The economic sustainability of land-based aquaculture systems:

An integrated analysis

by

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ABSTRACT

The global demand for fish is rising, caused by population growth and an increasing per capita consumption of fish. At the same time, production from capture fisheries has stagnated and there are growing concerns about the environmental impact of sea-based aquaculture. Future developments in the fishing industry must meet demand, without compromising the environment. Technological advancements have introduced land-based fish farming and Recirculating Aquaculture Systems (RAS) technology as a potential way forward. This type of production could potentially give an opportunity to produce large quantities of biomass in a controlled environment. There is, however, large uncertainty regarding the economic sustainability of this type of production.

This research aimed to evaluate under what conditions land-based aquaculture can be economically sustainable. The boundaries were set to a hypothetical land-based aquaculture facility in Norway, and a system dynamics approach was used. Land-based aquaculture systems are complex and consist of a large number of integrated components and processes. System dynamics is a useful method in this context, because it allows for an integrated and systemic analysis of the functioning of these systems.

The results of the study indicate that land-based aquaculture production can be economically sustainable, given optimal system performance, full capacity utilization and stable market conditions. The results also support the underlying assumption that land-based aquaculture production is relatively resource efficient and environmentally friendly. One limitation of this study is the uncertainty related to the aggregated effect of water quality on biomass growth and mortality rates, which is an important area for further research. One additional suggestion for further research is to extend the environmental analysis, in order to fully assess the potential environmental impact of land-based aquaculture production and how this links to economic sustainability.

Key words: Land-based aquaculture, Recirculating Aquaculture Systems technology, Atlantic salmon (*Salmo salar*), Biofilter management, System Dynamics.

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1. Introduction

The global demand for fish is rising, caused by population growth and an increasing per capita consumption of fish. At the same time, the production of capture fisheries has stagnated and reports are suggesting that around 90% of global capture fisheries are currently being over-fished, or fished at carrying capacity (Lem, Bjorndal, & Lappo, 2014). Aquaculture farming is an alternative to traditional capture fisheries. Aquaculture is "the farming of aquatic organisms" (Timmons, et al., 2002, p. 5). It gives an opportunity to increase production without putting additional pressure on marine ecosystems, or further contributing to over-fishing the seas. Aquaculture production has been growing rapidly over the last decades, and is expected to continue to do so. By 2030, it is projected that 62% of the global fish supply will come from aquaculture production, compared to 43% in 2012. By 2050, aquaculture production is likely to be the main source of fish on the global market (FAO, 2014; World Bank, 2013).

In Norway, aquaculture was introduced in 1970. Since then fish production has become a major source of income and an important factor for the Norwegian economy. The demand for Norwegian fish is rising, and the production of the Norwegian aquaculture industry has been growing steadily over the last decades. In some periods the annual production growth rate has been 35% (Bergheim, 1991). The dominant specie being produced is the Atlantic salmon, representing around 94% of the total production (Norwegian Ministry of Trade, 2014a). However, concerns have been raised about the ecological impact of the Norwegian aquaculture industry. These concerns are for instance related to pollution, the spread of disease, and fish escaping from the production sites. One example of a pollution related issue is that organic compounds, dissolved nitrogen and dissolved phosphorus are being discharged directly to the water surrounding the production sites (Norwegian Ministry of Trade, 2014b). One of the main challenges in terms of disease outbreaks is *Salmon lice,* a parasite found on salmonids. Salmon lice are naturally occurring, but the outbreaks are becoming larger and more severe as a consequence of intensive fish farming. Salmon lice affect not only the farmed fish, but also spread to wild salmon populations and to other species of fish. Salmon lice larvae move over large coastal areas with water currents, sometimes as far as 100 km from the source of the original outbreak (Thorstad, et al., 2014). There are methods to cope with the problem, for example chemical treatment of farmed fish, mechanical removal or use of lice eating fish. The long-term goal is to reduce the usage of chemical treatment and medicinal products, in order to ensure food security and as the lice have the ability to become immune to the medicines. If lice outbreaks become severe, authorities can demand slaughtering of the stocks (Norwegian Ministry of Trade, 2014b). Emerging bacterial disease could also become an issue as new fish species are becoming cultivated in Norway, with a rising use of antibiotics as a consequence (Gravea, et al., 2008). When it comes to the issue of farmed fish escaping from the production sites, a monitoring program was started in 1988. The number of escapes has been above recommended levels every year since the start of the program (NASCO, 2008). In total, over 5 million escapes have been reported to the Directorate of Fisheries, and it is likely that this is only a fraction of the real number of escapes (Norwegian Ministry of Trade, 2014b). Farmed salmon interbreeding with wild populations of salmon damages genetic diversity and lowers fish fitness and productivity. Hence, salmon escaping from the production sites poses a significant threat to wild salmon populations (McGinnity, 2003). In conclusion, future developments in the fish farming industry need to ensure a more environmentally friendly production.

One potential solution to the problems of sea-based fish farming is to move the production to land-based facilities. There have been advancements in fish farming technology in the last decades, and land-based aquaculture facilities and the related technology are now being considered as a potential way forward. A carefully managed land-based farm could minimize pollution, waste and spread of disease. On the other hand, land-based production comes with other types of environmental implications, mainly related to resource use. Concerns have been raised about the areas of land needed to build land-based farms, as well as about the energy- and water use required to run the facilities. The resource use for production depends on the design of the facility, as well as the technology used. Land-based aquaculture can employ a water flow-through system (where water flows through the facilities and is replaced with new water), a partial reuse system or a Recirculating Aquaculture System - RAS (Bergheim, Drengstig, & Fivelstad, 2009). This research will focus on land-based aquaculture using RAS technology. This type of technology consists of organized and integrated processes, making it possible to reuse water in the production cycle. After leaving one fish tank, the water is treated and then reused in the same or another fish tank (Timmons, et al., 2002). From a resource conservation point of view, RAS is beneficial since it minimizes the water demand for production. The facility would, however, still have environmental impacts in terms of land and energy use. Aside from the environmental aspect, the main challenge when scaling up land-based production is the long-term economic sustainability of the farms. Land-based fish farming requires significant investment costs, as well as high operational costs. It is also likely that the facilities need to run close to carrying capacity in order to be economically sustainable - which generates high levels of risk (Masser, Rakocy, & Losordo, 1992).

The remaining question is whether these facilities can be constructed in a way that makes them economically sustainable. Previous research in the field has mainly focused on understanding separate parts and specific relationships in a land-based aquaculture system. This research aims to integrate the separate parts into a dynamic model, in order to explore the behavior arising when the different components of the system interact over time. This gives an opportunity to conduct a systemic and integrated analysis of the long-term economic sustainability of these systems.

1.1 Research questions and objective

The research question to be answered in this research is:

- Under what conditions can land-based aquaculture systems in Norway, using RAS technology, be economically sustainable?

In order to answer the main research question, the following three sub-questions must be answered:

- What is the internal dynamic behavior of a land-based aquaculture system?
- Which are the main factors explaining the dynamic behavior of a land-based aquaculture system?
- What determines the economic performance of a land-based aquaculture facility?

The research objective is to develop a quantified, explanatory system dynamics model in order to understand the dynamic behavior arising when the different components of a land-based aquaculture system interact. The model will be used to perform an integrated and systemic analysis to evaluate the economic sustainability of a hypothetical land-based aquaculture system in Norway. The aim is also to construct the model in a way that makes it possible for actors considering market entry, as well as for policy makers, to use it as a learning tool.

1.2 Outline

The first chapter served to give an introduction to land-based aquaculture production. In addition, the research questions and research objective were stated. The remaining part of this thesis is structured as follows. Chapter 2 presents System Dynamics, and motivates why this method is applicable in the context of this research. Chapter 3 gives a theoretical background to the components and processes of a land-based aquaculture system. Thereafter, Chapter 4 introduces the model. A Causal Loop Diagram (CLD) is presented, as well as the model structure in the form of stock and flow diagrams. Chapter 5 gives a presentation and analysis of the simulated behavior under different scenarios. Chapter 6 discusses these results, both from an economic and environmental point of view. Finally, Chapter 7 provides concluding statements, scientific and practical implications of the results, as well as recommendations for further research.

2. Methods

This chapter gives an introduction to System Dynamics, and motivates this choice of method. It also presents the methods used for data collection and analysis. Lastly, it discusses how economic sustainability has been evaluated in the context of this research.

2.1 Research approach and design

"*System dynamics deals with the time-dependent behavior of managed systems with the aim of describing the system and understanding, through qualitative and quantitative models, how information feedback governs its behavior, and designing robust information feedback structures and control policies through simulation and optimization"* (Coyle, 1996, p. 10).

A system dynamics approach has been used in this research in order to create an integrated, quantitative model to assess the economic sustainability of land-based aquaculture production. System Dynamics is a methodology and a tool used to understand and manage complex systems. It dates back to the 1950´s, when it was created by Professor J. Forrester at the Massachusetts Institute of Technology. System Dynamics is truly interdisciplinary - grounded in physics, engineering and mathematics but also incorporating psychology, economics and other social sciences. A complex system is characterized by non-linarites, feedback loops, and cause and effect distant in space and time (Sterman, 2000). System Dynamics is a useful approach when exploring and analyzing land-based aquaculture systems, since they have all the characteristics of a complex system.

1) Feedback-loops: There are numerous feedbacks within an aquaculture facility, creating a complex web of interacting variables and processes that a manager of such a system needs to be aware of. For instance: oxygen concentration is one water quality parameter affecting fish growth rate and welfare. At the same time the fish consumes oxygen, and does so have an impact on the oxygen concentration. The more oxygen available, the larger the growth and survival rate of the fish, the more oxygen is consumed and the less oxygen becomes available. This is an example of a balancing feedback loop within the system. Managers of land-based aquaculture facilities need to know how different factors interact with each other and actively make sure that they fall within an optimal range at all times of system operation.
2) Non-linarites: There are many non-linear effects within a land-based aquaculture system, for instance the effect of temperature on biomass growth rate. At optimal temperatures the growth rate will be close to 100% of the maximum growth possible. If temperatures rise above or fall below the optimal, then the effect on biomass growth will change drastically, non-proportional to the change in temperature. A small disturbance in one part of the system can thus have a large, non-proportional impact on other parts of the system.
3) Cause and effect distant in space and time: In a closed aquaculture facility there are delays between cause and effect. One example is the accumulation of CO_2, nitrogen compounds, suspended solids, and other factors affecting the functioning of the system. These compounds need to be actively removed, which takes time. In addition, the effects of these particles and other factors accumulating in the system will become evident in different time horizons. Some effects will be visible in the long-term, such as the effect of insufficient photosynthesis on biomass growth rates. Other effects are more direct, such as the effect of low oxygen concentrations on fish mortality.

Understanding the complexity and the internal dynamics of a land-based aquaculture system is important in the context of this research, as the functioning of the system governs the biological production process. The biomass quantity produced will, in turn, affect the financial performance of the firm, through revenue streams and production costs. System dynamics modeling and analysis, based on simulation, can help explore the dynamic behavior arising when all parts of the system interplay – thus making it possible to evaluate the economic sustainability of land-based aquaculture production.

Using system dynamics also allows for testing of "what if"-scenarios. These scenarios could answer questions such as "what happens to profitability if the market price of fish decreases", or "how does the energy consumption change if the production intensity decreases?" Therefore, the model constructed in this research project could also function as a management tool, beyond the specific context of this study.

2.2 Data collection and analysis

Secondary data have been the main sources of data in this research. Departing from the research question, relevant data include cost estimates for production in aquaculture and safe ranges for water quality parameters in the system. Data have been retrieved from open sources such as the Norwegian Directorate of Fisheries, the World Bank, the Food and Agriculture Organization of the United Nations (FAO) and fisheries.no[1]. Additional data have been obtained from actors within the aquaculture industry in Norway. The data have been analyzed following the guidelines given in Saunders and Lewis (2012). The suitability of the data has thus been based on its relevance, the original purpose of the research from which the data was obtained, and the method used to collect the data (Saunders & Lewis, 2012, pp. 96-97).

In addition, one session using participatory modeling[2] was carried out. The participant in the session was an expert working with research and development at Norsk Sjømatsenter[3] in Norway. The session served to identify and validate relationships and parameter values used in the quantitative model, in particular where numerical data were missing or regarded as uncertain. In system dynamics, a distinction between numerical, written and mental data is often used. When dealing with complex systems, a large source of information is the mental

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[1] The official webpage for information on fisheries, aquaculture management and food safety in Norway, provided by among others the Institute of Marine Research, the Norwegian Food safety Authority, and the Norwegian Ministry of Trade.

[2] Participatory modeling aims to involve stakeholders in the modeling process, often used as a method to support decision making in organizations. For more information about participatory modeling, see Vennix (1996).

[3] Norsk Sjømatsenter is a foundation working with development of seafood, public outreach and consultancy towards companies - and one of the actors currently assessing the feasibility of land-based aquaculture in Norway. For more information, see http://en.sjomat.no/about-us/.

data stored in people’s minds - including both experiences and observations (Forrester, 1992). The person participating in the modeling session was therefore chosen based on her specific knowledge, expertise and real-world experience with aquaculture systems.

2.3 Evaluating the economic sustainability of land-based aquaculture

In the context of this research, economic sustainability refers to the ability of a land-based aquaculture facility to be profitable in the long-run, while using resources efficiently and minimizing environmental impact. Economic and environmental sustainability are interlinked. Therefore, the economic sustainability of land-based aquaculture cannot be assessed without taking environmental aspects into account. Land-based aquaculture is introduced as an alternative to sea-based fish farming, potentially offering a more environmentally friendly production process. Given the assumption that land-based aquaculture has the potential to be environmentally sustainable, there is still a need to evaluate the economic performance of this type of production.

In the context of this study, three indicators have been chosen to evaluate the economic sustainability of a hypothetical land-based farm:

1) Earnings before interest and tax (EBIT). Calculated as revenue minus expenses, not taking taxes or interest payments into account. EBIT serves to give an indication of the overall profitability of the firm. It is a useful indicator as it takes out the effect of different capital structures, tax rates and interest rates, hence making it easier to compare the profitability of different firms.
2) The simulated production cost of one kilogram biomass in a land-based facility, relative to the production cost of one kilogram biomass in a sea-based facility. The relative production cost will serve as an indicator of market competitiveness. In order for a land-based facility to be economically sustainable, it needs to be able to compete with other actors in the market.
3) The Total Loan Coverage, given an estimated interest rate and a specific mortgage time, which can be supported by the simulated EBIT of the firm. The Total Loan Coverage gives an idea of the ability to cover initial investments in the facility - giving potential investors and other actors an idea about the feasibility of establishing a land-based aquaculture facility.

The indicators have been chosen in collaboration with the participants from Norsk Sjømatsenter. Their expertise and practical experience with aquaculture systems served as a basis for the discussion regarding potential indicators to use. A main criterion in this process was to ensure that the indicators would be useful for potential investors and for other actors interested in land-based aquaculture. Additionally, economic reports on sea-based production were analyzed - evaluating whether or not the indicators used in these reports could be applicable also in the context of land-based aquaculture.

3. Theoretical background

The economic performance of a land-based aquaculture facility is dependent on a number of factors. Aquaculture is often classified as capital intense, requiring large initial investments and financial resources. To assess the economic performance of a land-based aquaculture facility, it is necessary to include both revenue streams and production costs. Production costs are related to factors such as the price of production inputs and the economic loss in case of a system failure. Revenue streams are directly linked to the market price of salmon and the biomass quantity a firm is able to send to the market over time (Marine Harvest, 2014). The biological production process is related to many risk factors. In order to make an economic analysis, it is therefore important to understand the dynamics of the system. What factors affect the growth rate of the biomass? What affects the mortality rate in the system? And how do these determining factors relate to each one another and to economic sustainability? Because of the nature of a land-based facility, it is necessary to conduct an interdisciplinary analysis – integrating theories and knowledge from different fields such as engineering, biology, thermodynamics, chemistry and economics. The remaining part of this chapter provides a theoretical background to the various components and processes of land-based aquaculture systems using RAS technology. The theoretical background serves as the foundation for the model structure.

3.1 Physical structure and components of a land-based aquaculture system

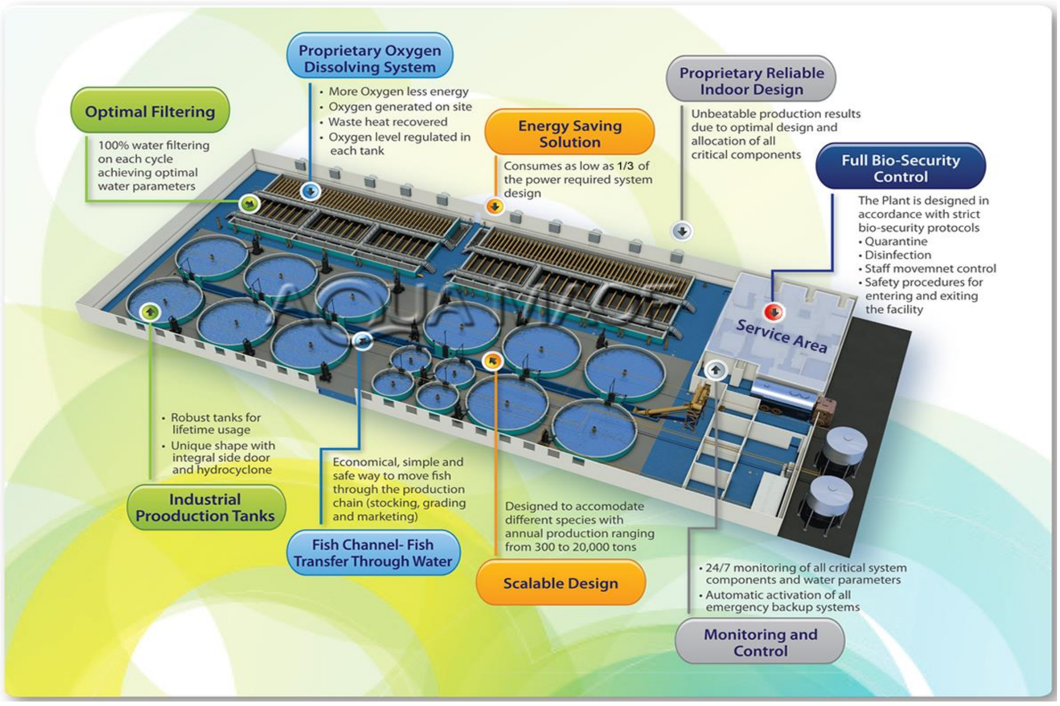

Figure 1. Potential design of a land-based facility in Tomrefjorden, Norway.
Source: AquaMaof (2014).

Figure 1 shows a potential design of a land-based facility, intended to be located in Tomrefjorden, Norway. Land-based aquaculture farms could be designed in different ways. In general, however, they consist of fish rearing tanks, back-up tanks, pumps, filters and instrumentation (Nazar, Jayakumar & Tamilmani, 2013). The fish rearing tanks could be square shaped with rounded corners, octagonal, or circular. The natural behavior of the fish is supported by a circular water flow in the tanks. New water is usually introduced at the side of the tank and then it moves tangential along the tank wall. Once the incoming water gains momentum it will adjust to the movement of the water already in the tank, and little energy will be required to keep its momentum (Nazar, Jayakumar & Tamilmani, 2013). The production capacity of the facility is determined by the total volume of the tanks in combination with the stocking density, measured in kilograms of biomass per cubic meter.

Water treatment processes are designed to ensure optimal water quality in the tanks. Depending on the specie being cultivated and the production intensity, one or more of the following treatment processes might be required; filters to remove particulate solids, biological filters to remove ammonia and nitrite, aerators to add oxygen and strippers to remove carbon dioxide. Other parameters to be monitored and controlled in order to ensure optimal production conditions are water temperature, light, and pH-levels (Losordo, Masser, & Rakocy, 1999). Most recirculation systems are designed to exchange 5-10 percent of the water volume in the system each day. After every production cycle all water in the rearing tanks should be replaced. These measures will prohibit the accumulation of nitrogen compounds and organic waste (Masser, Rakocy, & Losordo, 1992).

Figure 2 shows how water flows and treatment processes in the facility can be organized. Firstly, the water is moved from the fish rearing tank through a particle filter. The circular flow of water within the fish tanks will through centrifugal forces move solids towards the center drain area, where they can be removed relatively easily. Various types of filters may be used to remove the particulate waste, such as screen filters, drum filters, sand filters and bead filters. Very small particles can be removed using “foam fractionation”, a process where solids are absorbed by rising air bubbles in the column and subsequently removed when reaching the surface area (Nazar, Jayakumar & Tamilmani, 2013).

After passing through the first particle filter, the water reaches a water reservoir tank. In this tank the water pH-level is usually adjusted through the addition of alkalinity buffers, and new water is added. In the next stage the water will pass through the biofilter. Biological filtration is an important treatment process of water in a closed aquaculture system. A biofilter consists of bacteria attached to a medium, such as sand, gravel or plastic structures. It converts ammonia in to nitrite and nitrate. Hence it regulates these nitrogen compounds so that they do not reach toxic concentrations in the system. A larger surface area of the filter media yields a higher conversion rate. A relatively new biofilter solution is to introduce a moving bed reactor in the system - a plastic media that is continuously moving (Nazar, Jayakumar, & Tamilmani, 2013). Biofilters and the related processes will be explained more in depth in Section 3.2.5.

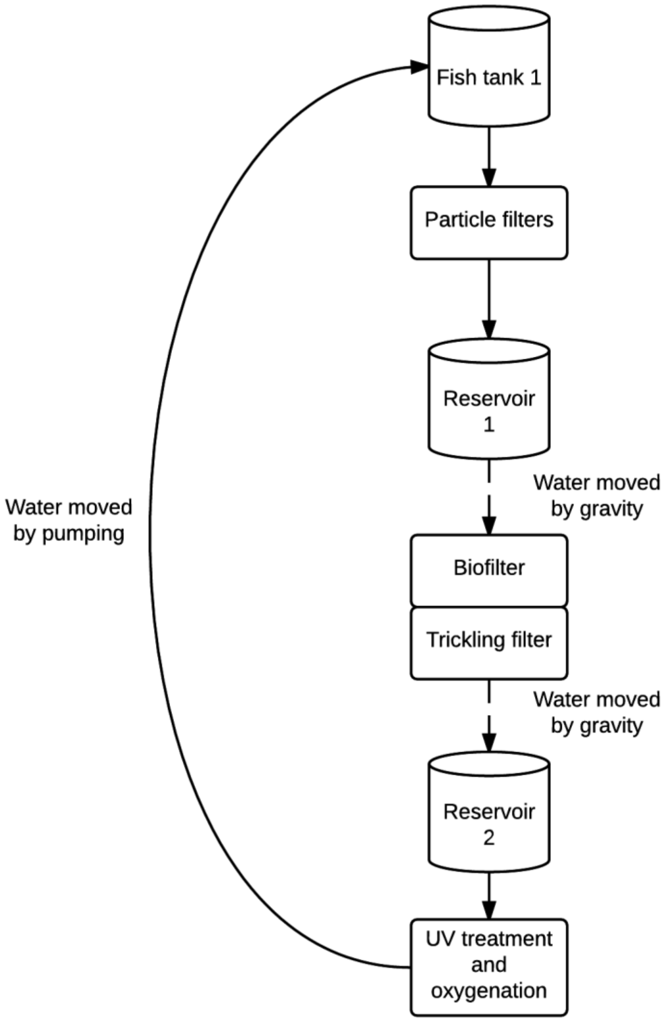

Figure 2. Water flows and treatment processes in a recirculating aquaculture system.
Source: Graphical representation adapted from Hald Olsen, 2015.

