35	0,5	0,66	0,81	0,95	1,1	1,14	1,4	1,54	1,66	1,8	1,94	2,08	2,2
125	0,32	0,46	0,6	0,74	0,88	1	1,08	1,27	1,4	1,53	1,66	1,79	1,91	2,04
175	0,3	0,44	0,57	0,7	0,83	0,98	1	1,24	1,33	1,45	1,57	1,69	1,81	1,94
250	0,29	0,4	0,53	0,65	0,77	0,87	0,94	1,1	1,23	1,33	1,45	1,56	1,67	1,79
350	0,25	0,38	0,5	0,61	0,73	0,83	0,86	1,05	1,16	1,26	1,37	1,47	1,57	1,67
450	0,23	0,34	0,45	0,55	0,67	0,76	0,83	0,97	1,07	1,17	1,27	1,37	1,47	1,56
550	0,22	0,32	0,42	0,52	0,63	0,72	0,81	0,91	1	1,1	1,2	1,29	1,38	1,48
700	0,2	0,3	0,4	0,48	0,58	0,66	0,75	0,83	0,92	1	1,09	1,19	1,27	1,35
900	0,2	0,27	0,36	0,44	0,52	0,61	0,7	0,78	0,86	0,95	1,02	1,1	1,18	1,26
1100	0,18	0,26	0,34	0,42	0,5	0,58	0,67	0,73	0,82	0,9	0,96	1,05	1,12	1,2
1350	0,16	0,24	0,32	0,39	0,47	0,54	0,6	0,69	0,77	0,83	0,9	0,95	1,04	1,1
1750	0,15	0,22	0,3	0,36	0,42	0,49	0,56	0,63	0,7	0,76	0,82	0,89	0,95	1,02
2250	0,14	0,21	0,27	0,33	0,4	0,46	0,52	0,58	0,65	0,71	0,77	0,83	0,89	0,95
2750	0,13	0,19	0,26	0,32	0,38	0,44	0,5	0,55	0,61	0,67	0,73	0,78	0,84	0,9
3500	0,12	0,18	0,23	0,29	0,34	0,4	0,45	0,51	0,56	0,61	0,66	0,71	0,77	0,82
5000	0,11	0,16	0,21	0,26	0,3	0,35	0,4	0,45	0,49	0,54	0,59	0,63	0,68	0,72
7000	0,1	0,14	0,19	0,23	0,28	0,32	0,37	0,41	0,46	0,5	0,54	0,58	0,62	0,66
13000	0,1	0,13	0,19	0,22	0,28	0,31	0,35	0,4	0,45	0,49	0,53	0,57	0,6	0,63

Figure C.1: Relative growth index (RGI) table with specific growth rates for given temperatures in °C and size in grams for Atlantic salmon, received from Næstvold (2020).

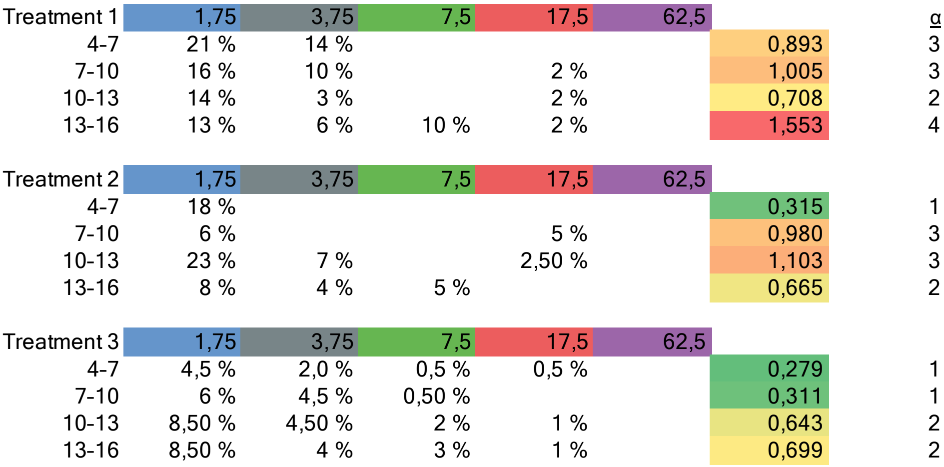
D Daily Natural Mortality



```
dag "pred"
1  0                0.096317531489911     51  66.1322645290581 0.0180761177854935  101 132.264529058116 0.0205680717429192
2  1.32264529058116 0.057617999700052     52  67.4549098196393 0.0181078010914253  102 133.587174348697 0.020625816056935
3  2.64529058116232 0.0442397688933241    53  68.7775551102204 0.0181410199790409  103 134.909819639279 0.0206836460748706
4  3.96793587174349 0.0372268420500988    54  70.1002004008016 0.0181756822692575  104 136.23246492986  0.020741555656793
5  5.29058116232465 0.0328615427168499    55  71.4228456913828 0.0182117023409414  105 137.555110220441 0.0207995389143611
6  6.61322645290581 0.0298707863554314    56  72.7454909819639 0.0182490005610752  106 138.877755511022 0.0208575901990324
7  7.93587174348697 0.027691927889224     57  74.0681362725451 0.018287502775853   107 140.200400801603 0.0209157040909172
8  9.25851703406814 0.0260353757678854    58  75.3907815631263 0.0183271398504402  108 141.523046092184 0.0209738753880858
9  10.5811623246493 0.0247359528497323    59  76.7134268537074 0.0183678472542254  109 142.845691382766 0.0210320990965884
10  11.9038076152305 0.0236921673426991   60  78.0360721442886 0.0184095646889022  110 144.168336673347 0.0210903704210432
11  13.2264529058116 0.0228380293778945   61  79.3587174348697 0.0184522357502385  111 145.490981963928 0.0211486847555832
12  14.5490981963928 0.0221286777093265   62  80.6813627254509 0.0184958076212257  112 146.813627254509 0.021207037675369
13  15.8717434869739 0.0215324958620182   63  82.0040080160321 0.0185402307959102  113 148.13627254509  0.0212654249286054
14  17.1943887775551 0.0210265284959311   64  83.3266533066132 0.0185854588270554  114 149.458917835671 0.021323842428845
15  18.5170340681363 0.0205936861779371   65  84.6492985971944 0.018631448095765   115 150.781563126253 0.021382286247739
16  19.8396793587174 0.0202209720266725   66  85.9719438877756 0.0186781576034238  116 152.104208416834 0.0214407526082352
17  21.1623246492986 0.0198983179506625   67  87.2945891783567 0.0187255487808609  117 153.426853707415 0.0214992378780109
18  22.4849699398798 0.0196177982633138   68  88.6172344689379 0.0187735853130923  118 154.749498997996 0.0215577385632552
19  23.8076152304609 0.0193730849896952   69  89.939879759519  0.018822329804851   119 156.072144288577 0.0216162513028491
20  25.1302605210421 0.0191590621236767   70  91.2625250501002 0.0188714595126385  120 157.394789579158 0.0216747728627411
21  26.4529058116232 0.0189715468967502   71  92.5851703406814 0.0189212344534598  121 158.717434869739 0.0217333001305952
22  27.7755511022044 0.0188070849695672   72  93.9078156312625 0.0189715290384246  122 160.040080160321 0.0217918301107901
23  29.0981963927856 0.0186627975878012   73  95.2304609218437 0.0190223160814318  123 161.362725450902 0.0218503599195858
24  30.4208416833667 0.0185362657774415   74  96.5531062124249 0.0190735698697945  124 162.685370741483 0.0219088867805003
25  31.7434869739479 0.0184254415511557   75  97.875751503006  0.019125266068335   125 164.008016032064 0.0219674080199968
26  33.0661322645291 0.0183285790627576   76  99.1983967935872 0.0191773816308602  126 165.330661322645 0.0220259210633143
27  34.3887775551102 0.0182441805674423   77  100.521042084168 0.0192298947176197  127 166.653306613226 0.0220844234304635
28  35.7114228456914 0.0181709536272731   78  101.843687374749 0.0192827846196009  128 167.975951903808 0.0221429127324904
29  37.0340681362725 0.0181077769534553   79  103.166332665331 0.0193360316886003  129 169.298597194389 0.0222013866678703
30  38.3567134268537 0.0180536728494623   80  104.488977955912 0.0193896172717514  130 170.62124248497  0.0222598430190291
31  39.6793587174349 0.0180077848267076   81  105.811623246493 0.0194435236512     131 171.943887775551 0.0223182796490942
32  41.002004008016  0.0179693593265778   82  107.134268537074 0.0194977339883732  132 173.266533066132 0.022376694498766
33  42.3246492985972 0.017937730649188    83  108.456913827655 0.0195522322716102  133 174.589178356713 0.0224350855832879
34  43.6472945891784 0.0179123084559608   84  109.779559118236 0.0196070032676764  134 175.911823647295 0.0224934509896111
35  44.9699398797595 0.0178925673761944   85  111.102204408818 0.0196620324769789  135 177.234468937876 0.0225517888736715
36  46.2925851703407 0.0178780382838717   86  112.424849699399 0.0197173060913512  136 178.557114228457 0.0226100974577447
37  47.6152304609218 0.0178683009391812   87  113.74749498998  0.0197728109547736  137 179.879759519038 0.022668375027963
38  48.937875751503  0.0178629777756579   88  115.070140280561 0.0198285345271037  138 181.202404809619 0.0227266199319387
39  50.2605210420842 0.0178617286093316   89  116.392785571142 0.0198844648498012  139 182.5250501002   0.0227848305764499
40  51.5831663326653 0.0178642461103464   90  117.715430861723 0.0199405905138743  140 183.847695390782 0.0228430054252587
41  52.9058116232465 0.0178702519304436   91  119.038076152305 0.0199969006302897  141 185.170340681363 0.0229011429970311
42  54.2284569138277 0.0178794933652549   92  120.360721442886 0.0200533848019572  142 186.492985971944 0.0229592418633073
43  55.5511022044088 0.0178917404616911   93  121.683366733467 0.0201100330973985  143 187.815631262525 0.0230173006465797
44  56.87374749499   0.0179067835168115   94  123.006012024048 0.0201668360264379  144 189.138276553106 0.0230753180184671
45  58.1963927855711 0.0179244309005286   95  124.328657314629 0.0202237845171596  145 190.460921843687 0.0231332926979303
46  59.5190380761523 0.017944507148035    96  125.65130260521  0.0202808698941456  146 191.783567134269 0.0231912234495746
47  60.8416833667335 0.0179668512942196   97  126.973947895792 0.0203380838583716  147 193.10621242485  0.023249109082043
48  62.1643286573146 0.0179913154117096   98  128.296593186373 0.0203954184681429  148 194.428857715431 0.0233069484464438
49  63.4869739478958 0.0180177633177492   99  129.619238476954 0.0204528661210085  149 195.751503006012 0.0233647404348486
50  64.809619238477  0.0180460694351276   100 130.941883767535 0.0205104195370295  150 197.074148296593 0.0234224839788729
```