In the next stage, the water passes through a trickling filter. The most important part at this stage is the removal of dissolved CO_2 gas. After passing through the trickling filter the water reaches reservoir two. In this tank the temperature is regulated to the optimal temperature for the specific type of fish being cultivated. Temperature can be controlled with either heaters or chillers (Nazar, Jayakumar, & Tamilmani, 2013). Next step is regulation of oxygen concentrations. Saturated water contains the maximum amount of oxygen that can be dissolved at a given temperature and pressure. In order to keep oxygen concentrations at the optimal level in the rearing tanks so called supersaturated water is mixed with the water in the tanks. Air diffusers are often placed in the bottom of a tank, putting air in contact with the water by producing small bubbles that rise through the tank. The amount of oxygen dissolved will depend on the size of the bubbles, as well as the depth of the tank – the smaller the bubbles and longer the water column the longer time it will take for the bubbles to rise and the higher the dissolution (Nazar, Jayakumar, & Tamilmani, 2013). Lastly, the treated water is pumped back to the fish tank. As shown in Figure 2, not all water has to be moved by pumps since the system can be designed to make use of gravity. This allows for more energy efficient transportation of water (Hald Olsen, 2015).

3.2 Water quality in a land-based recirculation system

Water quality management is one of the most critical challenges in a closed containment system. Water quality will affect the growth rate and welfare of the fish, as well as the biofilter efficiency. The following section gives an overview of important water quality parameters and processes, and in what ways these parameters affect the biomass and biofilter. The water quality parameters and other factors included are dissolved oxygen, temperature, light, pH, dissolved CO_2, nitrogen compounds, stocking density, feed and waste solids. Each one of these parameters and factors are important on their own, but it is the interrelationship of them that determines the aggregated effect on the system.

3.2.1 Dissolved oxygen

Oxygen is consumed both by the fish and the nitrifying bacteria in the biofilter. Oxygen demand will fluctuate over time, and the oxygen concentration in the tanks will change correspondingly. Hence, keeping oxygen concentrations within an optimal range and accommodating these fluctuations, without compromising the growth or welfare of the fish, is a fundamental requirement for a well-functioning system.

The oxygen consumption of the fish depends on a number of factors. As body mass increase, oxygen consumption per unit of body mass decreases exponentially. Oxygen consumption increases with increasing temperature, growth rate and swimming velocity. Oxygen consumption might also increase if the fish is exposed to stress. Additionally, oxygen consumption depends on feeding rate (Thorarensen & Farrell, 2011). There are different models to estimate oxygen demand in the rearing tanks. These models could however generate quite different estimates, as the oxygen demand depends on a number of factors that are interacting in complex ways. Empirically, oxygen consumption can be calculated using the *Fick equation*, measuring the difference between the oxygen concentration of the inflowing water ($O_{2\,IN}$) and the oxygen concentration of the outflowing water($O_{2\,OUT}$):

$$Consumption_{02} = Q * (O_{2\,IN} - O_{2\,OUT})$$

Where Q = water flow rate.

In this research a theoretical model, based on feeding rate, is used to estimate oxygen demand. Studies have suggested that the ratio between oxygen consumption and feed intake falls in the range of 0.25:1 - 0.5:1 (Timmons et al. 2002; Forsberg, 1997). The discrepancy between different estimates could potentially be explained by experimental errors. If for instance the feed intake is estimated to be higher than what it actually is, the calculated ratio between oxygen demand and feed intake will be too low. Additionally, the ratio between feed consumption and oxygen consumption is not constant. Oxygen consumption might be higher per feed intake when the fish is fed a small amount of feed. Moreover, if feed intake is doubled it would not lead to the oxygen consumption becoming twice as high (Forsberg, 1997). Hence, one should be aware of the relatively large error marginal when estimating the oxygen demand of the fish.

In the same way as the oxygen demand for fish could be estimated based on feeding rate, so can the oxygen demand of the biofilter. Studies suggest that, on average, 0.12 kg oxygen is consumed per kilogram feed introduced in the system (Parker, Couturier, & Benfey, 2013).

There is no consensus on the exact level of oxygen to be kept in the fish rearing tanks. One general management recommendation for fish farming is to keep oxygen concentrations above 60% air saturation. However, studies on salmonids found this level too low, and recommended using 71-81% air saturation for maximal growth and welfare among the fish. For oxygen concentrations below 50% air saturation the growth of the fish is inhibited. For oxygen concentrations above 100% air saturation there are conflicting results on the effects of these levels on the fish. There are studies indicating higher growth rates for oxygen concentrations above these levels, as well as studies finding no such evidence. Oxygen concentrations above 150% air saturation is however not recommended, as it could lead to oxygen stress, higher susceptibility to disease as well as higher mortality rates (Thorarensen & Farrell, 2011). The amount of oxygen that can be dissolved in water depends on water temperature and salinity. The higher the temperature and salinity the less oxygen can be dissolved in the water (Masser, Rakocy, & Losordo, 1992).

3.2.2 Water temperatures and light

In the natural environment of the fish, seasonal changes in growth rates are common. These cycles in growth performance can be explained by the fluctuations in temperature and hours of daylight (Thorarensen & Farrell, 2011). Aquaculture in a closed system gives the opportunity to fully control these parameters, which ensures optimal growth rates all year around (Masser, Rakocy, & Losordo, 1992). Salmon is cold-blooded and the optimal water temperature falls in the range of 8-14 degrees Celsius. Higher water temperatures make the fish more susceptibility to disease, and temperatures below 0 degrees Celsius could cause mass mortality (Marine Harvest, 2014). In addition, management should aim for extended or continuous photoperiod all year around. Only regulating water temperatures is not sufficient to reach optimal growth performance (Forsberg, 1995).

3.2.3 Water pH

The indicator of whether the water is acidic or basic, pH, is defined as the negative logarithm of the molar hydrogen ion concentration, ($-\log [H^+]$). Water with a pH below 7 is acidic and above 7 is basic. Managing pH-levels within the system is important, both for fish welfare and biofilter functioning. Fish have, on average, a blood pH of 7.4. Water in the aquaculture rearing tanks comes in contact with the fish blood when passing through blood vessels in the skin and gills. Therefore, it is desirable to keep pH-levels in the fish rearing tanks as similar as possible to the pH of fish blood. An optimal pH for fish and aquaculture falls within the range of 6-9.5, while pH-levels below 5 and above 10 cause stress and increase mortality rates (Wurts & Durborow, 1992). Rapid changes in pH (above two units) can also be stressful to fish (Masser, Rakocy, & Losordo, 1992).

Fluctuations in pH in a closed rearing system might occur as acid is produced during the nitrification process in the biofilter, and as a consequence of CO_2 being released through respiration of the fish. Optimum pH levels are maintained through addition of alkaline buffers, such as sodium bicarbonate (Masser, Rakocy, & Losordo, 1992).

3.2.4 Dissolved carbon dioxide

Fish produce CO_2 through aerobic metabolism. In seawater, dissolved CO_2 is normally not found in large concentrations. CO_2 can however start accumulating in a closed aquaculture system, especially if the system is running close to carrying capacity. Hence, CO_2 needs to be removed, either physically or chemically. Long term exposure to elevated CO_2 levels reduces growth rates, compromises welfare and has got anaesthetic effects on the fish. Exposure to highly elevated levels of CO_2 is lethal, even in the short term (Thorarensen & Farrell, 2011). CO_2 produced by the fish is mainly diffused across the gills in the form of CO_2 molecules. When released into the water a reaction occurs, where carbon acid (H_2CO_3), bicarbonate (HCO_3^-), and carbonate (CO_3^{-2}) is produced:

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{-2}$$

The proportion of CO_2 found as dissolved CO_2 gas depends on the pH-level in the water. In general, if the pH is within the range recommended for fish farming, a relatively small proportion CO_2 will remain as dissolved gas in the water. CO_2 concentrations and pH-levels are however interdependent. Releasing additional CO_2 will make the pH decrease. This will cause a shift the equilibrium, and a larger proportion dissolved CO_2 gas will be present in the water (Thorarensen & Farrell, 2011). Due to difficulties in measuring CO_2 concentrations in the system, estimates are often based on the measured pH-level.

How sensitive the fish is to elevated CO_2 concentrations, depends on a number of factors. A prominent factor is the life stage of the fish - evidence show that parr and smolts are more sensitive than post-smolts. Another factor is the water temperature, where lower temperatures increase the toxicity of dissolved CO_2 (Fivelstad, et al., 2007). Currently, the recommended maximum level of CO_2 is 20 mg/L. However, due to the interconnectedness of CO_2 toxicity and other factors, as well as findings indicating reduced growth rates and welfare at even lower levels than 20 mg/L, a precautionary approach is warranted (Thorarensen & Farrell, 2011).

3.2.5 The nitrification process the biofilter functioning

One important factor to monitor and control in a closed aquaculture system is the accumulation of nitrogen compounds. These compounds can be found in three different forms – ammonia, nitrite, and nitrate. They are all toxic to fish above certain concentrations, and could so have a negative impact on fish growth and health (Nazar, Jayakumar, & Tamilmani, 2013).

Ammonia

Ammonia (NH_3) is a by-product of the protein catabolism of the fish. It is excreted across the gills in the form of ammonia gas, and will as it is released into water bind hydrogen ions, forming the ammonium ion (NH_4^+):

$$NH_3 + H^+ \leftrightarrow NH_4^+$$

The total concentration of nitrogen, including both unionized and ionized ammonium, is called total ammonia nitrogen (TAN). The biggest concern is concentrations of ammonium in its unionized form, as it is highly toxic to fish. The relative concentration of the two ammonium compounds depends on salinity, pH and water temperature. Lowering water temperature and pH will make the concentration of ionized ammonia increase, as will an increase in salinity. A change in these factors will hence shift the balance, either making the concentration of unionized ammonia increase and the concentration of ionized ammonia decrease or vice versa (Boyd, 2000). The amount of TAN produced in a closed aquaculture system can be estimated in different ways. In this research a model based on feeding rate is used, estimating that 2.2 pounds of ammonia are added to the system per 100 pounds of feed fed to the fish (Masser, Rakocy, & Losordo, 1992).

Unionized ammonium is toxic to fish even in very small concentrations. It is toxic mainly because of its effects on the central nervous system of the fish. Other effects are gill damage, membrane instability, disturbances in the enzyme system and in osmoregulatory processes (Thorarensen & Farrell, 2011). In the short term this leads to reduced swimming ability, coughing and increased gill activity. Long term effects include increased metabolism, reduced growth rate and lower disease resistance, as well as increased mortality rates. There are different estimates of “safe levels” of unionized ammonia for Atlantic salmon production, ranging from 0.012 to 0.05 mg/l (Thorarensen & Farrell, 2011;Masser, Rakocy, & Losordo, 1992).

Nitrite and nitrate

Ammonia is converted into nitrite and nitrate by nitrifying bacteria growing on the surface area of the biofilter medium. This nitrification process takes several weeks. When the ammonia concentration increases certain types of nitrifying bacteria will start to grow - for instance *Nitrosomonas*. This occurs approximately two weeks after the biofilter activation has started. As ammonia is oxidised into nitrite other types of nitrifying bacteria, such as *Nitrobacter*, will start to grow, causing the nitrite to oxidize into nitrate (Thorarensen & Farrell, 2011). Figure 3 shows typical ammonia and nitrite development patterns during this process. In order to size the biofilter after the needs of a particular facility, manufacturers of biofilters generally use the TAN conversion rate (TAN/m^2/day or TAN/m^3/day), indicating the biofilter efficiency (Drennan, et al., 2006).

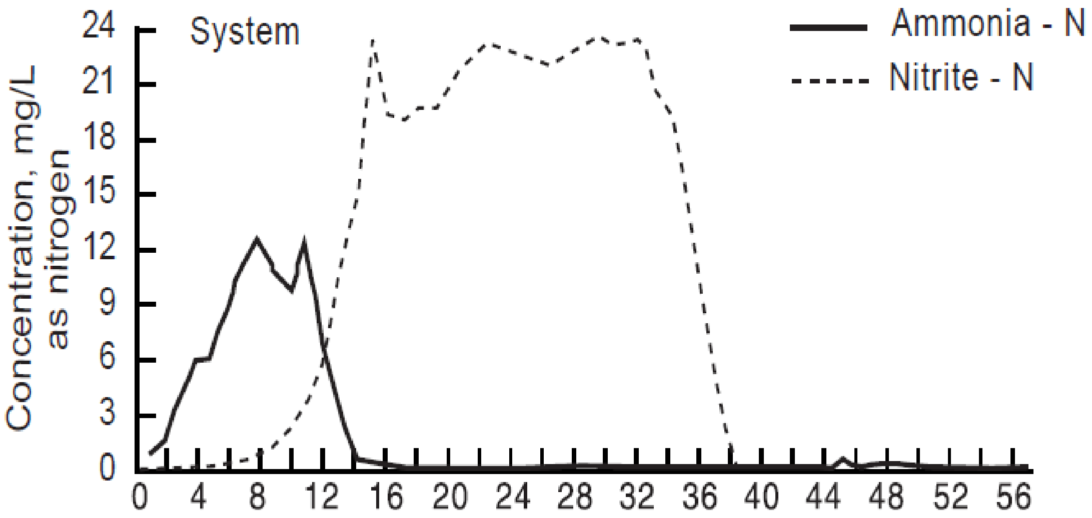

Figure 3. Ammonia and nitrite development patterns.
The horizontal axis shows the time in days. Source: Masser, Rakocy, & Losordo, 1992.

Nitrite could reach toxic concentrations in the start-up phase of the biofilter, or in case of a biofilter failure. The main effect of nitrite toxicity is methaglobemia - disturbing the oxygen transportation in the blood and inhibiting swimming performance. In severe cases methaglobemia will lower growth rates or lead to mortality. It is recommended to keep the concentration of nitrite below 0.1 mg/L (Thorarensen & Farrell, 2011).

Nitrate is the end product of the nitrification process, and the least toxic of the three types of nitrogen compounds. It is toxic only in relatively high concentrations, 300 ppm and above. In a recirculating system with a normal water exchange rate, such high concentrations are generally not reached (Masser, Rakocy, & Losordo, 1992).

Just as the fish, the biofilter is affected by water quality parameters in the system. The biofilter requires oxygen to function, and oxygen concentrations below 2 ppm will lead to biofilter failure (Masser, Rakocy, & Losordo, 1992). Moreover, the biofilter is sensitive to pH. The optimal pH is between 7 and 8. Below pH 6.8 the activity of the biofilter bacteria is inhibited. The nitrifying bacteria in the biofilter can decrease because of natural aging, or a disruption caused by chemical treatments and cleaning of the tanks. The effect of a biofilter failure is direct - a dysfunctional biofilter can cause ammonia or nitrite concentrations to rise to harmful levels within hours. Re-activating a disrupted biofilter will take 3-6 weeks (Masser, Rakocy, & Losordo, 1992).

3.2.6 Stocking density

In aquaculture, the maximum biomass that a given tank can hold (kg/m^3) is generally determined by the oxygen consumption of the fish and the volume of water available to dilute solid waste from the fish. Fish welfare in terms of the space needed to support natural behaviour is usually not a primary concern when determining stocking densities (Wedemeyer, 1996). This despite the fact that reports suggest that high stocking densities cause stress, increase metabolism, increase mortality rates, decrease biomass growth rates, decrease reproductive capacity, lower swimming performance, cause aggressive behaviour, and make the fish more susceptible to disease (Ellis, et al., 2002; Portz, Woodley, & Chech, 2006). Currently, the recommended maximum stocking density for both land-based and sea-based aquaculture is 15-25 kg/m^3. There are, however, studies suggesting that a stocking density up to 80 kg/m^3 would not significantly affect fish growth rates or welfare (Thorarensen & Farrell, 2011).

3.2.7 Feed and the feed conversation ratio

Feed management is crucial to ensure optimal biomass growth rates. Both feeding rates above and below the optimal levels will make the system function ineffectively. Underfed fish will not reach its maximal weight, and could become aggressive due to food scarcity. Overfeeding leads to uneaten feed remaining in the tanks, a degradation of the water quality and generation of more environmental pollution. Since feed is a costly production input, overfeeding will also negatively affect the economic sustainability of the facility (Timmons, et al., 2002). Biomass growth rates do also depend on the quality of the feed given. Monitoring the growth performance of the fish is easiest done by considering measurements such as the *feed conversion ratio,* a ratio giving the amount of feed required for a specific weight gain. A number of studies suggest that the feed conversion ratio generally falls within the range of 0.9-1.1. A lower feed conversion ratio indicates a more efficient growth (Thorarensen & Farrell, 2011).

3.2.8 Waste solids

Waste solids in closed aquaculture systems include bacteria, faeces and uneaten feed. It is estimated that as much as 60% of the feed fed to the fish in these systems could end up as particulate waste (Masser, Rakocy, & Losordo, 1992). These particles need to be removed, and that is one of the most complicated challenges within the system. The accumulation of waste solids will negatively affect processes within the system and could ultimately lead to system failure. It could lead to disturbances in the flow rates through clogging of pipes and air diffusers. This will inhibit the water treatment process and make the system mal-function. The breakdown of waste solids consumes oxygen, which will reduce the oxygen available for the fish. Additionally, they support the growth of heterophobic bacteria. This type of bacteria competes with the nitrifying bacteria for oxygen and could thus inhibit the nitrification process. The breakdown of waste solids will also increase the concentration of nitrogen compounds in the water (Nazar, Jayakumar, & Tamilmani, 2013). After being removed, the sludge produced by the recirculating system must be taken care of in a sustainable and sound manner, in order to reduce the environmental impact of land-based aquaculture farms.

3.3 The production of Atlantic salmon

One production cycle for Atlantic salmon is around three years, divided into two phases. During the first phase, the eggs are fertilized and the fish is grown to a weight of approximately 100 grams. This takes one year, during which the fish goes through the so called smoltification process. During this process the fish goes through structural and functional changes, preparing to migrate to sea-water (Stefansson, et al., 2008). During phase two the fish is moved to seawater rearing tanks in the case of land-based production, or to the sea. Here, the fish is grown out and reaches a harvestable size. This will take between 12-24 months, depending on the water conditions. Between years 2009 and 2014 the mean weight of marketed Atlantic salmon has been 4-5 kg. Smaller size fish could be a consequence of disease outbreaks, production failures and early harvesting. Larger fish could be a result of lower production costs or production for niche markets. After reaching a harvestable size, the fish is transported to slaughtering and processing facilities, before being sent to the markets (Marine Harvest, 2014).

4. Introduction to the model

This fourth chapter presents the model. The model represents a dynamic hypothesis of the functioning of a land-based aquaculture system. It is built in the software *iThink*[4]. First, the model boundaries are explained. Thereafter, a conceptual model in the form of a Causal Loop Diagram (CLD) is presented - giving an overview of the model as well as highlighting central feedbacks. The remaining part of the chapter displays the model structure in the form of stock and flow diagrams.

4.1 Model boundaries

The spatial boundary is a land-based aquaculture facility located in Norway. Such a facility usually contains a number of production units. The model represents the grow-out phase of the production, making each production cycle 12 months long. If every production unit contains biomass in different stages of the production cycle, one may harvest and send biomass to the market several times a year. It is assumed that one cohort reaches harvestable size and is sent to the market each month, resulting in a continuous flow of revenue. Hence, the facility is designed to contain 12 production units, equal in size and structure. The model shows the biomass development and production environment in one of these units. The parameter settings are adjusted for production of Atlantic salmon (*Salmo Salar*). The reason is that Atlantic salmon is considered the primary choice for commercial scale land-based production by the industry in Norway, mainly because of already large established commercial markets (AQUA MAOF , 2014).

A land-based facility contains a number of components and processes that could potentially be modelled. The model boundaries in this exercise are set to capture the internal dynamics of one land-based aquaculture facility. This includes how biomass in the system affects the surrounding environment, and how the environment in terms of water quality in turn affects the biomass growth and mortality rate. This biological production process is directly linked to the economic sustainability of the firm. Figure 4 conceptualizes these feedbacks and interactions in a CLD.

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[4] For more information about iThink, please visit: http://www.iseesystems.com/.

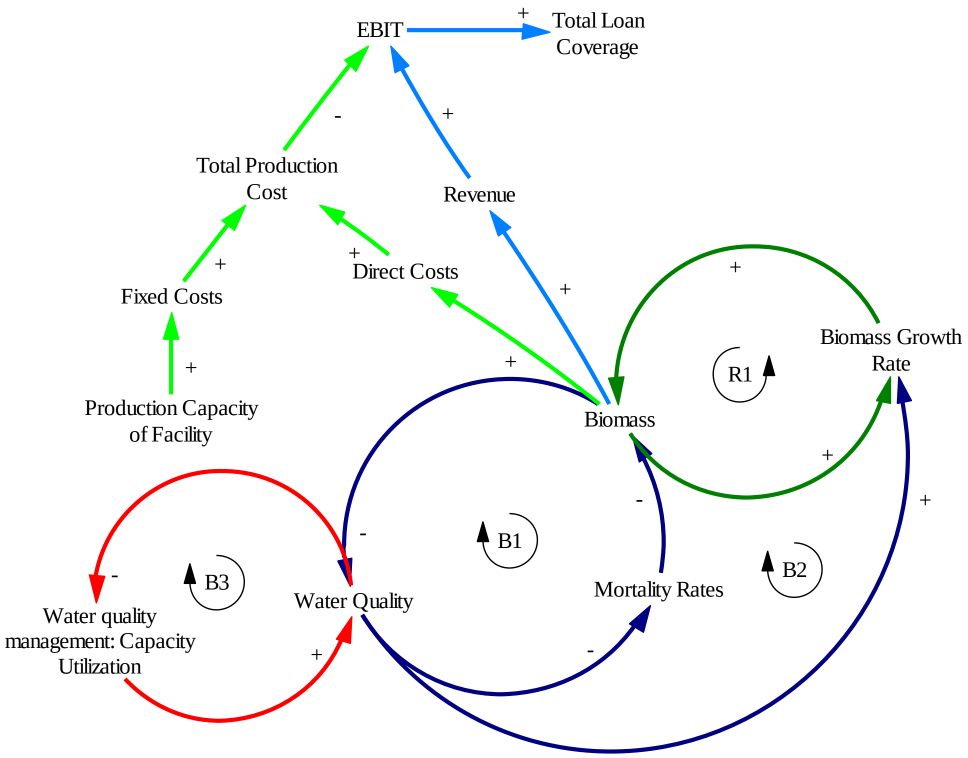

Figure 4. Causal loop diagram conceptualizing important feedbacks in the system.

The reinforcing loop, R1, represents the feedback from the biomass quantity in the system to the total biomass growth rate and back to the biomass quantity. The more biomass, the larger the total biomass growth rate - and the more biomass in the system. There are three additional feedbacks included in the CLD, the balancing loops B1, B2 and B3. B1, *the biomass mortality loop*, shows how water quality affects mortality rates. Higher water quality will lower the mortality rate in the system. Lower mortality rates mean more biomass. And the more biomass, the larger will the impact of the biomass on the water quality be. Hence, everything else equal, more biomass will lead to a lower water quality and through higher mortality rates this will give lower quantities of biomass. Therefore, B1 is a central balancing loop in the system. B2, *the biomass growth loop*, represents the effect of water quality on biomass growth rates. As water quality increases towards optimal levels, the biomass growth rate will increase. Higher biomass growth rates lead to more biomass in the system, which will have a negative impact on water quality. If the water quality decreases, so will the biomass growth rate.

Water quality must actively be managed, in order to keep water quality parameters within their recommended ranges. *The capacity utilization loop*, B3, shows the link between water quality and capacity utilization. The better the water quality, the less of the installed capacity must be utilized. On the other hand, making use of more of the installed capacity will lead to better water quality.

The biomass quantity does have a direct effect on revenue, and is consequently also linked to EBIT and Total Loan Coverage. The biomass quantity in the system does, however, also have a direct effect on the total cost of production, through the cost of production inputs such as feed and oxygen. In addition, there are fixed costs related to the production capacity of the facility.

The variable "Water quality" in the CLD represents the aggregated effect of all water quality parameters in the system. In the simulation model, these water quality parameters are modelled on a more disaggregated level. The simulation model does currently contain nine interrelated sectors, each including different water quality parameters and other production components. The sectors are: Production capacity and production requirements in terms of water- and land use, biomass and biomass growth rates/mortality rates, oxygen demand and supply, feed and the generation of waste solids, energy demand, management of CO_2-concentrations, and the biofilter and the related nitrification process. Two additional sectors contain structure to perform financial accounting and calculations of resource use per kilogram biomass produced.

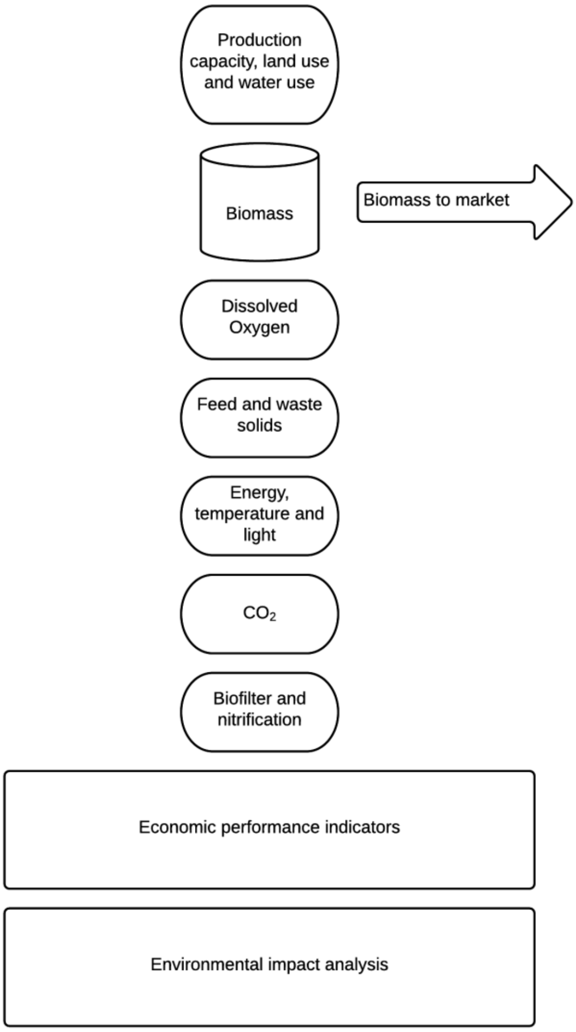

Figure 5. The model consists of nine sectors.

4.2 Stock and flow structures

The following section exhibits the model structure in the form of stock and flow diagrams. It presents one sector at a time, providing an overview of the relations, assumptions and graphical functions in the model. The variables that are color marked highlight the links between the sectors. For documentation in the form of model equations, see Appendix C.

Sector 1: Production capacity and production requirements

This sector determines the desired annual production volume in the facility. This is an important number since the facility will be designed to accommodate this production volume. Given the assumption that the facility contains 12 production units, each unit will produce an annual output of one twelfth of the total production volume. Other production specifications include the number of fish and maximum weight of the fish in each cohort, the maximum stocking density and the height of the fish rearing tanks. Based on these specifications the total land-use and water consumption per production unit may be calculated.

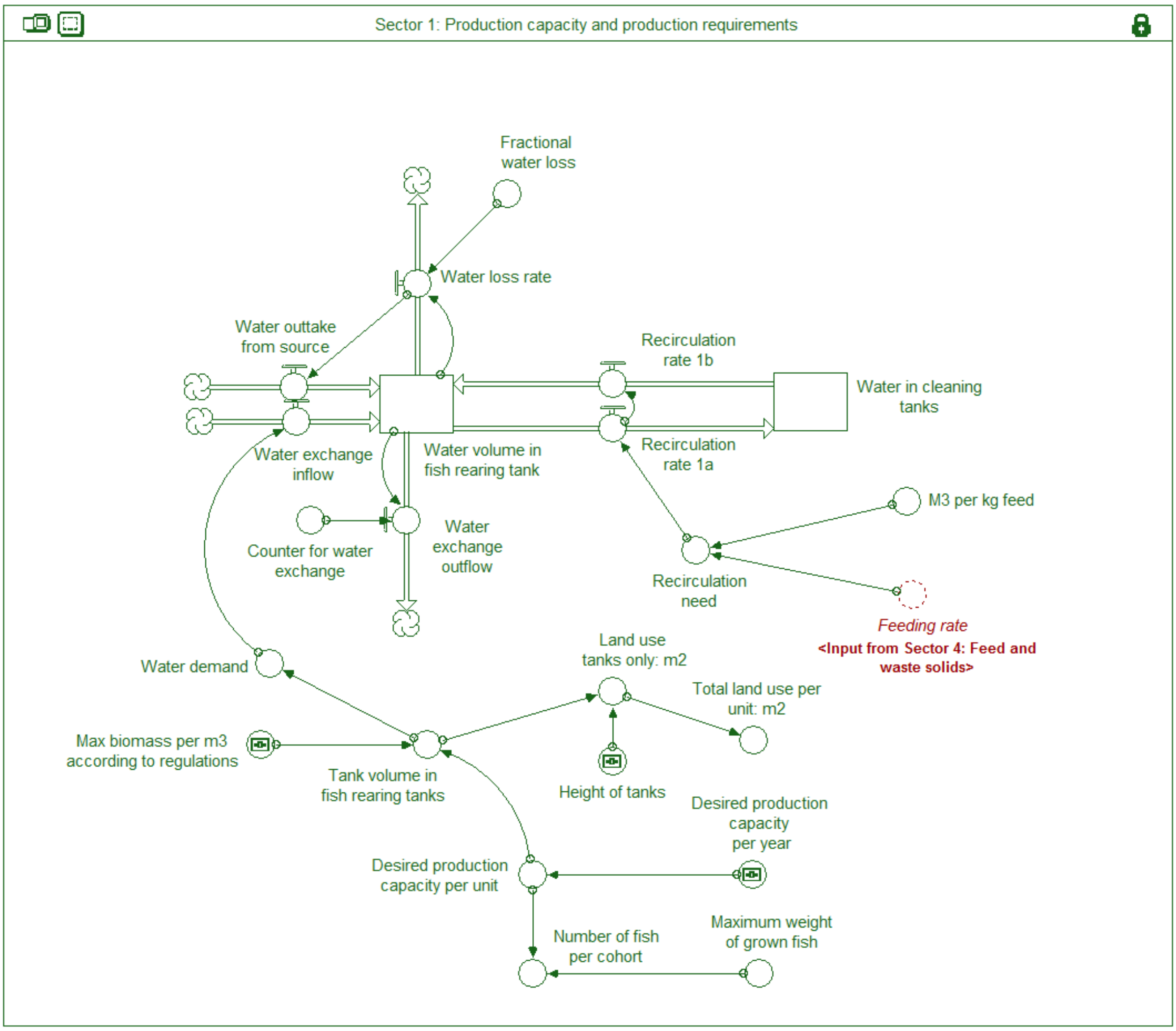

Figure 6. Stock and flow structure in Sector 1.

There are two stocks in Sector 1. The first one holds the water in the fish rearing tank, and the second one represent back-up water tanks. Three inflows and three outflows determine the level of water in the fish rearing tank. Each month a fraction of the water in the fish rearing tank is replaced with water from the back-up cleaning tanks. This recirculation flow is displayed in the model as “recirculation rate 1a” and “recirculation rate 1b”, respectively. These flows are equal to each other in order to keep the level of water in the fish rearing tank stable. The need for recirculation is determined by the feeding rate.

Each month, a percentage of water is lost as a consequence of evaporation or removal of solid waste. This water is replaced with new water from the original water source. These flows of water are represented in the model as “water loss rate” and the “water outtake from source”. After each production cycle the fish rearing tank is emptied, cleaned and filled up again with water from the back-up tanks. The corresponding flows are the “water exchange inflow” and the “water exchange outflow”.

Other assumptions in Sector 1 are:

- The fish rearing tanks are shaped as cylinders.
- Land use: Except from the actual bottom area of the cylinder, the tanks require an additional surrounding land area. The surrounding area makes up 21% of the total land use.
- Each fish rearing tank requires 10% of its volume in back-up tank volume.

Sector 2: Biomass and biomass growth rate

Sector 2 is a representation of the development of the biomass and how the surrounding environment affects the biomass growth rate and mortality rate. Since the model represents one production unit in the aquaculture facility, the biomass will remain in the stock for 12 months - one production cycle. A batch all-in-all-out loading approach is employed, instead of continuous biomass loading. A new cohort is placed in the production unit one month after the previous cohort has left the tank.

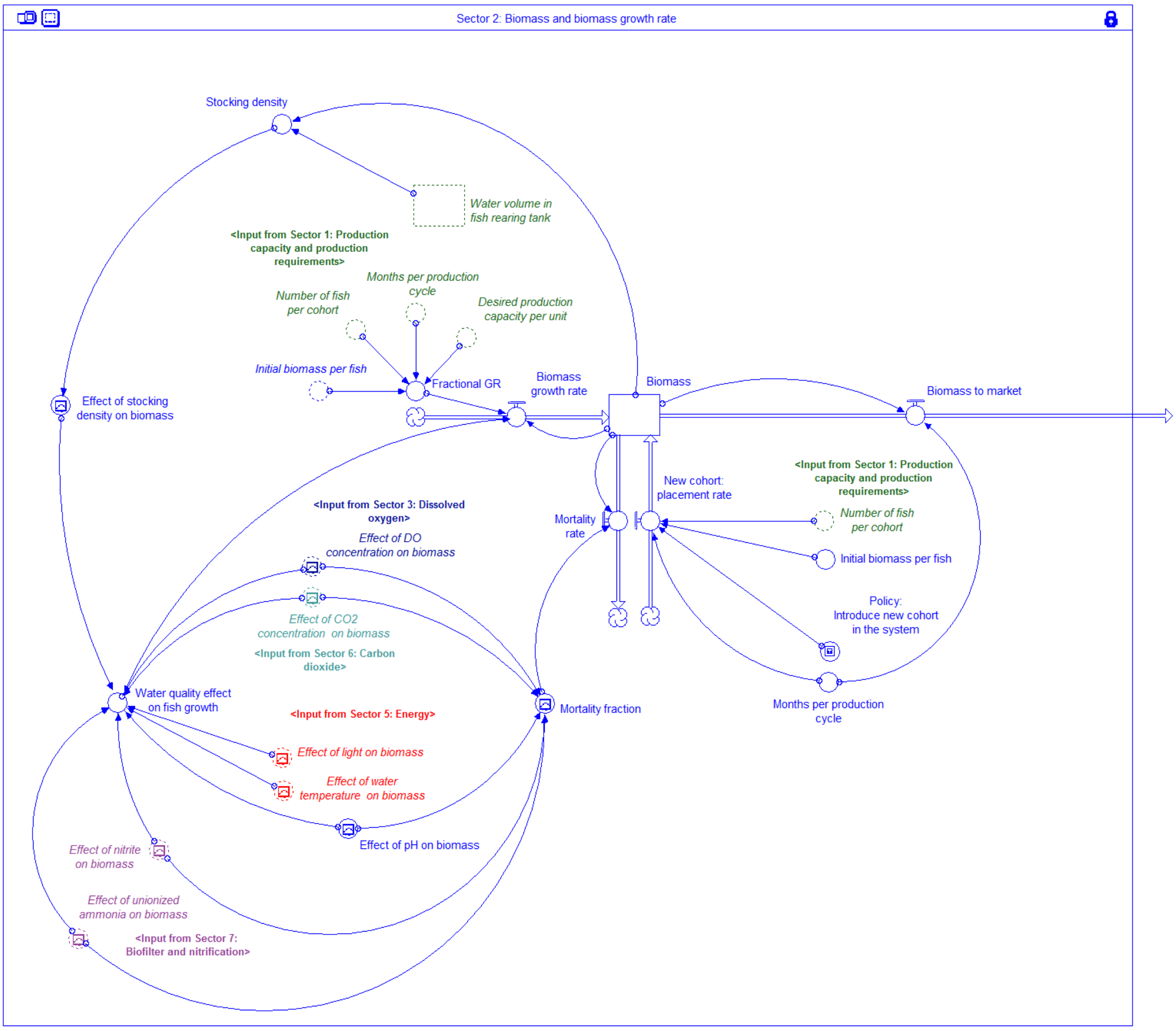

Figure 7. Stock and flow structure in Sector 2.

The mortality fraction is assumed to be 1.5% under optimal production conditions, representing a normal production loss. The biomass growth rate is based on a monthly growth fraction.

However, both the mortality rate and the biomass growth rate are affected by the environment in the production unit. Almost all other sectors, containing different water quality parameters and production factors, feed into Sector 2. The effects of the surrounding environment have both long-term and direct effects on the biomass. The variable "water quality effect on fish growth" is an aggregated effect of the overall environmental conditions in the facility on the biomass growth rate. The effect is multiplicative and ranges from zero to one. An aggregated effect equal to one represents optimal production conditions in all sectors. An effect below one is an indicator of poor performance in one or more of the other sectors. Good performance in one sector cannot make up for poor water quality conditions in another sector. The full effect does only become visible over time as it is determining the overall growth performance of the fish.

The effect of water quality on the variable “mortality fraction” is more direct. The mortality fraction is affected by a number of factors that are critical to the survival of the fish (pH, CO_2, dissolved oxygen, unionized ammonia and nitrite). In case any one of these variables reaches critical levels and the corresponding effect drops below one, the mortality fraction, and so the mortality rate, increases instantly. The worst case scenario is a mortality rate of 100%, with a consequent loss of all biomass currently in the production unit. The mortality fraction is shown in Figure 8, with the aggregated effect of all critical water quality parameters on the x-axis, and the mortality fraction on the y-axis.

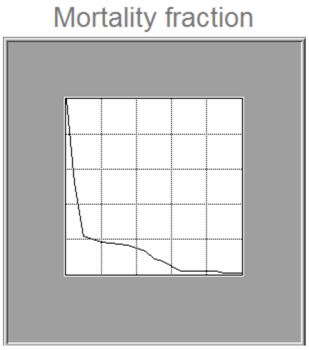

Figure 8. The mortality fraction

Each water quality parameter feeding into the variables “water quality effect on fish growth” and “mortality fraction” is modeled as a graphical function, explained in detail in its respective chapter. In Sector 2, only the effect of pH and stocking density on biomass growth rate and mortality rate are modeled, see Figure 9 and Figure 10.

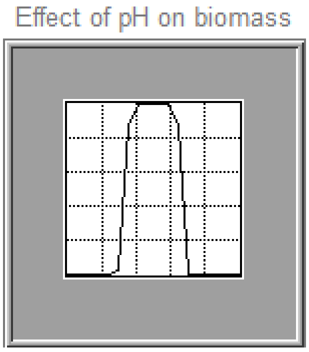

Figure 9. The effect of pH on biomass.

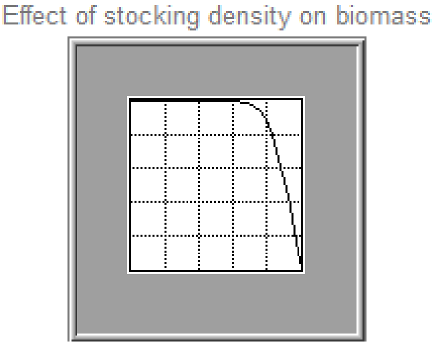

Figure 10. The effect of stocking density on biomass.

In both graphs, the effect (0-1) is on the y-axis, while the pH-range and stocking density values are on their respective x-axis. Figure 9 displays the effect of pH on biomass. In its optimal range, pH has got an effect of “1”, therefore not lowering the growth rate. Levels outside the optimal range will have an effect below one. If the pH-value reaches fatal levels, the effect is “0”. pH is a water quality parameter with a direct effect on the mortality fraction. If pH-levels are outside the optimal range, the mortality fraction will start to increase.

Figure 10 shows the effect of stocking density on biomass growth rates. If within recommended boundaries, the stocking density has got an effect of “1”. If the stocking density is above safe limits, the effect starts falling and will eventually reach “0”.

Sector 3: Dissolved oxygen

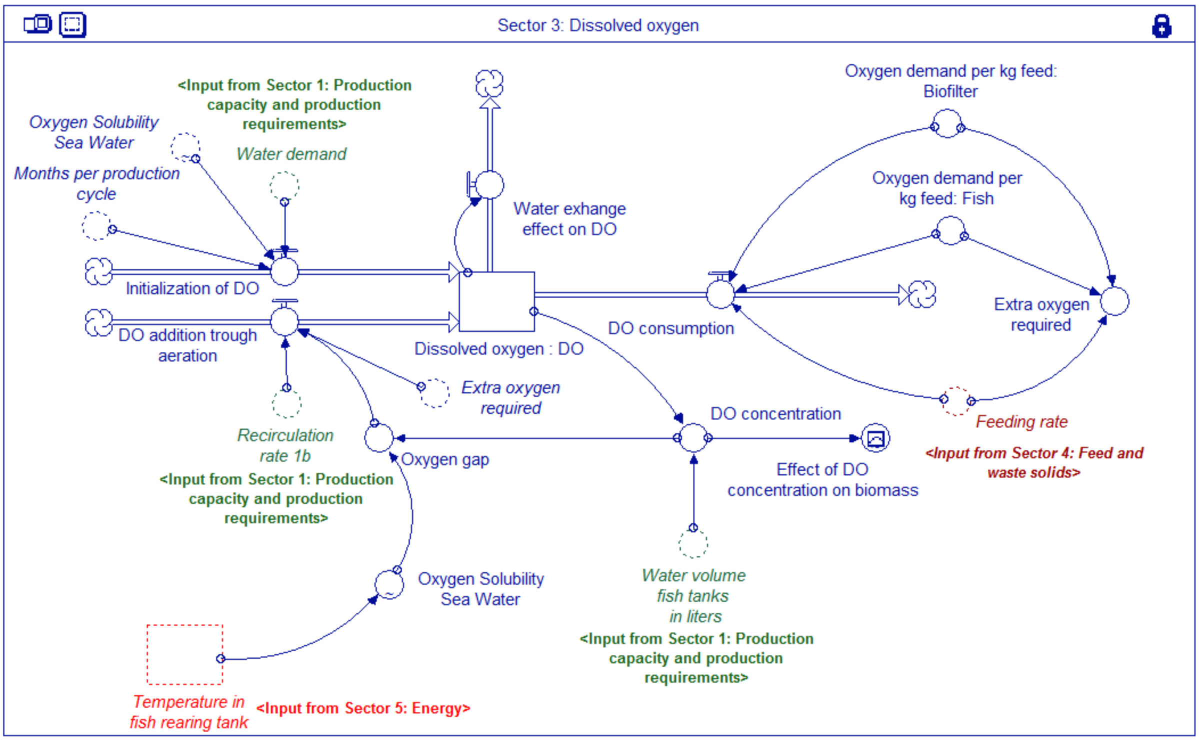

Figure 11. Stock and flow structure in Sector 3.

Oxygen is consumed by the fish and by the bacteria in the biofilter. Oxygen is added to the water to make up for this loss, in order to keep the concentration of dissolved oxygen within the optimal range. The oxygen concentration is determined by the stock "Dissolved oxygen: DO" in combination with the water volume in the fish rearing tank. Together with salinity, the water temperature determines the oxygen solubility. Fish in the grow-out phase requires sea water. Therefore the salinity is assumed to be constant and equal to 35 ppt.

The oxygen concentration affects biomass growth and mortality rate. The effect is modelled as a graphical function, displayed in Figure 12.

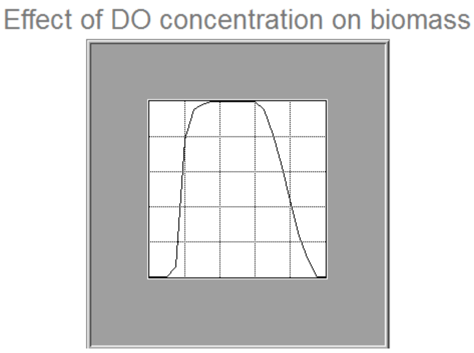

Figure 12. The effect of dissolved oxygen (DO) on biomass growth and mortality rate.

The effect (0-1) of dissolved oxygen (DO) concentrations is on the vertical axis in Figure 12, and the concentration of DO on the horizontal axis. Within the optimal concentration range, the effect is “1”, hence not limiting biomass growth. However, if DO concentrations falls below safe limits, or reaches too high concentrations, the effect will fall and approach “0”. Additionally, if DO concentrations fall below or reach above the recommended level, the mortality fraction will start to increase.

Sector 4: Feed and waste solids

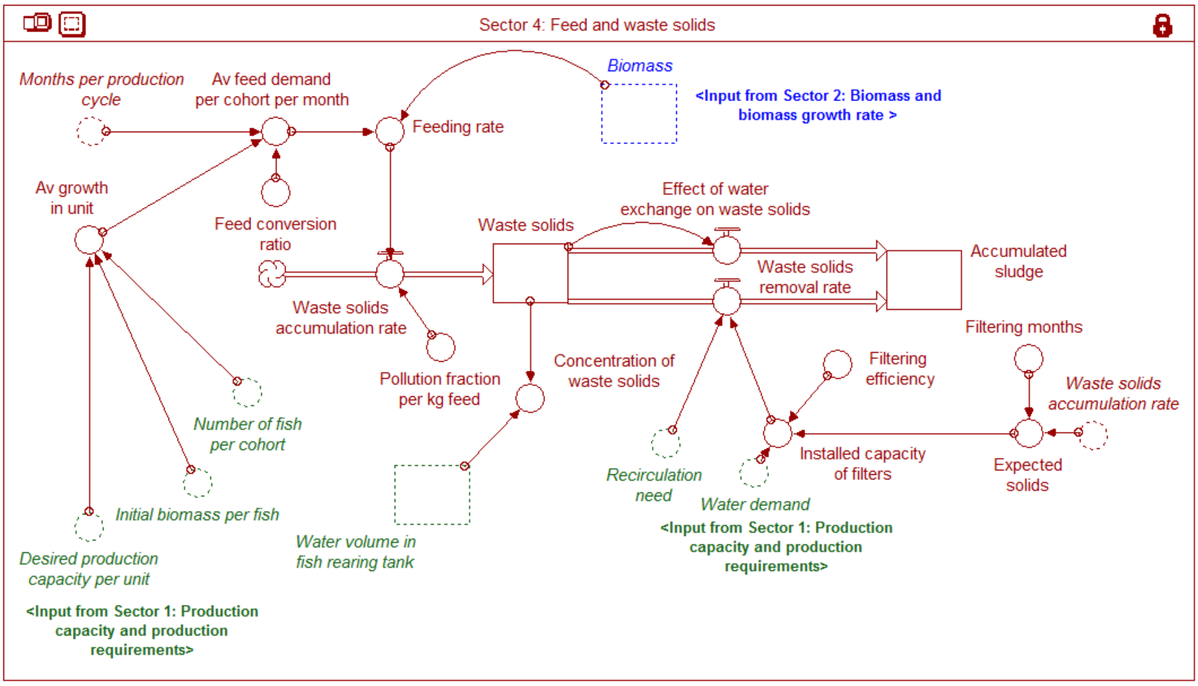

Figure 13. Stock and flow structure showing feed and waste solids accumulation.