Figure D.1: Predictions of daily mortality in percent based on ongoing research from the Norwegian Computing Center. Displays the first 150 of 500 days after release, given in percent, (Tvete, 2020).

E Estimates of Treatment Mortality

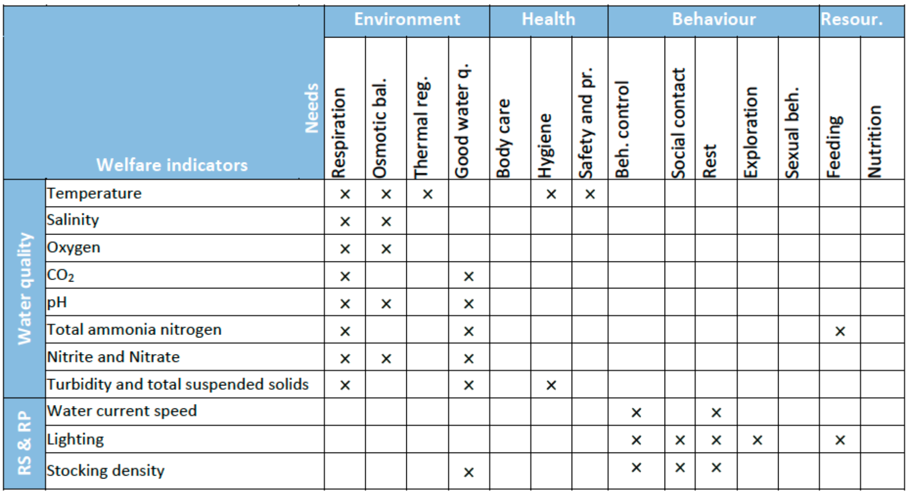


Treatment 1	1,75	3,75	7,5	17,5	62,5		α
4-7	21 %	14 %				0,893	3
7-10	16 %	10 %		2 %		1,005	3
10-13	14 %	3 %		2 %		0,708	2
13-16	13 %	6 %	10 %	2 %		1,553	4
Treatment 2	1,75	3,75	7,5	17,5	62,5		
4-7	18 %					0,315	1
7-10	6 %			5 %		0,980	3
10-13	23 %	7 %		2,50 %		1,103	3
13-16	8 %	4 %	5 %			0,665	2
Treatment 3	1,75	3,75	7,5	17,5	62,5		
4-7	4,5 %	2,0 %	0,5 %	0,5 %		0,279	1
7-10	6 %	4,5 %	0,50 %			0,311	1
10-13	8,50 %	4,50 %	2 %	1 %		0,643	2
13-16	8,50 %	4 %	3 %	1 %		0,699	2

Figure E.1: Determination of α-values, ranging from 1–4 and 4 being the worst case. Mortality was given as an increase in %-points and sorted into five intervals, and here the mean value of the intervals are used. Frequencies are based on treatment mortality from 2015–2017, despite treatment type 3 which had data from 2012, (Glover K et al., 2018). Finally, expected values for treatment mortality was used for estimating α-values.