In Sector 4 the feeding rate is determined. It is based on the expected biomass growth from smolt to market-size fish and the feed conversion ratio. It is here assumed that the feed conversion is constant and equal to 1.1. The total amount of feed required per month is then calculated and introduced in the system.

A fraction of the feed will end up as particulate waste. This waste must be actively removed to avoid accumulation and sub-optimal functioning of the system. In this model, the particulate waste does not have a direct effect on the biomass growth or mortality rate. The feeding rate does, however, determine the water recirculation need in Sector 1. Higher feeding rates require higher recirculation - partly because of the accumulation of particulate waste.

Sector 5: Energy

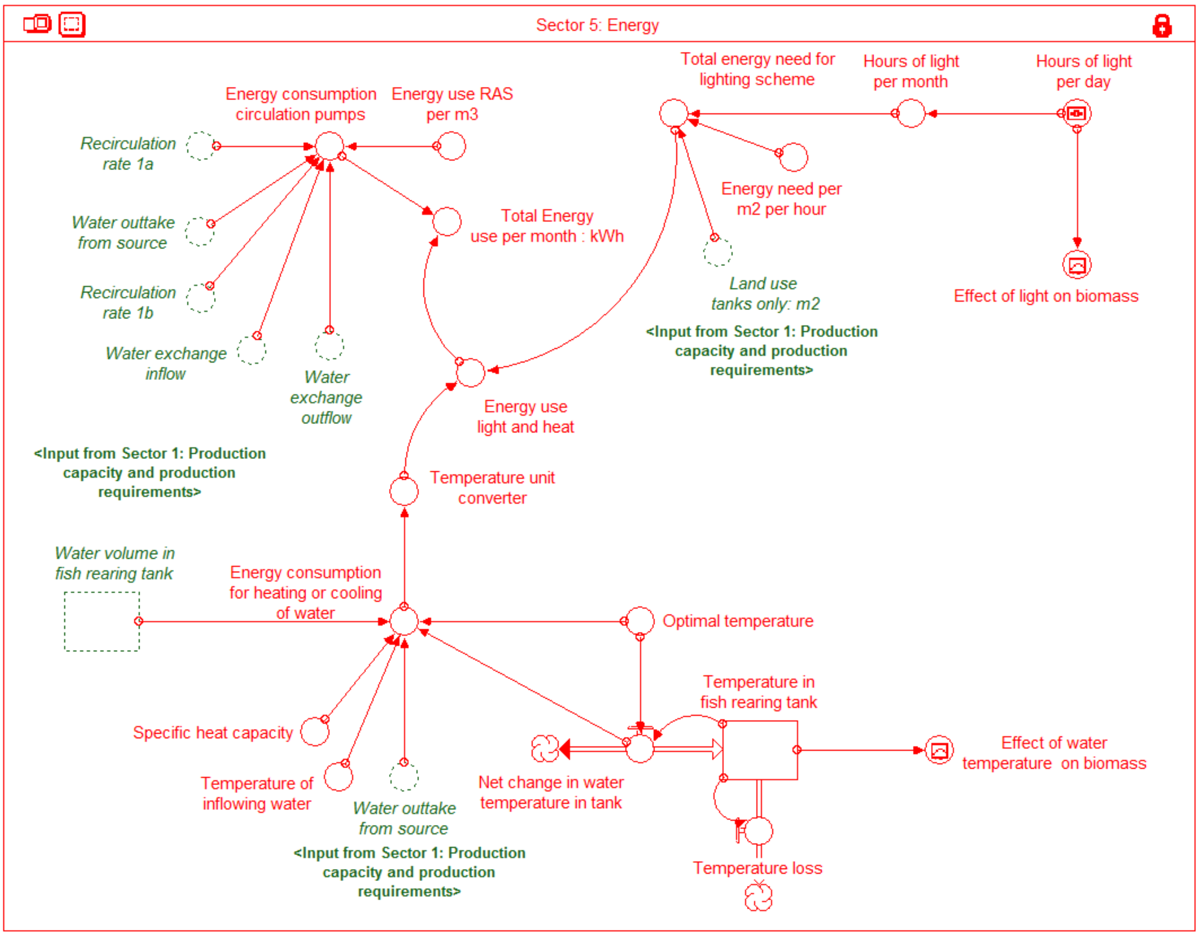

Figure 14. Stock and flow structure in Sector 5.

Several components in a recirculating aquaculture system require energy. Making use of energy as efficiently as possible is beneficial both from an environmental and an economic perspective. The energy demand accounted for in this model is the energy needed for heating/cooling of water, for the circulation pumps and for lighting. The energy demand for oxygen provision is not included in absolute numbers. It is however accounted for in monetary terms, as the energy consumption for production of oxygen is included in the price of oxygen. Not included in the model is the energy needed for water UV-treatment, ventilation, bioreactors or feed refrigeration.

The energy sector includes one stock, representing the current temperature in the fish rearing tank. The water source for this particular facility is assumed to be ground water, with an average temperature of 6 °C. Hence, the inflowing water must be heated up to reach an optimal temperature (15 °C), which requires energy. Additional energy is needed for the lighting scheme. A continuous lighting scheme is assumed. Finally, energy is required to support the flow rates of water in the system - the inflow of new water from the source, the water exchange rates and the flow from the fish tank to the backup part of the facility and the flow back to the fish rearing tank. The effects of temperature and light on biomass growth rates are modeled as graphical functions, displayed in Figure 15 and 16.

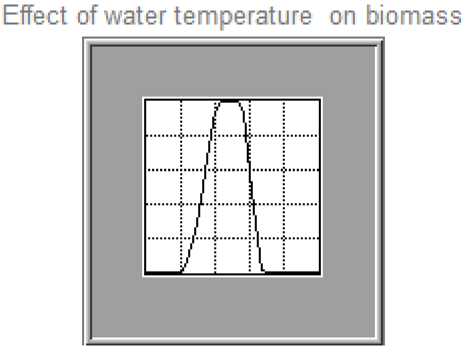

Figure 15. The effect of water temperature on biomass.

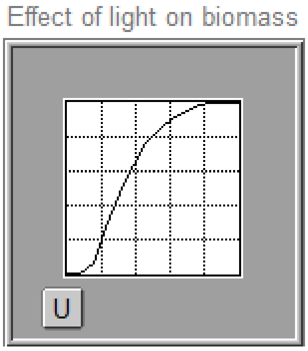

Figure 16. The effect of light on biomass.

Figure 15 shows the effect of water temperature on biomass, with the effect (0-1) on the y-axis and the water temperature on the x-axis. When the water temperature is within the optimal range, the effect of temperature on the biomass growth rate is “1” and will not lower the growth rate of the fish. If the temperature is below or above the optimal values, the effect will fall towards “0”, hence have a negative impact on biomass growth rates. The effect of light is shown in Figure 16, with the effect (0-1) on the y-axis and the number of hours with light per day on the horizontal axis. The larger the number of hours of light per day, the closer to “1” the effect becomes.

Sector 6: Carbon dioxide

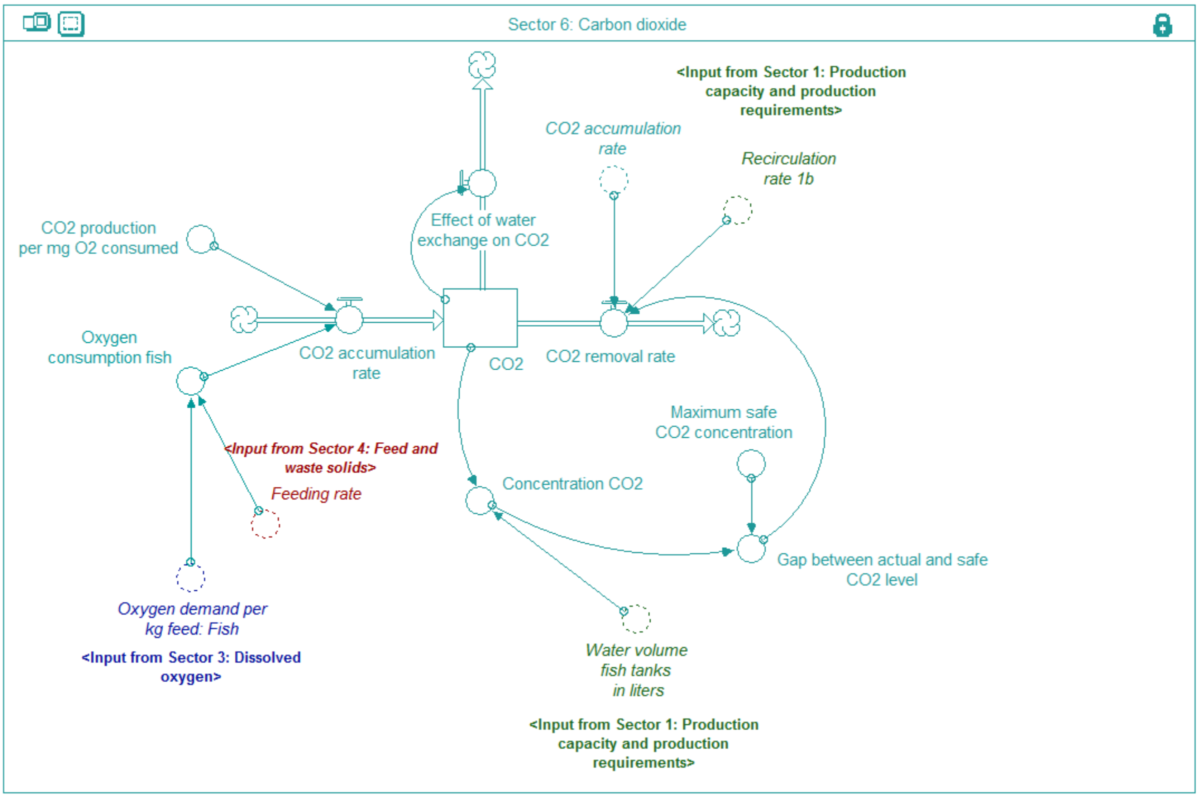

Figure 17. Stock and flow structure in Sector 6.

Carbon dioxide is accumulated in the system as a consequence of the respiration of the fish. An estimated amount of carbon dioxide is released into the system per milligram oxygen consumed. Carbon dioxide is actively removed as a part of water quality management. The effect of carbon dioxide concentrations on biomass growth and mortality rates is modeled as a graphical function, displayed in Figure 18.

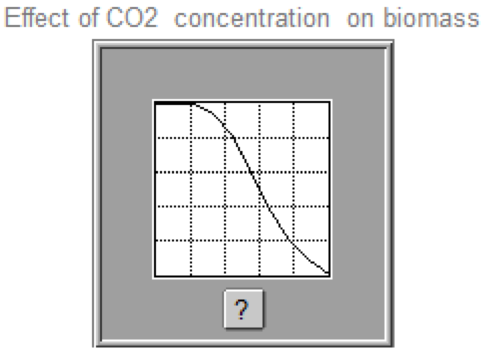

Figure 18. The effect of CO_2 concentrations on biomass.

On the vertical axis in Figure 18 is the effect (0-1) and on the horizontal axis is the CO_2 concentration in the fish rearing tank. For concentrations below the safe limit, the effect will be equal to “1”, not limiting the biomass growth rate. If the CO_2 concentration reaches a value above the safe limit, the effect will fall towards “0”. CO_2 does also have a direct impact on the mortality fraction. In case the effect of CO_2 is below “1” the mortality fraction will increase.

Sector 7: Biofilter and nitrification

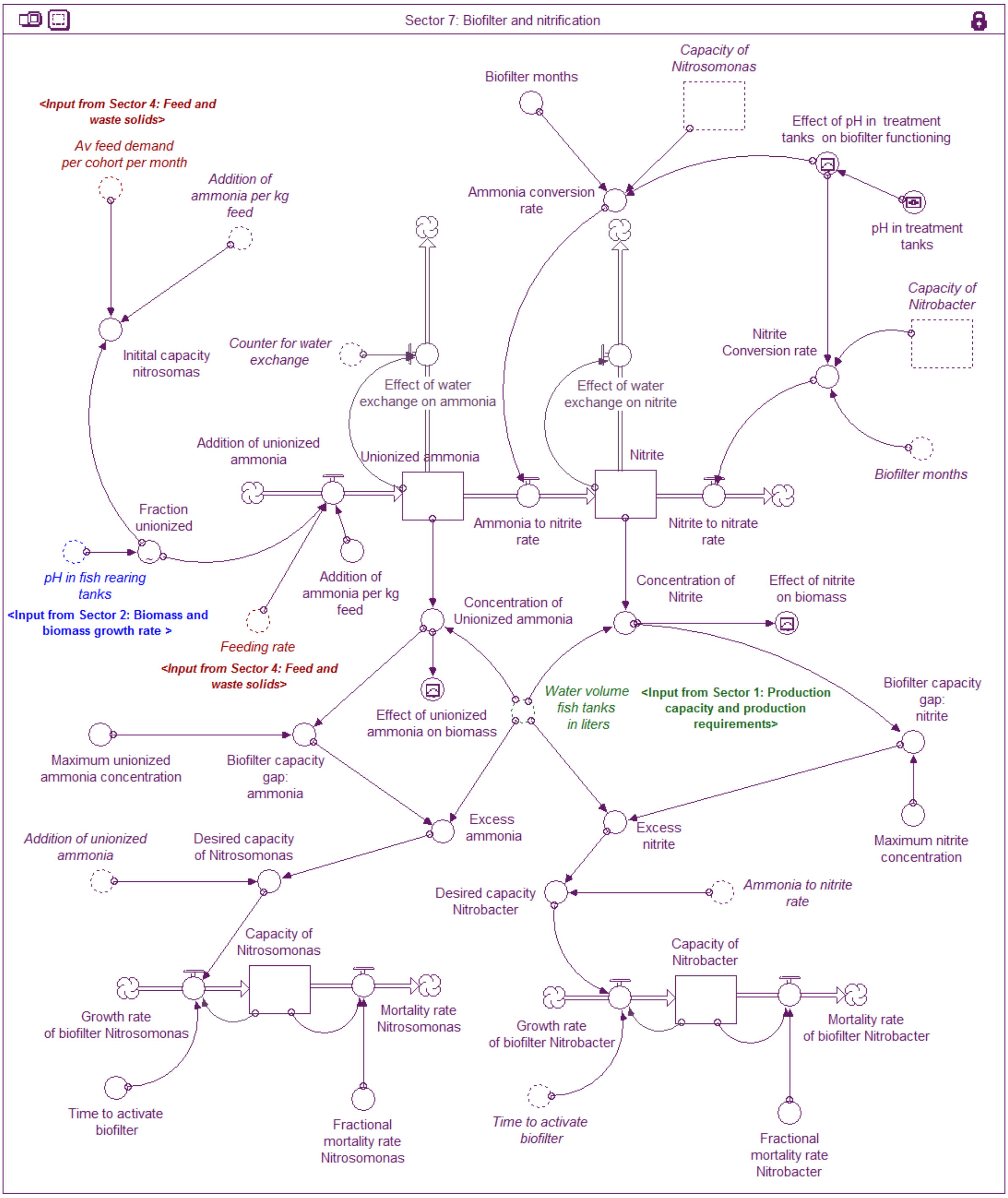

Figure 19. Stock and flow structure in Sector 7.

There are four stocks in Sector 7 - the accumulated ammonia, the accumulated nitrite and the two stocks containing different types of nitrifying bacteria (nitrosomonas and nitrobacter). Together, the nitrifying bacteria make up the biofilter. The end product of the nitrification process, nitrate, is not included in the model as it seldom reaches toxic concentrations in a closed aquaculture system.

Ammonia starts accumulating as feed is introduced in the system. A fraction of the feed ends up as TAN, and a fraction of the TAN will be found in the unionized form. Biofilters are usually built up gradually, to avoid concentrations of unionized ammonia and nitrite reaching toxic concentrations during the biofilter start-up process. Here it is assumed that the biofilter is already established when the first cohort of fish is introduced in the system.

The biofilter efficiency is usually measured as TAN conversion rate per m^2 or m^3 of biofilter medium per day. Here, the stocks represent the biofilter capacity, measured in milligrams. Divided by the time the biofilter is active (months) it gives the biofilter efficiency in terms of biofilter conversion of milligram unionized ammonia or nitrite per month.

The effects of the concentration of unionized ammonia and nitrite on the biomass growth rate are modeled as graphical functions, displayed in Figure 20 and Figure 21.

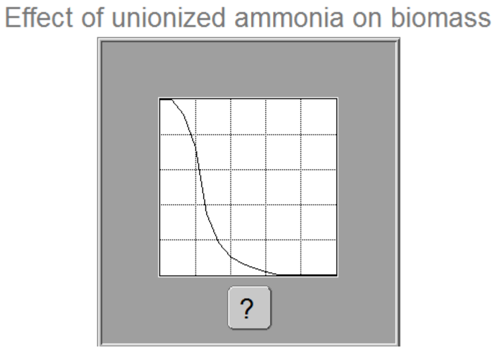

Figure 20. The effect of unionized ammonia on biomass.

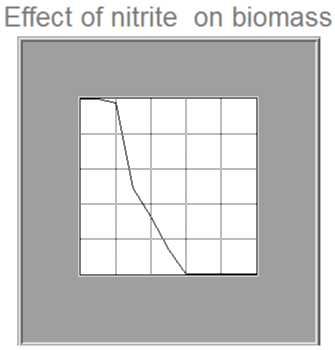

Figure 21. The effect of nitrite on biomass.

The effect (0-1) of unionized ammonia on the biomass growth rate is displayed on the y-axis in Figure 20, and the concentration of unionized ammonia on the x-axis. Below the safe limit of unionized ammonia the effect is “1”, and will not lower biomass growth rates. As the concentration rises above the safe limit, the effect will approach “0”. The concentration of unionized ammonia does also have a direct effect on the mortality fraction. As the effect in Figure 20 falls below “1” the mortality fraction will increase.

The effect (0-1) of nitrite on biomass is displayed on the y-axis in Figure 21 and the concentration of nitrite on the x-axis. Below the safe limit of nitrite, the effect is “1”, and will not lower biomass growth rates. If the concentration rises above the safe limit, the effect will start falling towards “0”. The nitrite concentration also has a direct effect on the mortality fraction. If the effect in Figure 21 falls below one, the mortality fraction will increase.

Sector 8: Economic performance indicators

The financial sector contains a number of economic parameters and calculations, displayed in Figure 22. This section will list the cost estimates and underlying assumptions used in this sector.

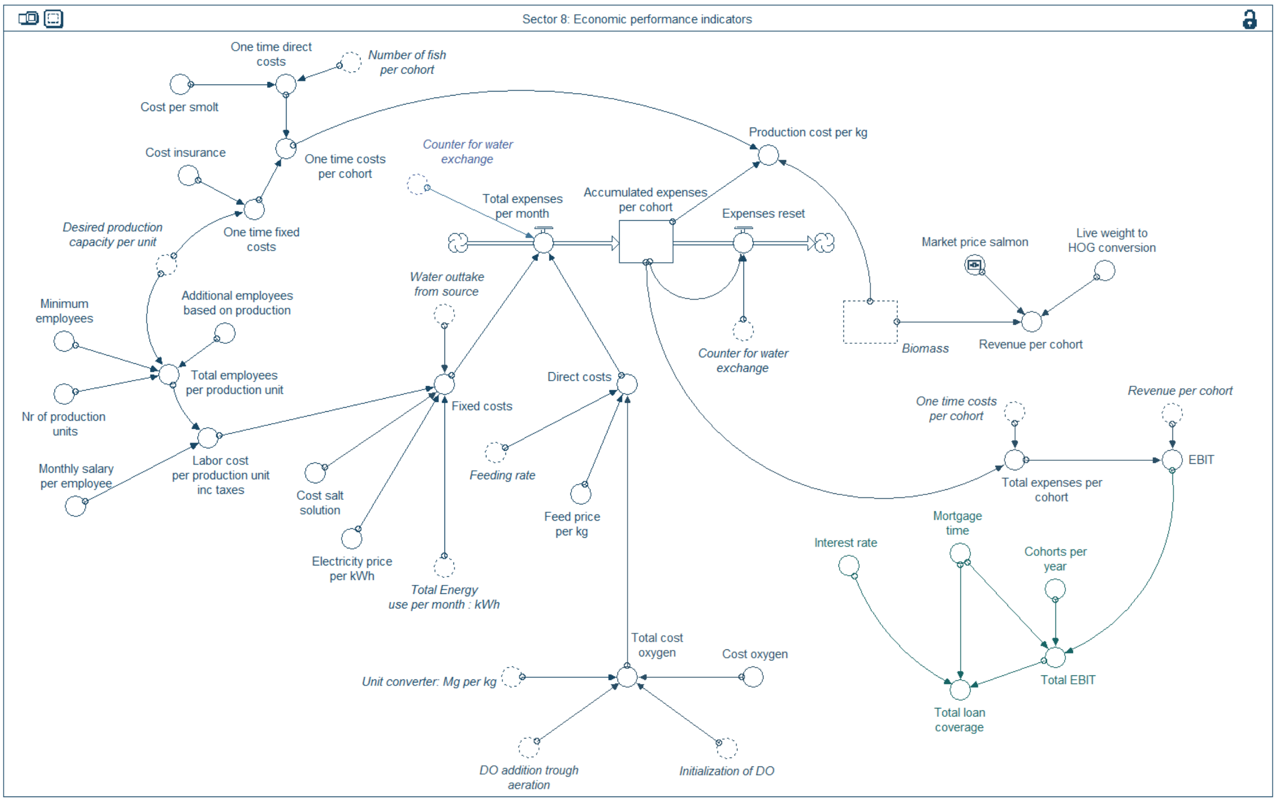

Figure 22. Stock and flow structure in Sector 8.

The total production cost in a land-based aquaculture facility includes both fixed and variable costs. Fixed costs occur whether or not output is produced, and is sometimes referred to as the “overhead”. The fixed costs accounted for in this model include the cost of electricity, labor, salt solution and insurance. The electricity cost is estimated to 0.8 NOK/kWh. The total labor cost is estimated based on the following assumptions: Each aquaculture facility requires five full-time employees per year, regardless of production capacity. In addition, one additional employee is required per 200 ton produced output. Each full-time employee cost the company 600 000 NOK per year (including taxes). The cost of adding salt solution to the fresh water introduced in the system is estimated to be 0.2 NOK/m^3. The total insurance cost is based on the desired production volume and estimated to 0.2 NOK per kilogram biomass.

Direct costs are proportional to the amount of biomass actually produced in the system. The direct costs include the cost of smolt, feed and oxygen. Not included in the analysis are processing and transportation costs. The cost of smolt depends on whether the production is placed "in-house" or if the smolt is bought from a third party producer. An estimated cost of 8 NOK/smolt is used in the model. Feed usually makes up the largest part of the total production cost. The cost of feed is determined by feed quality, logistics and the feed conversion ratio. The feed cost in this model is assumed to be 11 NOK/kg feed. Oxygen is assumed to be produced in-house, at a total cost of 1 NOK/kg. Waste management is assumed to have a net cost of zero in this model. The underlying reason is that sludge produced in a recirculation aquaculture system may serve as an economic input factor in a commercial setting. Sludge can be transformed into value-added product, for instance biogas or fertilizer. Table 1 provides a summary of the costs included in the model.