F Environment Based Welfare Indicators

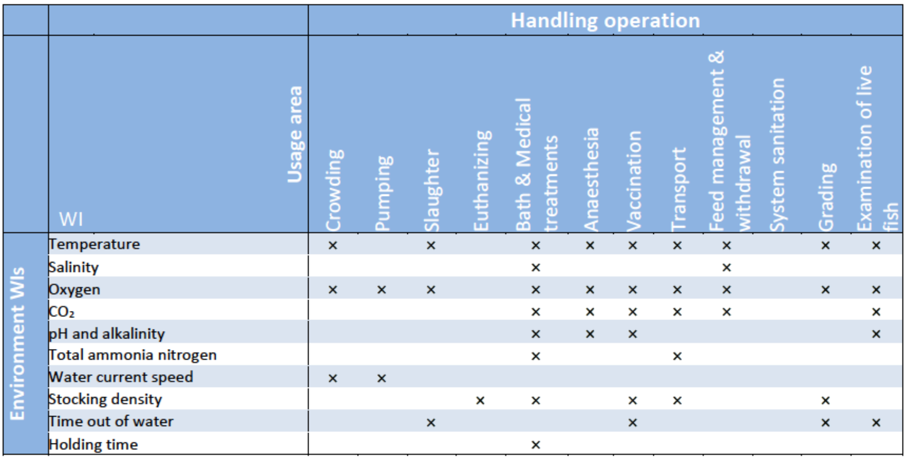
F.1 Welfare Needs



	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 F.1: List of environment based welfare indicators and the welfare needs of salmon they affect. RS & RP = rearing systems and rearing practices, (Noble et al., 2018).