Table 1. *Cost Estimates in Sector 8.*

Cost item	**Cost estimate**[1]
Electricity	*0.8 NOK/kWh*
Labor	*600 000 NOK/employee/year*
Salt solution	*0.2 NOK/m^3*
Insurance	*0.2 NOK/kg biomass*
Feed	*11 NOK/kilogram feed*
Oxygen	*1 NOK/kilogram*
Waste management	*0 NOK*
Smolt	*8 NOK/smolt*

[1] *All estimates obtained from Norsk Sjømatsenter*

Financial accounting

The model includes the following performance indicators of the financial health of the facility:

Accumulated expenses per cohort: Monthly expenses per cohort, including both fixed and direct costs, accumulate in a stock (Figure 22). After each production cycle, the stock resets to zero, before the next cohort enters the system.

Revenue per cohort: The revenue per cohort is the biomass sent to the market multiplied by the estimated market price of the product. The total biomass produced is, however, first converted to a standardized measure, in this case Head on Gutted (HOG). The live weight to HOG conversion ratio is 0.84. The market price of salmon is assumed to be 30 NOK/kg. These estimates are based on data and the historic price development of salmon, obtained from Marine Harvest, (2014).

Total revenue: Since each production unit produces the same volume, and the facility is designed to contain 12 units, the same biomass volume is sent to the market each month in the base-run scenario. Hence, the total revenue is calculated by multiplying the revenue per cohort by 12.

Total expenses: The total expenses are calculated by multiplying the expenses per cohort by 12, with the underlying assumption that all production units perform equally in a base-run scenario.

Earnings before interest and tax (EBIT): EBIT is an indicator of a firm’s profitability, without taking interest payments and taxes into consideration. It is calculated as revenue minus expenses. It is a useful indicator as it takes out the effect of different capital structures, tax rates, and interest rates, thereby making it easier to compare the profitability of different firms.

Production cost per kilogram biomass: This is a useful measure in order to compare the production cost of the facility with, for instance, the production cost of a sea-based facility. The production cost per kilogram biomass is calculated by dividing the accumulated expenses per cohort with the total amount of biomass produced each cohort.

Total Loan Coverage: A land-based aquaculture facility requires large initial investments. The "loan coverage" of the firm is based on yearly EBIT. It is calculated as the maximum sum that can be taken as a loan and repaid within a specific time period, covered only by the profit (EBIT) of the firm. The mortgage time is 5 years and the interest rate is assumed to be 4% in the base-run scenario.

Sector 9: Resource use for production

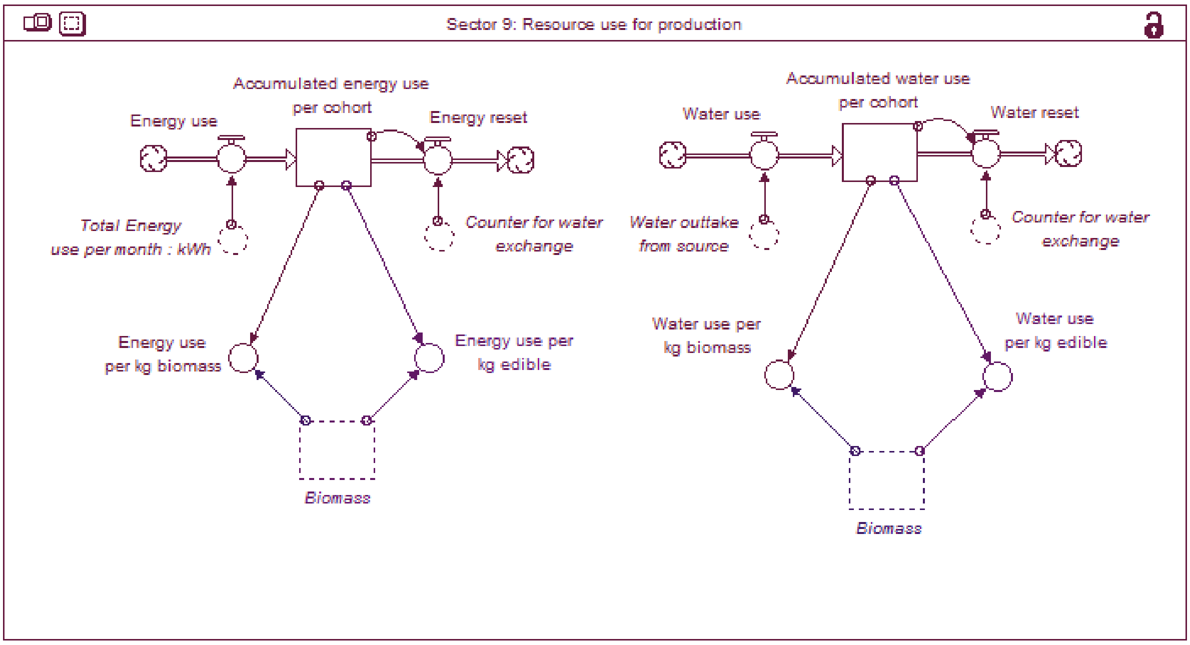

Figure 23. Stock and flow structure in the resource use sector.

The last sector represents the resource use accounting, calculating the water and energy use per kilogram biomass produced. The energy and water use per month is accumulated in the respective stock, and divided by the total production output in each production cycle. After each production cycle, the stocks are reset to zero, before the next cohort enters the production unit. The resource use is presented both as energy or water per kilogram biomass produced, and as energy or water per kilogram edible meat produced.

4.3 Model validity

Is the model an accurate and sufficient representation of a real world aquaculture system? Are the simulated behavior and subsequent conclusions reliable? This section serves to discuss the concept of validity - in the context of system dynamics modeling in general and in this study in particular.

The iterative nature of system dynamics modeling causes validation to be a gradual process of building confidence in the model. Validation is carried out during the entire modeling process and there is no single test that could serve to validate a system dynamics model. Also, validity is often stated to be confidence in the models usefulness. Hence, the validity of a model cannot be evaluated without considering its purpose. Furthermore, model validity cannot be based entirely of objective or formal procedures (Barlas, 1996;Forrester & Senge, 1979; Sterman, 2000). Yet, there are guidelines and standards for model validation available in the literature. Validation testing in the context of this study has been carried out based on the guidelines presented by Forrester and Senge (1979). The tests performed aim at building confidence in both model structure and the behavior generated by this structure. Structure verification includes “comparing structure of a model directly with the real system that the model represents” (Forrester & Senge, 1979, p. 9). In this study structure verification has been conducted by comparing descriptions of land-based aquaculture systems found in the literature with the relationships and assumptions included in the model. Structure verification has also been conducted by presenting the model to experts and practitioners within the field of aquaculture, thereby receiving valuable insights from people with real world experience with these systems. Parameter verification tests have been performed in the same manner. Additional tests, for instance the dimensional consistency test and extreme condition tests, have also been carried out.

Another group of tests are behavior oriented. Behavior tests serve to “evaluate adequacy of model structure through analysis of behavior generated by the structure” (Forrester & Senge, 1979, p. 18). Belonging to this group of tests are the “behavior reproduction test” and “behavior sensitivity tests”. The behavior reproduction test aims to evaluate whether the simulated behavior corresponds to a reference mode of behavior that is observed in the real system. The simulated behavior in this research shows consistency with the expected behavior, based on the available theoretical knowledge on land-based aquaculture systems. Altogether, the tests performed create a degree of confidence in the simulated results and in the ability of the model to capture the dynamics of a land-based aquaculture system.

Yet, a model is a simplified representation of a real world system. When analyzing the behavior generated by the model, emphasis should be put on the patterns of behavior, rather than exact point predictions (Barlas , 1996). With this in mind, the results obtained from this research should not be treated as exact predictions. Rather, the model should serve to give insights on the internal dynamics of a land-based aquaculture system and an indication of the economic sustainability of such a system.

Because one of the research objectives is for this model to be used as a learning tool, the model is supplemented with an interface feature. The interface is designed to allow the user to interact with the model - for instance through changing various production specifications and explore the corresponding changes in the simulated behavior. For a more detailed explanation of the interface feature, see Appendix B. For more details on model validation and the tests performed, see Appendix A.

5. Simulation results and analysis

This chapter presents the simulated results and an analysis of these results. First, three scenarios are introduced. These scenarios show the development in one production unit in the facility during one production cycle (12 months). After a presentation and analysis of the simulated behavior under each scenario, the economic sustainability indicators are presented. This financial outlook does not only focus on one specific production unit, but on the performance of the facility as a whole. It does also have an extended time period of analysis, taking into consideration five years of system operation.

Lastly, an environmental impact analysis is presented. In the financial outlook, environmental impact is included as a direct cost of resource use for the producing firm. The last section is intended, however, to highlight the environmental aspect of land-based aquaculture production. It does also aim to put the resource use for land-based aquaculture production in perspective, by including relative numbers on resource use for production of other sources of protein.

5.1 Introduction to scenarios

Three different scenarios are presented in this section. All scenarios assume that the facility, as a whole, has got a production capacity of 5 000 tons per year. The simulated behavior shows the dynamics in one specific production unit. The integration method used is Euler´s method, and the time period for analysis is set to be months. One production cycle is 12 months. Scenario 1, the base-run, shows the simulated behavior under optimal system performance. Many things could, however, cause the system to malfunction. Scenario 2 shows the simulated behavior under sub-optimal production conditions. In this scenario the heating system fails to warm the water to optimal temperatures during a part of the year (a scenario that could occur where the installed capacity of the heating system is insufficient or under extreme weather conditions). Lastly, Scenario 3 shows what happens if the biofilter does not function optimally -a failure leading to an instant break-down of the system and a consequent loss of all biomass in the facility.

5.1.1 Scenario 1: Base-run

The base-run shows the simulated behavior when the production conditions are optimal. Optimal production conditions mean that all water quality parameters are within their recommended range. For instance, the water temperature is equal to the optimal water temperature and the concentration of dissolved oxygen is close to 100% air saturation, as displayed in Figure 24 and 25.

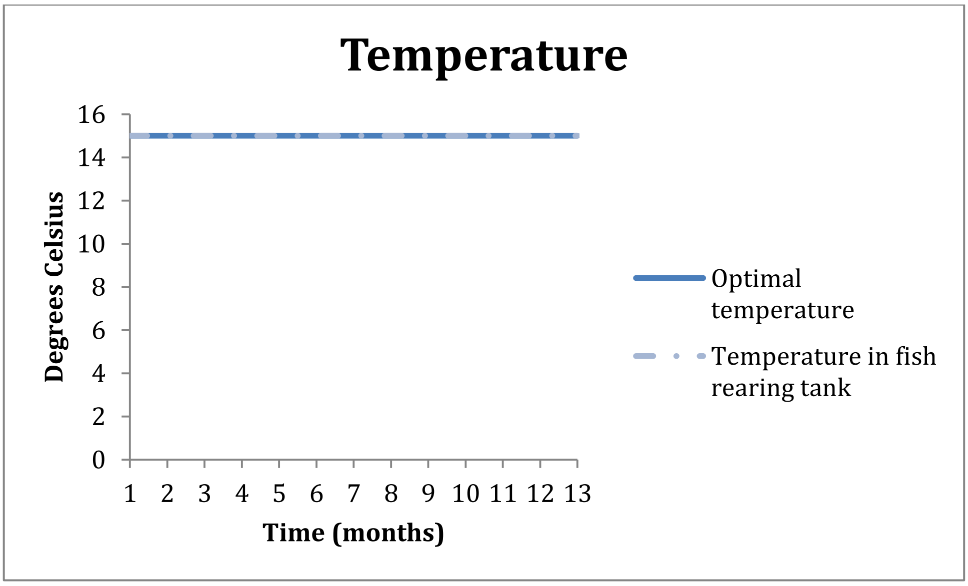

Figure 24. Temperature is an important water quality parameter. In the base-run the temperature is equal to the optimal temperature.

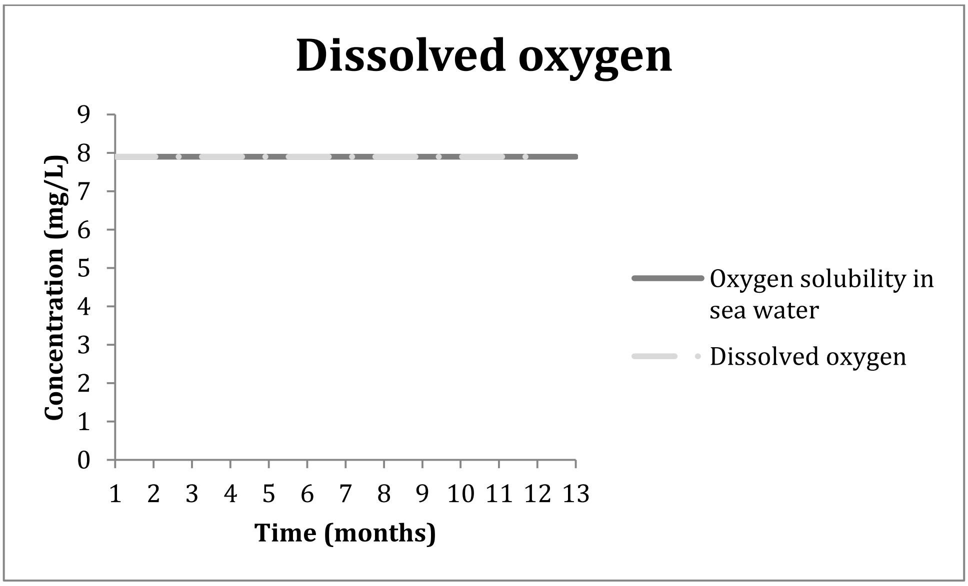

Figure 25. Oxygen solubility in sea-water and the concentration of dissolved oxygen.

A new cohort is introduced in month one. Twelve months later it leaves the production unit. The biomass growth is displayed in Figure 26.

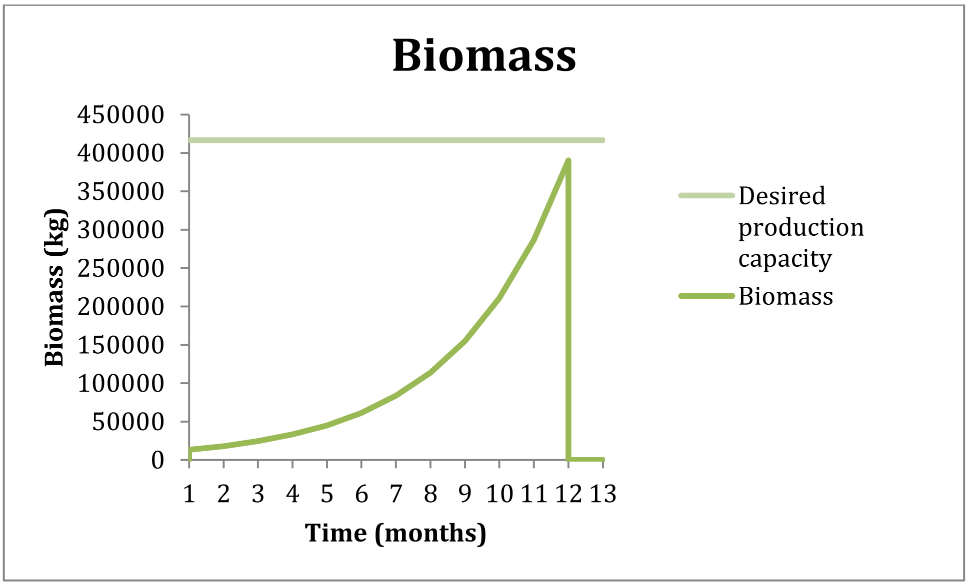

Figure 26. Biomass growth during one production cycle.

The biomass shows a steady, uninterrupted exponential growth during the whole production cycle. The mortality fraction is constant and equal to 1.5%, as shown in Figure 27. This corresponds to a normal production loss under optimal production conditions.

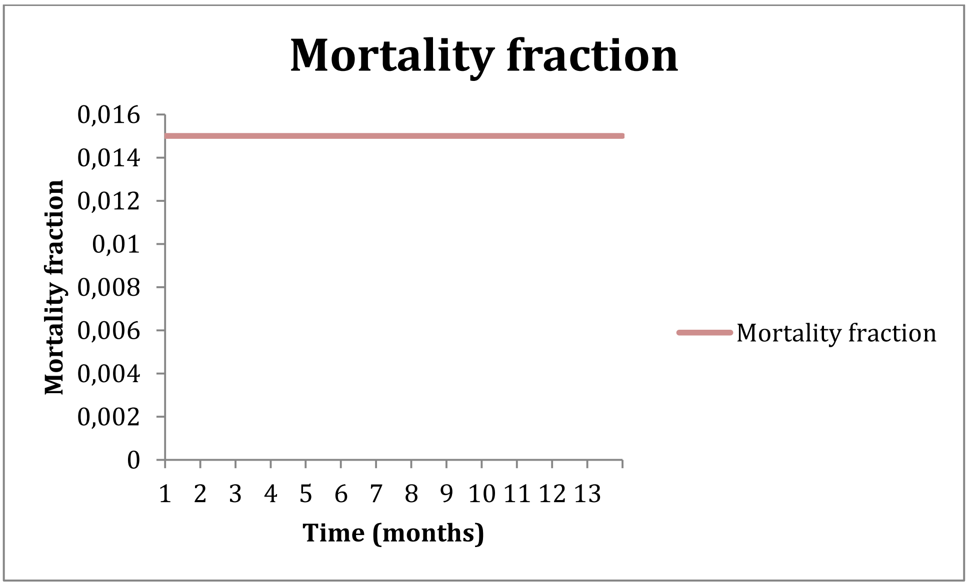

Figure 27. The mortality fraction is equal to 1.5% during the whole production cycle.

In the base-run scenario, revenue will be maximized. For a more detailed analysis of the economic and environmental performance in this scenario, see section 5.2-5.4.

5.1.2 Scenario 2: Sub-optimal system performance

In scenario 2, the production conditions are sub-optimal over an extended period of time. In this example, the capacity to heat the water is not sufficient to keep the temperature at its optimal level during the whole year (potentially due to cold weather during the winter). Water temperature is a water quality parameter with a large impact on biomass growth rates, but does generally not have a direct impact on mortality rates in an aquaculture facility. Figure 28 shows the temperature development in the fish rearing tank. During the first months of production the temperature is within its optimal range. In month five the temperature starts falling, and stabilizes at 10 degrees Celsius - five degrees below the optimal temperature. At month nine the temperature starts to rise again.

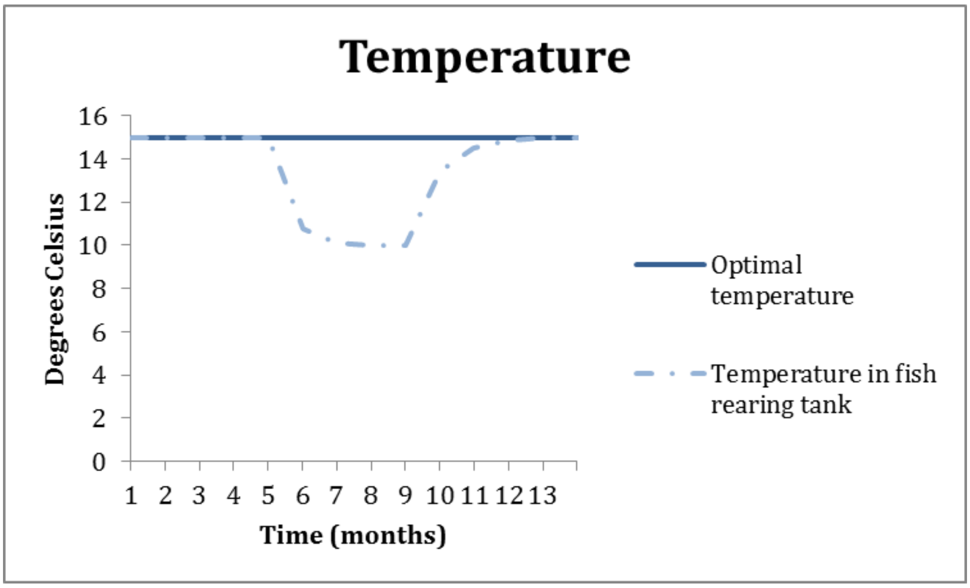

Figure 28. Failure to keep an optimal water temperature in the fish rearing tank.

The mortality fraction will remain constant as a water temperature of 10 degrees Celsius does not directly affect the biomass mortality rate, see Figure 29. Other water quality parameters, interrelated with water temperature, might be affected by the drop in temperature, but do not have an impact on the biomass growth or mortality rate as the rest of the system functions optimally. Figure 30 shows how oxygen solubility is fluctuating as a consequence of changing water temperatures. This does however not make the concentration of dissolved oxygen reach harmful levels.

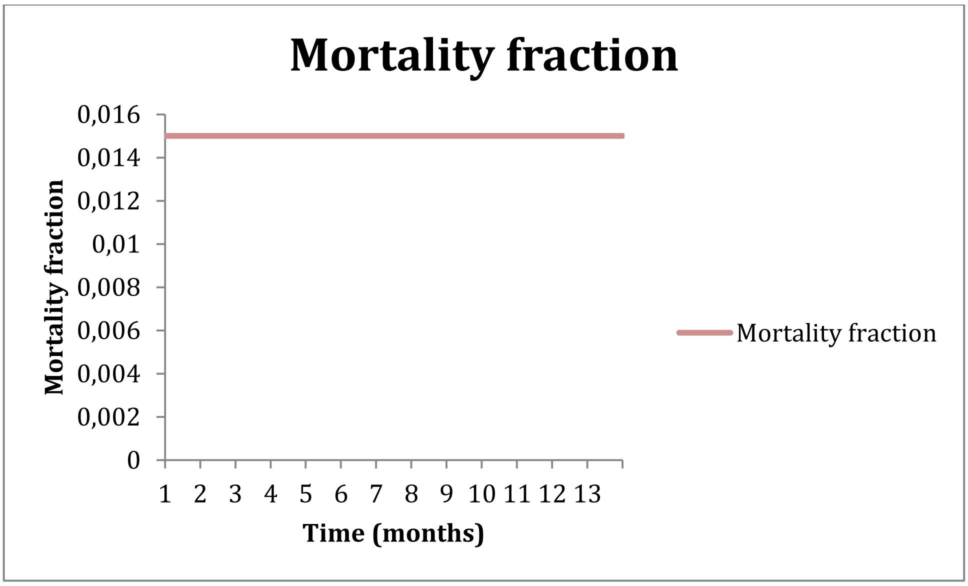

Figure 29. Mortality fraction.

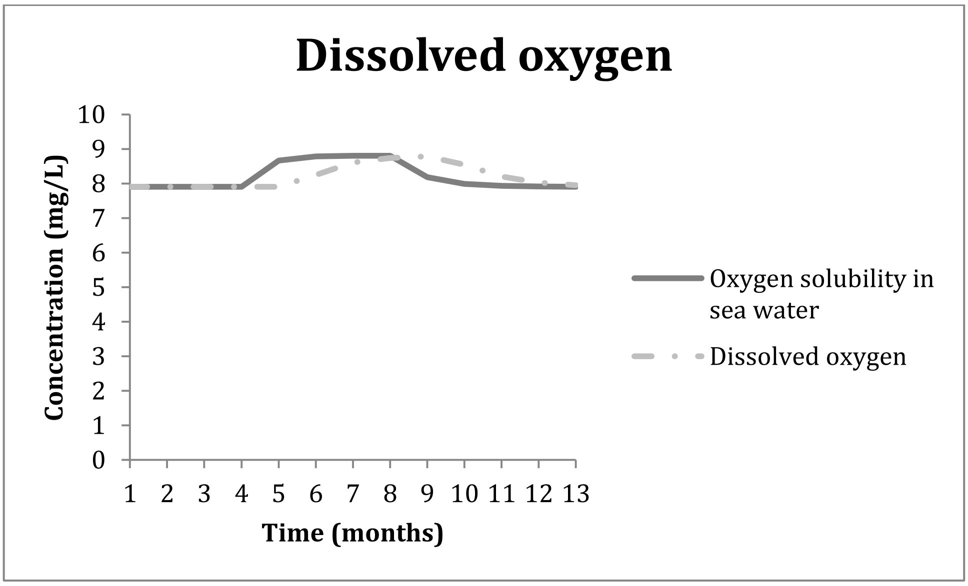

Figure 30. Oxygen solubility is affected by water temperature.