F.2 Operational Welfare Indicators

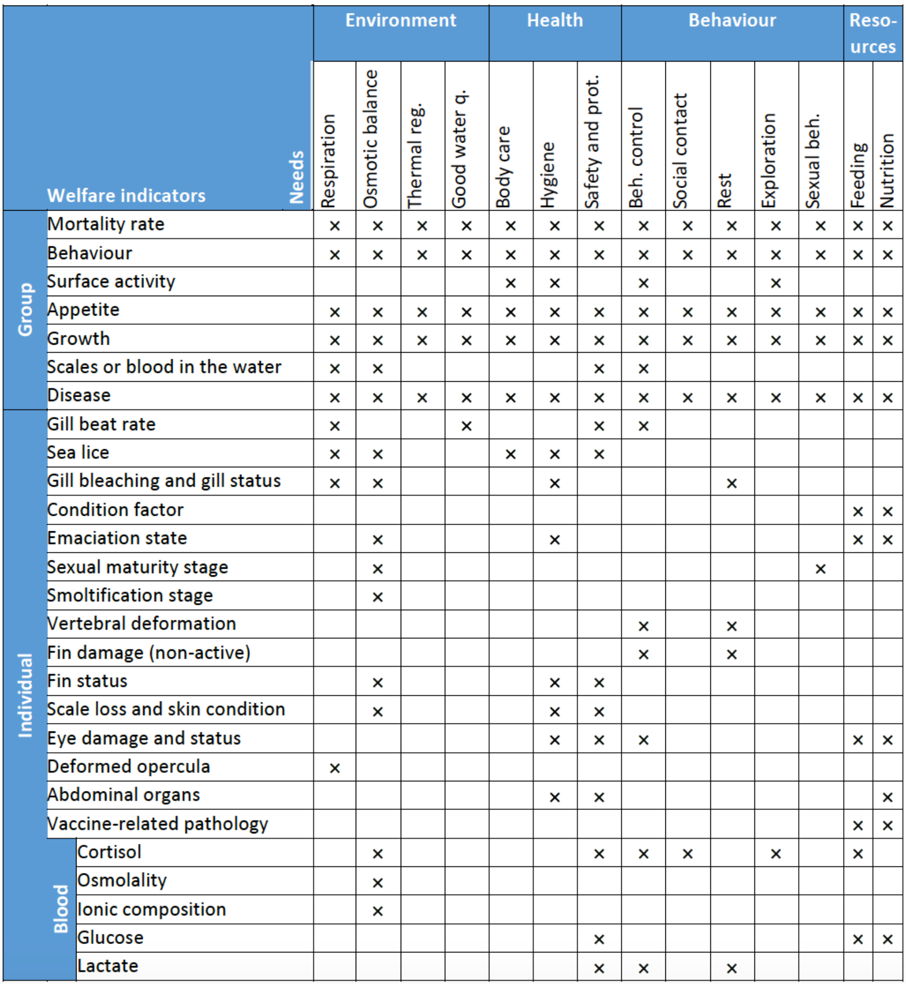


		Handling operation											
	WI / Usage area	Crowding	Pumping	Slaughter	Euthanizing	Bath & Medical treatments	Anaesthesia	Vaccination	Transport	Feed management & withdrawal	System sanitation	Grading	Examination of live fish
Environment WIs	Temperature	×		×		×	×	×	×	×		×	×
	Salinity					×				×			
	Oxygen	×	×	×		×	×	×	×	×		×	×
	CO_2					×	×	×	×	×			×
	pH and alkalinity					×	×	×					×
	Total ammonia nitrogen					×			×				
	Water current speed	×	×										
	Stocking density				×	×		×	×			×	
	Time out of water			×				×				×	×
	Holding time					×							

Figure F.2: List of environment based welfare indicators that are intended for different handling operations, (Noble et al., 2018).

G Animal Based Welfare Indicators

G.1 Welfare Needs



		Needs	Environment				Health			Behaviour					Reso-urces	
		Welfare indicators	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 G.1: List of animal based welfare indicators and the welfare needs of salmon they affect, (Noble et al., 2018).

G.2 Operational Welfare Indicators

		Handling operation											
	WI / Usage area	Crowding	Pumping	Slaughter	Euthanizing	Bath & Medical treatments	Anaesthesia	Vaccination	Transport	Feed management & withdrawal	System sanitation	Grading	Examination of live fish
Group WIs	Mortality rate - acute	×	×	×		×	×	×	×		×	×	×
	• Longer-term	×	×			×	×	×	×	×	×	×	×
	Behaviour	×	×	×	×	×	×	×	×	×	×	×	×
	• Bellies showing	×	×		×	×	×	×	×		×	×	×
	• Equilibrium loss					×	×	×	×		×	×	×
	• Abnormal swimming	×	×		×	×	×	×	×	×	×	×	×
	• Crowding Scale	×	×			×		×	×			×	×
	• Gasping at the surface	×	×		×	×	×	×	×		×		×
	• Vertical swimming	×				×		×					
	• Head shaking					×	×		×				
	• Clumping	×				×		×	×		×	×	
	• Aggression									×			
	Appetite	×	×			×	×	×	×	×	×	×	×
	• Growth	×	×			×		×		×	×	×	
	Disease and health status	×	×	×	×	×	×	×	×	×	×	×	×
	Emaciated fish									×			×
	Scales or blood in water	×	×	×	×	×	×	×	×				×
	Bulk oxygen uptake								×				
	Change in skin colour – blue to green	×			×	×							
Individual WIs	Handling trauma	×	×	×	×	×	×	×	×		×	×	×
	• Scale loss and skin condition	×	×	×	×	×	×	×	×	×	×	×	×
	• Mouth jaw wound	×	×	×	×	×			×		×	×	×
	• Fin damage and fin status	×	×	×	×	×	×	×	×	×	×	×	×
	• Eye haemorrhage and status	×	×	×	×	×			×	×	×	×	×
	• Haemorrhaging		×	×									
	Cataract					×							
	Reflex, eye rolling			×	×		×	×					×
	AGD score	×	×			×							×
	Gill bleaching and status	×	×			×		×	×				×
	Gill beat rate	×		×	×	×	×	×	×				×
	Opercula damage	×	×							×	×		×
	Condition factor									×			×
	Moribund fish			×		×			×		×	×	×
	Emaciation state			×						×			
	Correctly adjusted blow if percussive stunning/killing			×	×								
	Vaccine related pathology (Speilberg score)							×					
	Feed in the intestine			×		×		×		×			
	Muscle pH	×	×	×						×			
	Pre-rigor time	×	×	×									
Blood	Cortisol	×	×						×				
	Glucose	×	×						×	×			
	Lactate	×	×						×	×			
	pH			×									

Figure G.2: Summary of the animal based OWIs and LABWIs that are intended for different handling operations, (Noble et al., 2018).

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