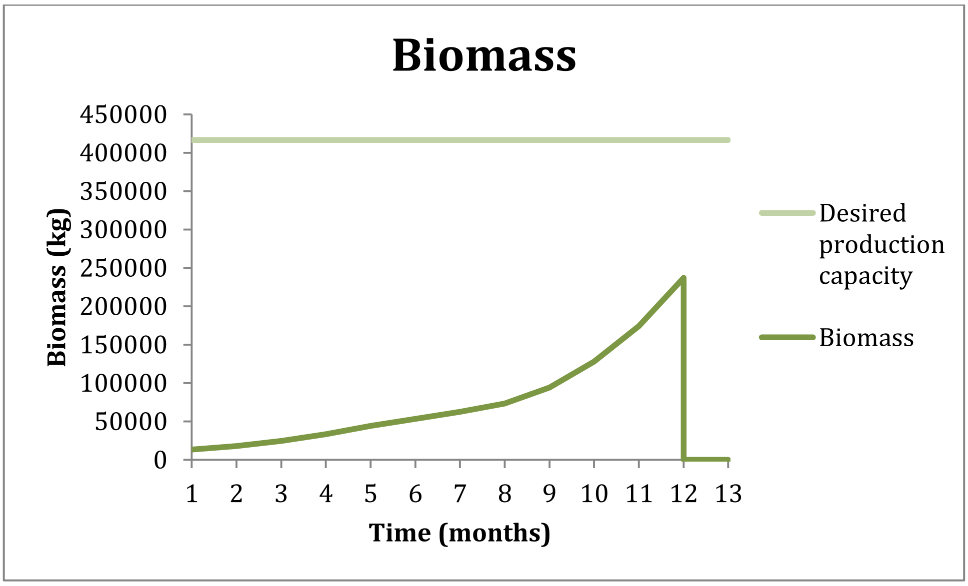

Figure 31. Biomass development in Scenario 2.

Figure 31 shows the development of the biomass in Scenario 2. The sub-optimal water temperature causes a lower biomass growth rate than the optimal during the months of colder water. The total biomass reached at the end of the production cycle does not correspond to the biomass quantity of the base-run. This development will have an impact on the economic sustainability of the firm. For a more detailed analysis of the economic and environmental performance in this scenario, see section 5.2-5.4.

5.1.3 Scenario 3: System failure

Many components may cause an acute system failure. In scenario 3, the pH-level increases from 7 to 8 at month five in the production cycle. In this model, pH is an exogenous variable. In Scenario 3 the increase in pH is modelled using a step function, as displayed in Figure 32.

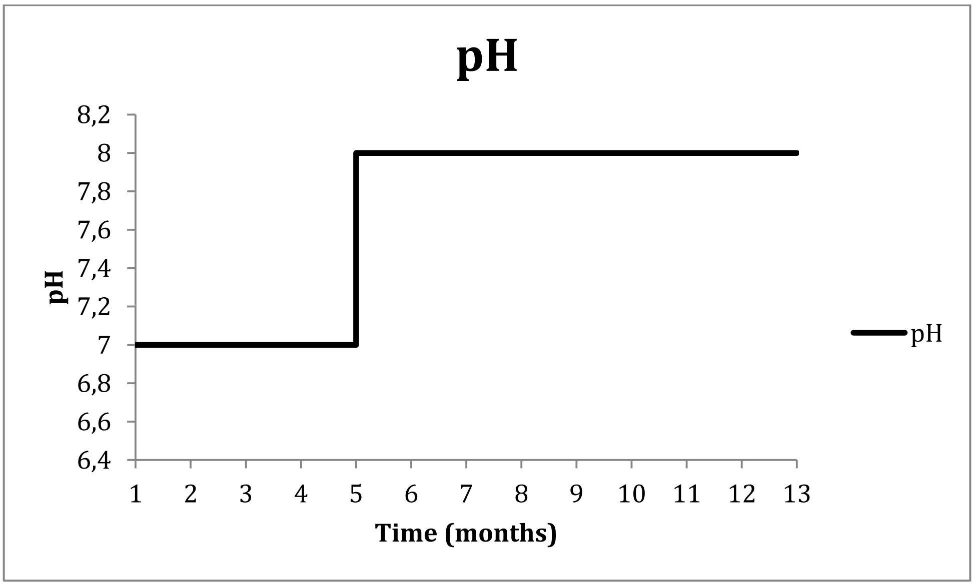

Figure 32. A sudden increase in pH during the fifth month of the production cycle.

pH has direct effects on the growth and mortality rates of the fish. A pH-level of 8 is, however, still in the range of what is considered optimal for farming of Atlantic salmon. Hence, the system failure is not caused by the direct effects of pH on the fish, but by the following: For every kilogram feed given to the fish, a fraction will end up as ammonia in the fish rearing tank. Only the unionized form of ammonia is toxic to fish, and this fraction is, among other things, affected by the pH-level in the water. In the base-run, the pH-level is 7 and the temperature 15 degrees Celsius, with a corresponding fraction of ammonia in its unionized form equal to 0.003. The sudden increase in pH in month five of the production cycle will, however, cause the unionized fraction to rise to 0.03 (i.e. tenfold) within a relatively short period of time. The biofilter is functioning, but it takes time for it to adjust to the new level of unionized ammonia. Unless measures are taken, the concentration of unionized ammonia will reach toxic levels (Fig. 33). As the biofilter conversion ratio increases, also the concentration of nitrite will start to build up (Fig. 34).

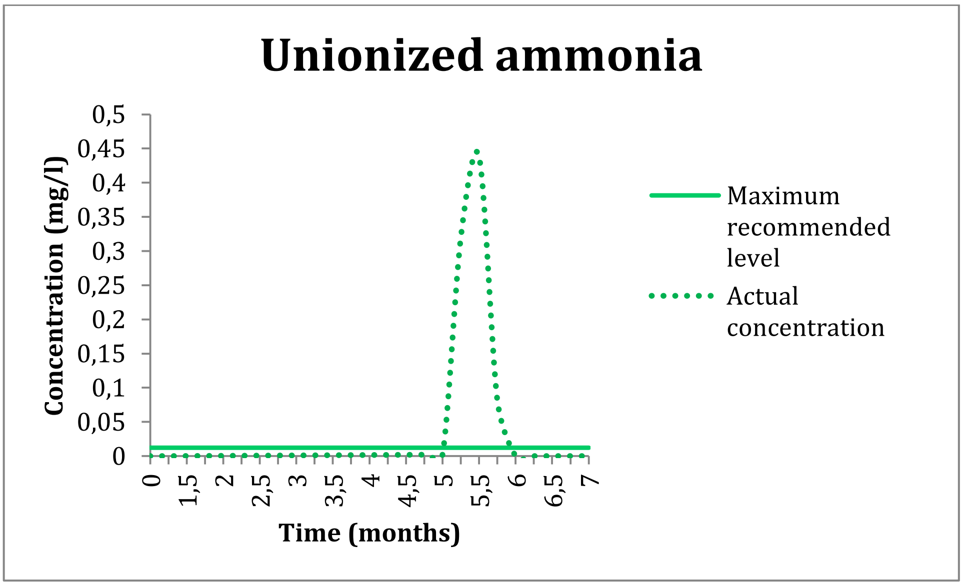

Figure 33. The concentration of unionized ammonia in Scenario 3.

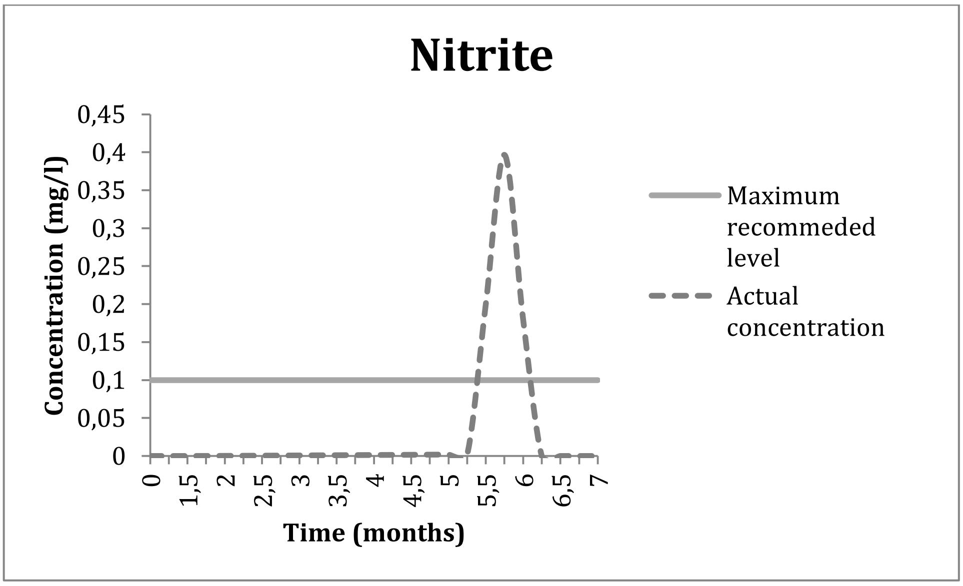

Figure 34. The concentration of nitrite in Scenario 3.

Nitrosomonas, the type of nitrifying bacteria converting unionized ammonia into nitrite, will start to multiply as the concentration of unionized ammonia increases. Nitrobacter, the type of nitrifying bacteria converting nitrite into nitrate, will start to multiply as the nitrite concentration increases. Because of this time delay in the biofilter build-up process, elevated nitrite concentrations will be present in the system even after the concentration of unionized ammonia is back to safe levels (Fig. 35).

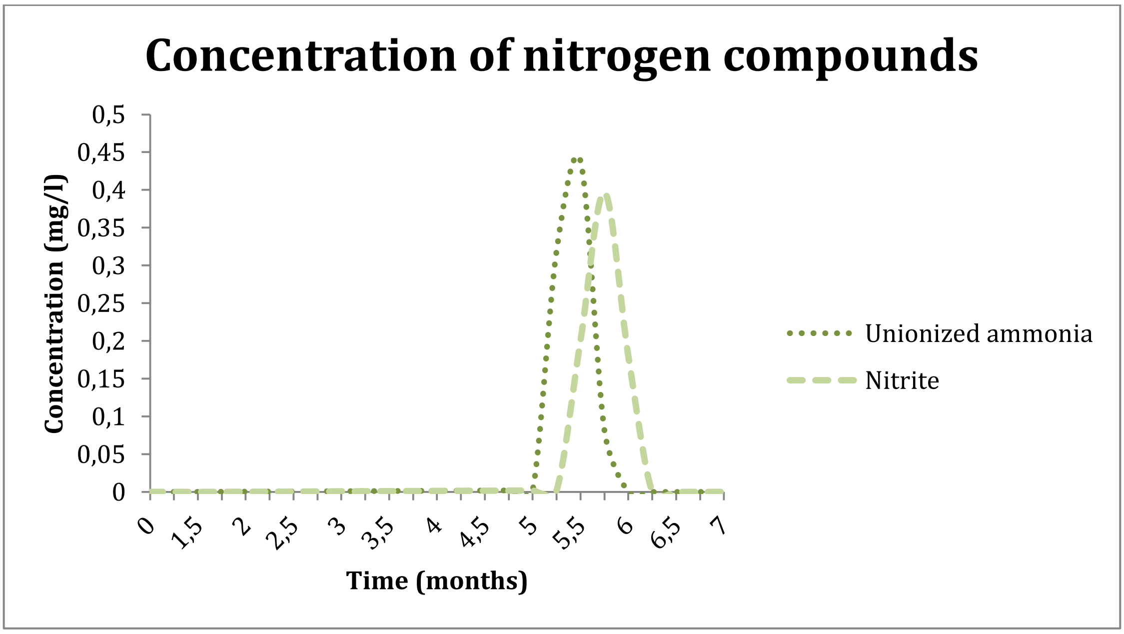

Figure 35. Levels of unionized ammonia and nitrite reaching toxic levels.

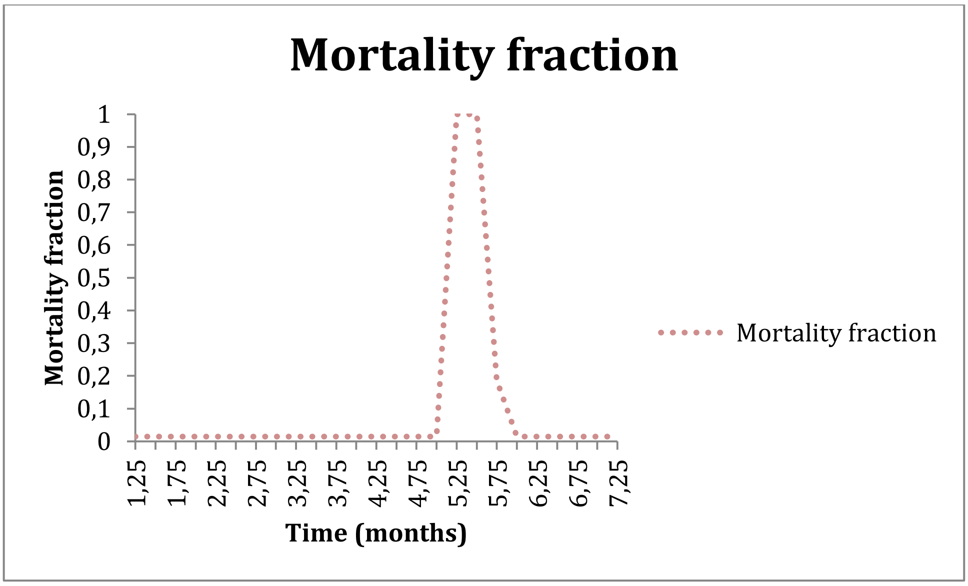

Figure 36. A rapid increase in the mortality fraction due to high concentrations of unionized ammonia and nitrite.

As the unionized ammonia and nitrite are reaching toxic levels, the mortality fraction will increase until it reaches one, see Figure 36. Consequently, all biomass in this production cycle will be lost, as displayed in Figure 37.

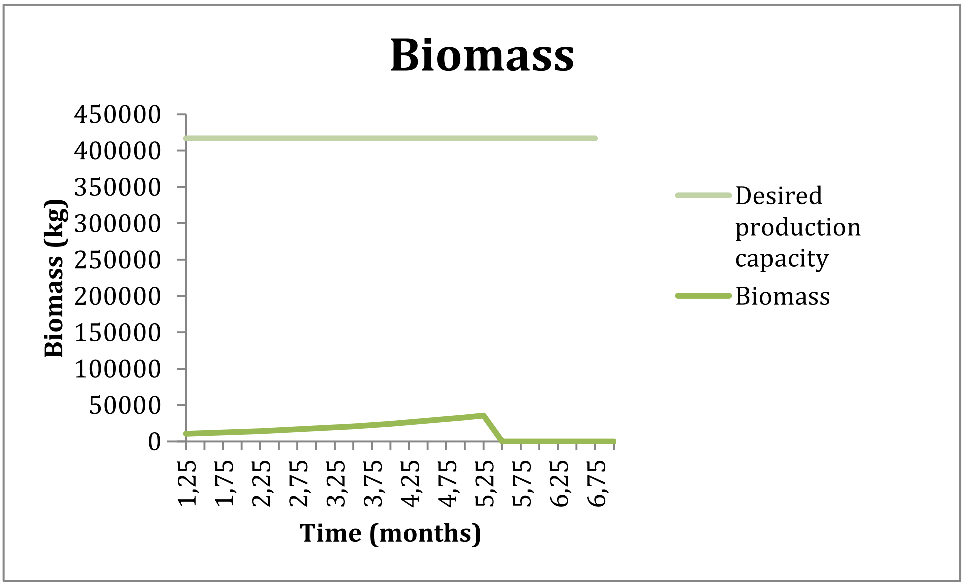

Figure 37. A loss of all biomass in one production unit.

The simulated results presented in this section shows the development in one production unit, where the cohort has been in the unit for five months at the time of the system failure. The biofilter is however affecting *all* production units in the facility, meaning that a biofilter failure will affect all cohorts in the system in the same way[5]. Consequently, the total amount of biomass in the facility will be lost. The fish in each unit will however be in different stages of the production cycle at time of the system failure. This has implications for the financial performance of the firm, since the economic loss per cohort will differ. A cohort that has been in production longer has accumulated a higher value, and a larger investment has been made, compared to a cohort that more recently was put into production. For a more detailed analysis of the financial performance under Scenario 3, see section 5.2.

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[5] Given a recirculation rate of 18 620 m^3/mo, the fraction unionized ammonia being equal to 0.03, the fish rearing tank volume being 16 667 m^3, with a total back-up tank volume of 10% (→12*0.1*16 667). Under these conditions, the concentration of unionized ammonia will accumulate and reach toxic levels in all production units. Given other production specifications, or a smaller increase in the fraction unionized ammonia, this might not be the case. In practice, it is also possible to have a back-up system for each production unit, separating them from each other. This type of solution could, however, be relatively costly.

5.2 Economic sustainability: Indicators of financial performance

Table 2 summarizes the financial performance of the facility under different scenarios.

Table 2. *Financial Performance*

	SCENARIO		
	1. Base-run[1]	**2. Sub-optimal production**[2]	**3. System failure**[3]
Expenses (NOK)	8 007 777	8 342 901	Cohort in unit: 4 693 081 Cohorts in the rest of the facility, total: 60 684 065
Revenue (NOK)	9 829 298	5 969 029	-
EBIT (NOK)	1 821 522	- 2 373 872	- 65 377 146
Production cost (NOK/kg)	21	35	-
Relative cost margin (NOK)[4]	29 -21 = 8	29 - 35 = - 6	-
Total Loan Coverage (NOK)	89 829 474	-	6 486 453

[1] *Revenues are displayed before tax. The Total Loan Coverage assumes a mortgage time of 5 years and an interest rate of 4%. The whole loan is assumed to be repaid in year five. The revenue, expenses and EBIT are calculated per cohort. The relative cost margin is the difference between the cost of sea-based production (per kg) and land based production (per kg). The numbers are rounded.*

[2] *The underlying assumptions in scenario 2 are the same as in the base-run. This scenario does however show the consequences of sub-optimal system performance. The production-conditions are assumed to be sub-optimal for a number of months in every year of system operation.*

[3] *The expenses include the loss of all biomass currently in the system. No revenue can be collected that year. Given the assumption that the facility can operate normally the next coming year, it is however possible to cover the losses with the revenue generated during the years remaining before the loan needs to be repaid. Therefore, the Total Loan Coverage is positive.*

[4] *The estimated production cost in sea is 29 NOK/ kg, see Marine Harvest, 2014.*

In the base-run scenario, with the related assumptions about optimal production conditions, the facility will have a positive EBIT from month one. The production cost is 21 NOK/kg biomass produced, as compared to 29 NOK/kg in a sea based facility. The EBIT will cover a loan of approximately 90 million NOK, given an interest rate of 4% and a mortgage time of five years (where the whole loan is paid back in year five). Under scenario 2, where the temperature is sub-optimal during several months per year, the EBIT is negative. The revenue from the produced and sold biomass quantity cannot cover the production related expenses. The production cost is 35 NOK/kg, which is 6 NOK more than the production cost in a sea-based facility. Since the EBIT is negative it is not possible to cover a loan solely by the revenues of the firm.

In Scenario 3, a system failure in year one of operation leads to a loss of all biomass in the facility. The expenses under this scenario are estimated to around 65 million NOK. This number represents the money invested in each cohort in the facility at the time of system failure. As no revenue can be collected that year, EBIT is negative and equal to the expenses. Assuming that the facility is back to optimal performance during the next year of operation, the financial loss can be covered by the revenue streams generated the following years. This makes it possible to cover a loan of approximately 6.5 million NOK.

5.3 Sensitivity analysis

This section presents sensitivity tests performed to explore the robustness of the simulated results. First, key variables were chosen to be included in this analysis. Thereafter, the values of these variables were changed, and the corresponding change in behavior explored.

Table 3 shows how the estimated production cost per kilogram biomass vary with changes in the annual production capacity - considering potential cost advantages of increased production output. As shown in the table, the production cost per kilogram biomass produced decreases with increasing production volumes. Hence, economies of scale may be achieved. The results do however also show that this effect is diminishing for production volumes above 1 000 000 kg per year.

Table 3. *The Simulated Production Cost for Different Production Capacities.*

	Yearly production capacity (kg)				
	1 000 000	**2 000 000**	**3 000 000**	**4 000 000**	**5 000 000**
Production cost (NOK/kg)[1]	23	21	21	21	21

[1] *Rounded numbers.*

Table 4 shows how the market price of salmon affects EBIT and the Total Loan Coverage of the firm. As seen in the table, a market price of 15 or 20 NOK per kilogram biomass generates a negative EBIT. Consequently, the Total Loan Coverage is equal to zero. For a market price above the value in the base-run scenario, 25 NOK per kg biomass, the estimated EBIT becomes significantly higher. Everything else equal, a market price of salmon at 30 NOK/kg generates an EBIT of approximately 1.8 million NOK per cohort. The EBIT for a market price of 35 or 40 NOK/kg is approximately 3.5 and 5 million NOK per cohort, respectively. The Total Loan Coverage ranges from 9 million NOK in the base-run scenario, up to around 250 million NOK in case of a market price equal to 40 NOK/kg.

Table 4. *EBIT and Total Loan Coverage for Different Market Prices of Salmon.*

	Market price of Atlantic salmon (NOK/kg)					
	15	**20**	**25**	**30**	**35**	**40**
EBIT (NOK)	- 3 093 128	- 1 454 911	183 305	1 821 522	3 459 738	5 097 954
Total Loan Coverage (NOK)	-	-	9 039 806	89 829 474	170 619 143	251 408 810

Table 5 displays the results of changing the costs of production inputs. Three important production inputs were selected - feed, labor and electricity. The table displays how the production cost, EBIT and Total Loan Coverage vary with changes in the total cost of the production inputs chosen. In the best case scenario, with a 20% cost reduction, the production cost per kilogram biomass is estimated to 17 NOK. This results in an EBIT of around 3 million NOK per cohort, and a Total Loan Coverage of approximately 157 million NOK. In contrast, increasing the cost of these production inputs with 20% generated a production cost of 24 NOK per kilogram biomass - generating an EBIT of 458 367 NOK and a Total Loan Coverage of around 23 million NOK.

Table 5. *The Effect of Changing Costs of Production Inputs.*

	Change in the cost of production inputs (%)				
	- 20%	**-10%**	**Base-run**	**+ 10%**	**+ 20%**
Production cost (NOK/kg)	17	19	21	22	24
EBIT (NOK)	3 184 676	2 503 099	1 821 522	1 139 944	458 367
Total Loan Coverage (NOK)	157 054 283	123 441 879	89 829 474	56 217 070	22 604 666

5.4 Environmental impact analysis

Table 6 shows estimated water- use for production of different sources of protein. It also shows an estimate of the Carbon Footprint of salmon produced in a land-based facility, compared to estimates for other types of protein.

Table 6. *Relative Environmental Impact of Production.*

Relative environmental impact of production				
	Salmon (land-based aquaculture)	**Salmon (sea-based aquaculture)**	**Beef**	**Chicken**
Carbon Footprint (CO_2/kg edible meat)	1.4[1]	2.9	30	3.4
Water consumption (Liter/edible meat)	74	1 400	15 400	4 300

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[1] *The Carbon Footprint estimate is based solely on the energy use for production (2.4 kWh per kg edible meat). The CO_2 emission factor used is 0.527 kg/kWh.*

The results indicate that, compared to the production of other types of protein, land-based aquaculture using RAS technology require significantly less water per kilogram biomass produced. The model does not estimate the total Carbon Footprint of the facility. It does, however, calculate the energy use per kilogram biomass produced. In the base-run, the energy per kilogram biomass (edible meat) is estimated to be 2.4 kWh - translating into a Carbon Footprint of 1.4 kg CO_2/kg biomass. The Carbon Footprint of the land-based facility is, however, also dependent on other factors, such as transportation. Hence 1.4 kg CO_2/kg biomass is likely to be an underestimation of the total Carbon Footprint.

The land-use requirements of the facility depend on the production volume, stocking density and overall design of the buildings. Table 7 shows land-use requirements for different stocking densities and heights of fish rearing tanks and back-up tanks. As shown in the table, the land-use requirements vary from around 29 000 m^2 up to 139 000 m^2, depending on the design and production specifications.

Table 7. *Land-use Requirements for Production.*

Land-use				
	Base-run: 25 kg/m^3+ height 2 m	**Run 2: 50 kg/m^3 + height 2 m**	**Run 3: 25 kg/m^3 + height 3 m**	**Run 4: 80 kg/m^3 + height 3 m**
Land-use per production unit (m^2/unit)	11 603	5 802	7 736	2 417
Total land-use (m^2/ facility)	139 236	69 624	92 832	29 004

Specifications: All runs assume a production capacity of 5 000 tons per year. There are 12 production units in the facility. The table shows how land-use requirements change with different stocking densities (25 – 80 kg/ m^3) and tank heights (2-3 m).

6. Discussion

The results indicate that aquaculture can be economically sustainable under certain conditions. This section discusses the results in more detail, both from an economic perspective and from an environmental point of view.

6.1 Economic sustainability

The results presented in Chapter 5 suggest that a land-based aquaculture facility has the potential to generate a positive EBIT, under optimal system performance. Given a positive EBIT, there is an opportunity to cover loans for the initial investment in the facility solely by the revenue generated by the firm. The Total Loan Coverage can serve as an indicator of the feasibility of land-based aquaculture for potential investors. Moreover, the estimated production cost per kilogram biomass was lower than the corresponding estimate for sea-based production. This indicates that land-based aquaculture has the potential to be competitive in the market.

On the other hand, the results suggest that the economic sustainability of the firm is heavily dependent on the performance of the system. Sub-optimal functioning or system failures have a large negative impact on the economic sustainability of the firm. Scenario 2, where production conditions were sub-optimal over an extended period of time, generated a negative

EBIT - in spite of an annual production output of around 3 000 tons. Therefore, it is likely that a land-based aquaculture facility must run close to carrying capacity in order for it to be economically sustainable. In scenario 3, a system failure occurred in the first year of production. The simulated results revealed how large impact such an event could have on the firm’s ability to cover initial investment costs and loan repayments, also in the long-run. The Total Loan Coverage in scenario 3 was about 14 times less than the amount covered in the base-run scenario. Additionally, scenario 3 demonstrated how only a small shift in one water quality parameter may cause a complete system failure.

Moreover, the sensitivity analysis demonstrated how EBIT and the Total Loan Coverage depend on the market price of salmon, as well as the price of production inputs. In practice, this means that if the producer is able to lower the cost of production inputs, then this could have a large positive effect on the economic sustainability of the firm. On the other hand, this makes the firm extremely vulnerable to unfavorable market conditions.

One important reminder is that the Total Loan Coverage is based on EBIT. Hence, these numbers need to be adjusted to include taxes as well as some of the costs not included in the original analysis (e.g. processing and transportation costs).

6.2 Resource use for production

Land-based aquaculture production is introduced as an alternative to traditional capture fisheries and sea-based fish farming, as it has got the potential to offer a more environmentally friendly production. Yet, land-based production, as any other production process interacting with the environment, has the potential to cause environmental damage. Land-based aquaculture production requires resources - mainly water, energy and land. The results in this research do, however, indicate that the resource use in the case of land-based aquaculture production is relatively small - compared to production of other sources of protein. For instance, significantly less water is needed to produce salmon in a land-based facility using RAS compared to the water requirements for salmon production at sea. Moreover, the results indicate that the energy use per kilogram biomass produced is relatively small. Based on the energy use, the Carbon Footprint of the facility was calculated. Also this number was comparatively small. However, in order to obtain a more reliable estimate, other factors than energy use must be included in the calculation.

Resource requirements in terms of land-use vary with the design of the facility and with other production specifications. A well designed and capacity utilizing facility provides an opportunity to minimize land-use. Additionally, a land-based facility may be located at nearly any location. Therefore, it must not necessarily compete with other interests over scarce coastal land. Rather, the facility may be located in close proximity to the end market. This type of solution would also have a positive impact on the Carbon Footprint of the firm, since the need for transportation would be smaller.

Finally, there is the challenge of waste management. A high production volume will create a significant amount of sludge - with the potential to affect the surrounding environment. Waste management was not explicitly included in this model, hence no further conclusions can be drawn based on the results of this research. The literature does, however, suggest that a highly controlled production process and the possibility to refine sludge to added-value product offer both opportunities and incentives for responsible waste management.

Altogether, these results indicate that the production process of a land-based aquaculture facility has the potential to be resource efficient, with a relatively small environmental impact. This is important because environmental sustainability is a prerequisite for economic sustainability. However, the environmental analysis needs to be extended in order to fully assess the potential environmental impact of land-based aquaculture.

7. Conclusions

Global demand for fish is rising, and is expected to continue to do so in the coming decades. Meanwhile, the production from capture fisheries has stagnated and concerns about the environmental impact of sea-based aquaculture are growing. Pollution, insufficient waste management, spread of disease, biodiversity loss, and resource scarcity are some of the current challenges facing the industry. Technological advancements have introduced land-based fish farming and recirculating aquaculture systems technology as a potential way forward. Uncertainty and a variety of risk factors are, however, associated with this type of production. One source of uncertainty is the economic sustainability of land-based aquaculture systems, particularly as no land-based aquaculture facility is currently operating on a commercial scale. The production process is considered capital intensive, requiring a large amount of financial capital for both initial investments and daily operations.

Under what conditions can land-based aquaculture, using RAS technology, be economically sustainable? That was the question this research aimed to answer. Based on the underlying assumptions and specific context of this research, the results of this study indicate the following:

1) Land-based aquaculture can be economically sustainable, in the sense that it generates positive EBIT and has a production cost lower than in sea-based production, given optimal system performance and full capacity utilization.
2) Land-based aquaculture can be economically sustainable, if the initial investment in the facility requires a loan within the range of the estimated Total Loan Coverage. Given optimal system performance, there is a possibility to cover a relatively large loan for initial investments in the facility, solely by the revenue generated by the firm.
3) The results are sensitive to the development of the market price of salmon, as well as to changes in the price of production inputs. Hence, additional conditions for economic sustainability apply - stable market conditions for Atlantic salmon and no unexpected changes in the supply of production inputs.

In addition, the results generated in this research support the underlying assumption that land-based aquaculture can offer a more environmentally friendly production process, compared to both the production of fish in sea-based aquaculture as well as to the production of other types of protein. Environmental and economic sustainability are interrelated. Given favorable conditions, land-based aquaculture has the potential to achieve both.

7.1. Reflections and further research

Previous research in the field of aquaculture has mainly focused on understanding separate parts and specific relationships in aquaculture systems. Using a system dynamics approach in this research allowed for an integrated and systemic analysis of the functioning and economic sustainability of such a system. The results produced by this research demonstrated how the interplay of different variables governs the system, and how small disturbances in one part of the system can have large impacts on the system as a whole. In a scientific context, these findings support the use of whole systems approaches, such as System Dynamics, when further exploring and evaluating the functioning of land-based aquaculture systems.

In practice, the results imply that land-based aquaculture has the potential to be a worthwhile investment, both for the individual firm and for society at large. Yet, the results also demonstrate that managing risk and making use of the installed capacity of a land-based aquaculture facility is crucial.

Although the model structure and the behavior generated by this structure seem valid, the model has got known limitations. These limitations include insufficient representations of the interdependence of the water quality parameters, uncertainty regarding the effects of water quality on the biomass, and the limited environmental impact analysis. The remaining part of this section reflects on these limitations, and provides suggestions for future research and model developments.

7.1.1 Modeling the interdependence of water quality parameters

One important feature of a land-based aquaculture system is the interdependence between different water quality parameters. In the model, each water quality parameter has got an individual effect on the biomass. The interrelatedness of the parameters is represented by the variable “water quality effect on biomass” - a multiplicative variable integrating all water quality parameters into one aggregate effect. Additionally, the relationships between the parameters are captured by links between the sectors, such as the effect of water temperature on oxygen saturation, or the effect of pH on unionized ammonia. Yet, there are additional relationships and interdependencies that could be included in the model - especially when more data and knowledge about the exact relationships between the variables become available. In the meantime, not having a representation of these links is a limitation of the model, as it reduces its ability to fully capture the dynamics of the system - especially in case of a system failure.

Modeling the relationships between the water quality parameters in greater detail would require a more disaggregated level of analysis, and could potentially be accomplished by adding sub-models to the main model. To fully capture the dynamics of the system on a more disaggregated level, it is likely that the granularity of the time period of analysis would have to be increased - simulating the behavior of the system in minutes or hours rather than in months.

A methodological concern with respect to the interdependency of these variables, is the methods currently available to estimate the levels of certain variables within the system and how they change over time. Both in theory and practice, it is common that concentrations and processes are based on indirect measurements. For instance, due to the difficulties of estimating CO_2-concentrations in the water, pH is used as an indicator of the concentration of dissolved CO_2. As system dynamics is a method emphasizing causality, using indirect measurements of variables included in the model reduces the explanatory power of the model and its ability to clearly display cause and effect relationships.

7.1.2 Modeling the effects of water quality on biomass growth rates and mortality

Fully understanding the relationships between water quality on the one hand and biomass and growth and mortality rates on the other, is an important part of modeling a land-based aquaculture system. From previous research and knowledge among practitioners within the field, it is possible to identify safe limits and recommended ranges for water quality parameters in the system. Within the safe operating space of these parameters, the mortality rate will be equal to the “normal” mortality rate, and the biomass growth rate will close to its maximum.

Outside of the recommended ranges, the exact relationship between a specific water quality parameter and the biomass growth rate and welfare is, however, more uncertain. This relationship also depends on a number of factors, such as the life-stage and stress level of the fish. Consequently, the fish may be more or less resilient against changes in a specific water quality parameter, depending on the state of all other water quality parameters in the system as well as the current fitness and life-stage of the fish.

In the model, the biomass quantity sent to the market has a direct effect on the revenue streams generated by the production, and, as a result on the overall economic sustainability of the firm. Therefore, the exact relationship of water quality parameters and the biomass matters, in the same way as the exact relationships and interdependence between the water quality parameters matters.

7.1.3 Missing feedbacks: Economic and environmental sustainability

The economic analysis in this research concerns the potential economic sustainability of a single land-based aquaculture farm. The analysis aims at exploring the feasibility of land-based production, can it be economically sustainable? Under what conditions can this type of production be competitive in the market? The numbers presented in this analysis are, however, not adjusted to take the full environmental impact of aquaculture production into account, and should be considered in future research.

The simulated production cost for land-based aquaculture includes the direct cost of resource use, i.e. the cost of energy and water consumption for production. The analysis does not, however, extend to include other types of environmental impact. If it did, the estimated production cost could potentially be higher. Likewise, the production cost for sea-based aquaculture does not include the full environmental impact caused by the industry. If this impact was transmitted through prices, it is likely that the production cost of sea-based production would be higher than what the current estimates suggest. Therefore, the financial performance indicators presented in this research could be adjusted in the following way:

1) The cost of the environmental damage that sea-based production causes could be included in the estimated production cost.
2) The cost of the environmental impact of land-based production could be included in the estimated production cost.
3) If, as suggested, land-based aquaculture is more environmentally friendly than sea-based aquaculture, then the evaluation of land-based production could also take into account the potential economic gain of moving production from sea to land for society as a whole.

Incorporating the cost of environmental damage caused by aquaculture production would change the estimated costs of production. Because of the large environmental impact of sea-based production, this might make the perceived economic sustainability of land-based production higher. If there are environmental gains to be made by moving production from sea to land, there are also economic gains to be made - from the perspective of the individual firm but also for society at large.

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Appendix A: Model validation

The structure oriented tests performed in this research include the dimensional consistency test, as well as extreme condition testing. In this section, the results from the extreme condition test will be presented in more detail. Additionally, the section ends with a discussion on the behavior oriented tests performed.

Structure oriented tests

The extreme condition test was performed by assigning a value of zero to the variable “New cohort: placement rate” at the end of the first production cycle. This means that no new biomass will be introduced in the system after the first cohort. This is an extreme condition under which it is relatively easy to anticipate the behavior of the variables in a real aquaculture system. Biomass is the driving factor of the dynamics in the system, affecting every part of it. For example, if there is no biomass in the system, then no oxygen is consumed. Additionally, there is no water recirculation (as there is no need for removal of waste solids or addition of oxygen). Moreover, there is no need to introduce feed in the system, hence the anticipated feeding rate is equal to zero. The results from the extreme condition test are displayed in Figure 38 to Figure 45.

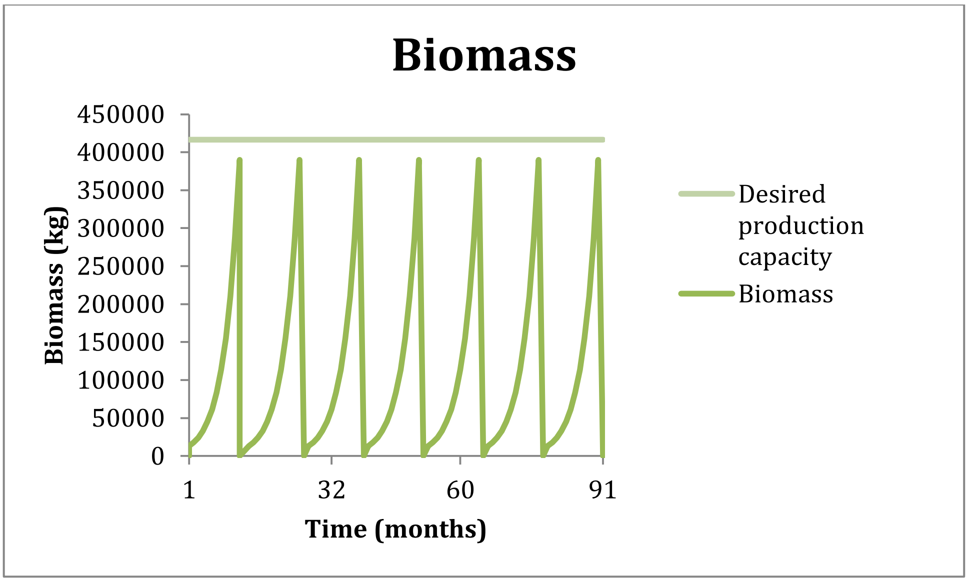

Figure 38. Biomass development under normal system operation.

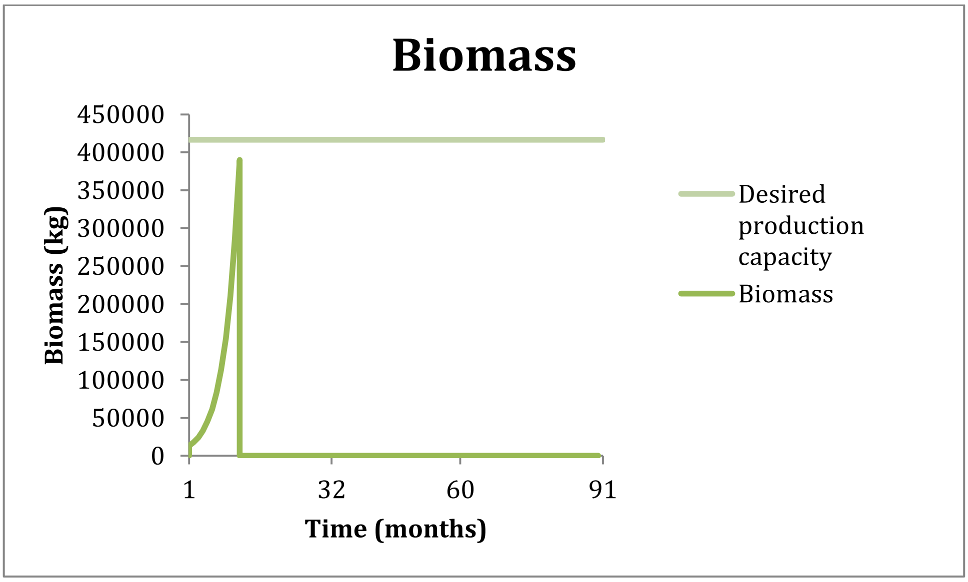

Figure 39. Extreme condition test.

Figure 38 shows the biomass development under normal system operation. Each cohort remains in the production unit for 12 months, and a continuous biomass loading is employed. After each cohort the tank is empty for one month, before the next cohort is introduced. During optimal system performance the biomass shows uninterrupted growth, utilizing the production capacity to the fullest (except from the "normal" mortality occurring). Figure 39 shows the biomass development after assigning a value of zero to the "New cohort: placement rate" after the first production cycle. As anticipated, the production unit is empty during the remaining time of the simulation.

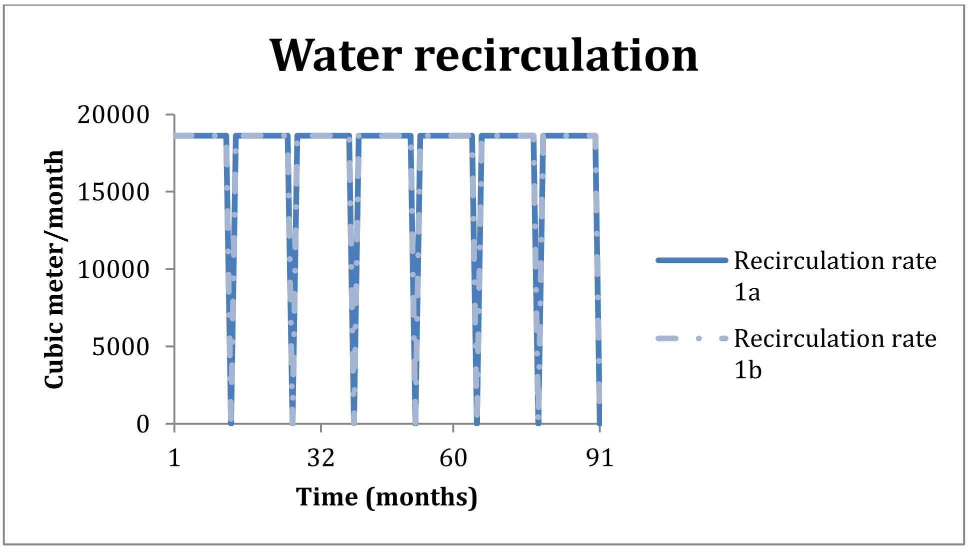

Figure 40. Water recirculation under normal system operation.

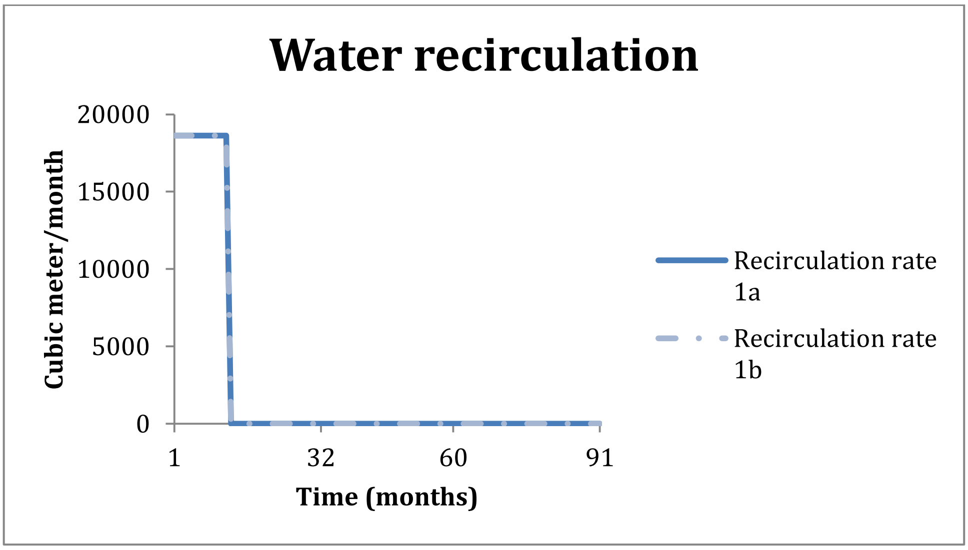

Figure 41. Extreme condition test.
Water recirculation after assigning a value of zero to the new cohort placement rate.

Under normal system operations, the recirculation rates are constant and equal to each other as long as there is biomass in the facility. If no new cohort is placed in the fish rearing tank after the first production cycle, there is no need for recirculation. As anticipated, the resulting recirculation rate is equal to zero, as displayed in Figure 41.

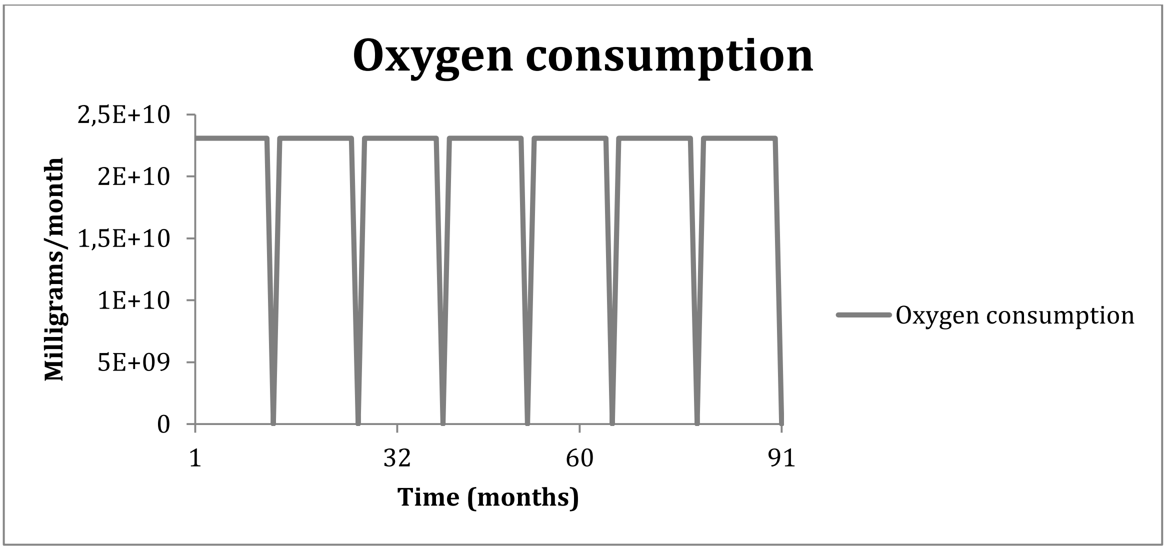

Figure 42. Oxygen consumption under normal system performance.

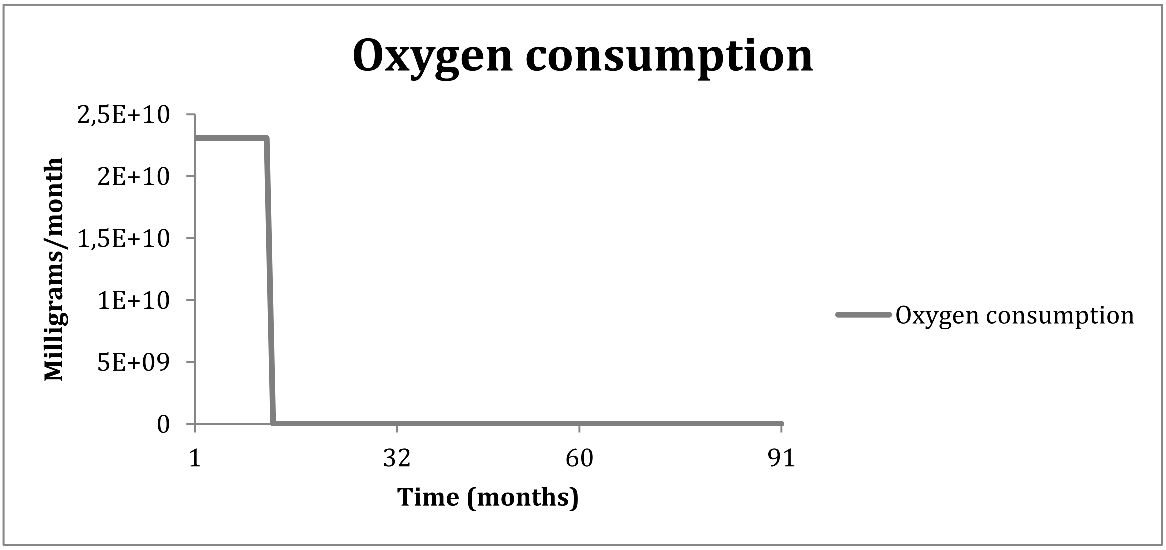

Figure 43. Extreme condition test: The oxygen consumption is equal to zero when no biomass is in the production unit.

The fish consumes oxygen. Figure 42 shows the average oxygen consumption per month when there is biomass in the facility. When there is no biomass in the fish rearing tank, naturally no oxygen is consumed, as displayed in Figure 43.

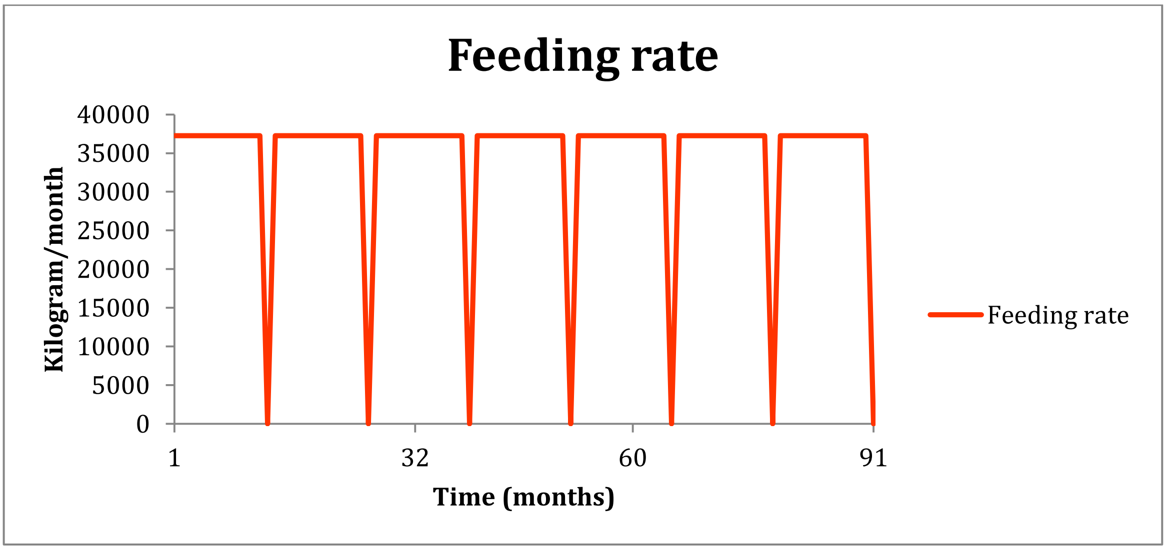

Figure 44. Monthly feeding rate under normal system performance.

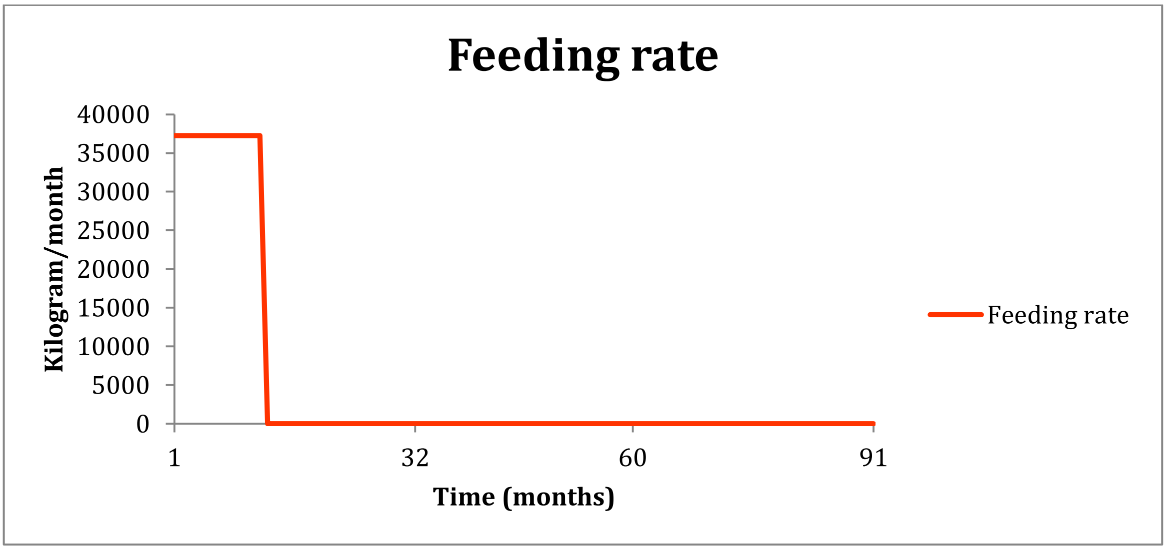

Figure 45. Extreme condition test: The feeding rate becomes equal to zero when no biomass is in the system.

Feed is an important production input. As long as there is biomass in the facility, the monthly feeding rate is constant. When the cohort placement rate is set to zero after the first cohort, the feeding rate drops to zero and remains there, as shown in Figure 45.

Behavior oriented tests

In addition to structure oriented tests, the validity of the model has been evaluated with behavior oriented tests - mainly behavior replication tests and sensitivity analysis. The simulated behavior generated by the model structure shows consistency with the expected behavior of a land-based aquaculture system. For instance, biomass shows uninterrupted growth towards the maximum biomass loading during one production cycle, unless there is an interruption in the system or if the production conditions are sub-optimal. The ammonia and nitrite curves show a typical behavior pattern in case of a biofilter interruption. Oxygen consumption reaches estimated levels as long as there is biomass in the system. When it comes to the financial performance of the facility, there is no specific “reference mode of behavior”, since no commercial scale land-based aquaculture facility is currently operating. Therefore, the validity and plausibility of the financial performance indicators were evaluated mainly through sensitivity analysis, but also through reviews from one of the employees at Norsk Sjømatsenter.

Appendix B: Model interface

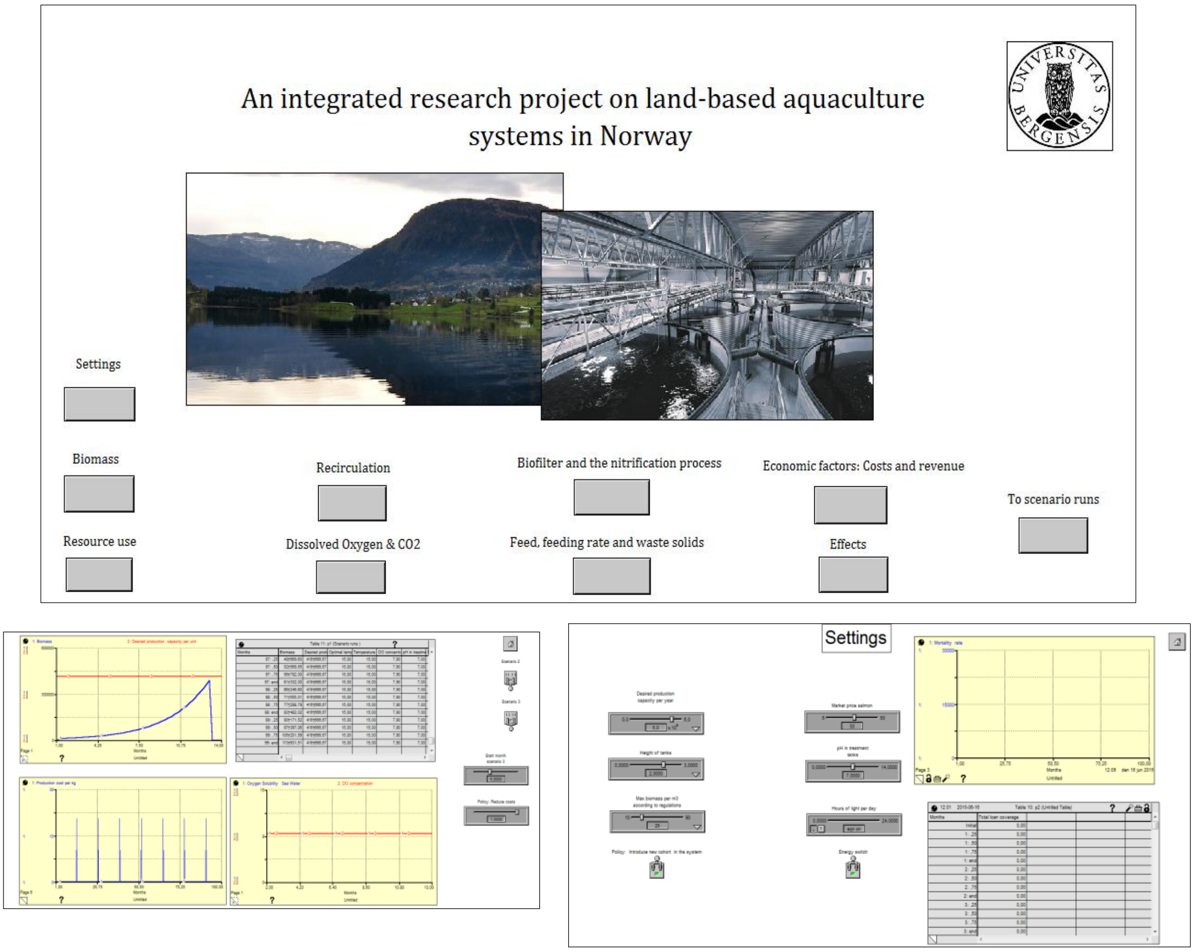

Figure 46. The model interface.

The model is supplemented by an interface. The interface creates an opportunity for the user to interact with the model. It is for example possible to change underlying assumptions and parameter values, run simulations and explore the output for all variables of interest. The interface consists of different parts, easy to navigate to from the start page. Under *settings*, the user can change a selected number of production specifications. Under the page *scenario runs*, the user can find switches to simulate the scenarios presented in this research. The remaining navigation buttons on the start page redirects the user to output graphs, sorted after what sector it belongs to.

Appendix C: Model formulations

Table 8.*Model Formulations in Sector 1: Production Capacity*

Formulations and comments	**Units**
Water in cleaning tanks(t) = Water in cleaning tanks(t - dt) + (Recirculation rate 1a Recirculation rate 1b) * dt *This stock represents the water level in the system backup rearing tanks.*	Cubic meters (m^3)
Recirculation rate 1a = if Counter for water exchange>=13 AND Counter for water exchange<14 THEN 0 else Recirculation need *The recirculation rate (1a) is the water leaving the fish rearing tank to go through water treatment. It is equal to the Recirculation need.*	Cubic meters per month (m^3/mo)
Recirculation rate 1b = Recirculation rate 1a *Recirculation rate (1b) is equal to Recirculation rate 1a, and represents the water flowing from the treatment tanks and back to the fish rearing tank. The recirculation rates are equal to each other to ensure stable water levels in the fish rearing tank.*	Cubic meters per month (m^3/mo)
Water volume in fish rearing tank(t) = Water volume in fish rearing tank(t - dt) + (Recirculation rate 1b + Water outtake from source + Water exchange inflow - Recirculation rate 1a - Water loss rate - Water exchange outflow) * dt *The stock of water in the fish rearing tank is affected by six flows. The recirculation rates are the water flows managing water circulation under system operations, the water loss rate is water lost due to for instance evaporation and the water outtake from source makes up for this loss by introducing new water in the system. Lastly, the water exchange outflow and inflow empties and fills the stock up again between cohorts.*	Cubic meters (m^3)
Water outtake from source = Water loss rate*Energy switch *The water outtake from source is equal to the water being lost due to, for instance, evaporation. In case of a power outage the pumps will not function, and so the water outtake will be equal to zero.*	Cubic meters per month (m^3/mo)
Water exchange inflow = PULSE(Water demand,1,Time per cohort in module) *After each cohort the water in the fish rearing tank is*	Cubic meters per month (m^3/mo)

exchanged, modeled as a PULSE function. The water exchange inflow fills the tanks up again before a new cohort is introduced.	
Water loss rate = if Counter for water exchange>=13 AND Counter for water exchange<14 THEN 0 else Water volume in fish rearing tank*Fractional water loss *The water loss rate is a fraction of the total water in the fish rearing tank that is being lost every month.*	Cubic meters per month (m^3/mo)
Water exchange outflow = if Counter for water exchange>=13 AND Counter for water exchange<14 THEN Water volume in fish rearing tank/DT else 0 *After each cohort, the water in the fish rearing tank is exchanged, modeled as a PULSE function.*	Cubic meters per month (m^3/mo)
Counter for water exchange = COUNTER(1,14) *The nature of the production process in an aquaculture facility, and a biomass loading policy where all biomass is moved at a specific point in time (as opposed to continuous loading)creates a need to empty a stock/fill a stock fully within one DT on the model. The COUNTER function fills this purpose.*	Months (mo)
Desired production capacity per unit = Desired production capacity per year/12 *Given the assumption that the facility contains 12 production units, each unit must produce one twelfth of the total desired production of the facility per year - in order to send one cohort to the market each month.*	Kilograms (kg)
Land use tanks only: m2 = (Tank volume in fish rearing tanks*1.1)/Height of tanks *The land use of the tanks depends on the height and volume of the tanks. Each fish rearing tank requires 10% of its total volume in backup volume.*	Square meters (m^2)
Number of fish per cohort = Desired production capacity per unit/Maximum weight of grown fish *The desired production capacity per unit divided by the maximum weight the fish can reach will determine the number of fish in each cohort.*	Fish
Recirculation need = Feeding rate*M3 per kg feed*Energy switch *The recirculation need (the amount of water exchanged in the fish rearing tanks each month) depends on the feeding rate. The energy switch makes the recirculation need zero*	Cubic meters per month (m^3/mo)

in case of a power outage.	
Tank volume in fish rearing tanks = Desired production capacity per unit/Max biomass per m3 according to regulations *In this model, the tank volume is based on the desired production capacity and the maximum stocking density.*	Cubic meters (m^3)
Total land use per unit: m2 = Land use tanks only: m2/0.79 *The total land use is the area needed for the fish rearing tanks, plus an additional area surrounding the tanks.*	Square meters (m^2)
Water demand = Tank volume in fish rearing tanks *It is assumed that the whole fish rearing tank is filled with water: hence the water demand is equal to the tank volume.*	Cubic meters (m^3)
Water volume fish tanks in liters = Water volume in fish rearing tank*Unit converter: Liters per m3 *This unit converter expresses the water volume in the fish tanks in liters. It is used as an input to those sectors containing a concentration, since these concentrations are expressed in the unit (mg/L) and not (mg/m^3).*	Liters (l)

Table 9. *Parameter Settings in Sector 1: Production Capacity*

Parameter	**Initial value**	**Units**
Desired production capacity per year	5 000 000	Kilograms (kg)
Fractional water loss	0.1	Unitless
Height of tanks	2	Meters (m)
Maximum weight of grown fish	4	Kilogram per fish (kg/fish)
Max biomass per m3 according to regulations	25	Kilogram per m^3 (kg/m^3)
Unit converter: Liters per m3	1 000	Liters/cubic meters (l/m^3)

Table 10. *Model Formulations in Sector 2: Biomass.*

Formulations and comments	**Unit**
Biomass(t) = Biomass(t - dt) + (Biomass growth rate + New cohort: placement rate - Biomass to market - Mortality rate) * dt *The biomass stock represents the biomass quantity in the production unit.*	Kilograms (kg)
Biomass growth rate =	Kilograms per month (kg/mo)

((Fractional GR*Biomass)-Biomass)*Water quality effect on fish growth*Per mo *The biomass growth rate is determined by the fractional growth rate and the water quality in the production unit. The water quality in the production unit is represented by the variable "Water quality effect on fish growth".*	
New cohort: placement rate = (Policy: Introduce new cohort in the system*(PULSE((Number of fish per cohort*Initial biomass per fish),1,Time per cohort in module))) *Every new cohort is introduced in the system with a PULSE function. It introduces a specific biomass, depending on the number of fish per cohort and the initial weight per fish. The interval is determined by the variable "Time per cohort in module".*	Kilograms per month (kg/mo)
Biomass to market = PULSE(Biomass/dt,13,Time per cohort in module)/Per mo *In the end of each production cycle the biomass is sent to the market, using a PULSE function. This function empties the whole stock of biomass at once. The interval is determined by the variable "Time per cohort in module".*	Kilograms per month (kg/mo)
Mortality rate = if Mortality fraction=1 then (Biomass*Mortality fraction)/DT else (Biomass*Mortality fraction) *The mortality rate is a fraction of the total biomass.*	Kilograms per month (kg/mo)
Fractional GR = (Desired production capacity per unit/(Initial biomass per fish*Number of fish per cohort))^(1/(Time per cohort in module-0.5)) *The fractional growth rate (GR) is based on the total biomass change in one production cycle and the time the biomass will remain in the production unit each cycle.*	Unitless
pH in fish rearing tanks = 7+STEP(1,Start month scenario 3)*Scenario 3 *The initial pH value in the fish rearing tank is 7.In Scenario 3 this value increases to 8, modeled as a STEP function.*	Unitless
Stocking density = if Biomass<=0 OR Water volume in fish rearing tank<=0 then 0 else (Biomass/Water volume in fish rearing tank) *The stocking density is the total biomass in the fish rearing tank divided by the water volume in the fish rearing tank.*	Kilogram per cubic meter (kg/m3)
Water quality effect on fish growth = Effect of nitrite on biomass*Effect of pH on	Unitless

biomass*Effect of DO concentration on biomass*Effect of unionized ammonia on biomass*Effect of stocking density on biomass*Effect of CO2 concentration on biomass*Effect of light on biomass*Effect of water temperature on biomass *The water quality effect on fish growth is a multiplicative effect capturing all effects from the different water quality parameters in the system. It affects the biomass growth rate, determining whether or not the fish reaches its maximum weight.*	
Effect of pH on biomass = GRAPH(pH in fish rearing tanks) (0.00, 0.00), (0.824, 0.00), (1.65, 0.00), (2.47, 0.00), (3.29, 0.00), (4.12, 0.0421), (4.94, 0.877), (5.76, 1.00), (6.59, 1.00), (7.41, 1.00), (8.24, 1.00), (9.06, 0.874), (9.88, 0.00), (10.7, 0.00), (11.5, 0.00), (12.4, 0.00), (13.2, 0.00), (14.0, 0.00) *The effect of pH on biomass is modeled as a graphical function.*	Unitless
Effect of stocking density on biomass = GRAPH(Stocking density) (0.00, 1.00), (5.17, 1.00), (10.3, 1.00), (15.5, 1.00), (20.7, 1.00), (25.9, 1.00), (31.0, 1.00), (36.2, 1.00), (41.4, 1.00), (46.6, 1.00), (51.7, 1.00), (56.9, 1.00), (62.1, 1.00), (67.2, 1.00), (72.4, 1.00), (77.6, 1.00), (82.8, 1.00), (87.9, 1.00), (93.1, 1.00), (98.3, 0.996), (103, 0.989), (109, 0.972), (114, 0.944), (119, 0.905), (124, 0.803), (129, 0.662), (134, 0.542), (140, 0.391), (145, 0.176), (150, 0.00) *The effect of stocking density on biomass is modeled as a graphical function.*	Unitless
Mortality fraction = GRAPH(Effect of pH on biomass*Effect of CO2 concentration on biomass*Effect of DO concentration on biomass*Effect of unionized ammonia on biomass*Effect of nitrite on biomass) (0.00, 1.00), (0.05, 0.523), (0.1, 0.225), (0.15, 0.207), (0.2, 0.189), (0.25, 0.186), (0.3, 0.179), (0.35, 0.172), (0.4, 0.154), (0.45, 0.137), (0.5, 0.0947), (0.55, 0.0842), (0.6, 0.0526), (0.65, 0.0281), (0.7, 0.0281), (0.75, 0.0246), (0.8, 0.0246), (0.85, 0.0246), (0.9, 0.015), (0.95, 0.015), (1.00, 0.015) *The mortality fraction determines the mortality rate.*	Per month (1/mo)

Table 11. *Parameter Settings in Sector 2: Biomass.*

Parameter	**Initial value**	**Units**
Initial biomass per fish *The fish is introduced in the system as smolts.*	0.1	Kilograms (kg)
Per mo	1	Per month (1/mo)
Time per cohort in module *The time per cohort is one production cycle (the time it takes for the fish to reach harvestable seize), plus one month for emptying and cleaning of the tanks.*	13	Months (mo)
Policy: Introduce new cohort in the system *This is a policy switch, enabling the user to explore what happens to the system in case the driving factor, biomass, is not introduced in the system.*	1	Unitless
Scenario 3 *This is a switch, enabling the user to simulate Scenario 3.*	1	Unitless
Start month scenario 3 *This switch specifies the starting time for the modifications in Scenario 3.*	5	Months (mo)

Table 12. *Model Formulations in Sector 3: Dissolved Oxygen.*

Formulations and comments	**Units**
Dissolved oxygen : DO(t) = Dissolved oxygen : DO(t - dt) + (DO addition trough aeration + Initialization of DO - DO consumption - Water exchange effect on DO) * dt *The stock represents the total amount of dissolved oxygen in the production unit.*	Milligrams (mg)

DO addition trough aeration = if Counter for water exchange>=13 AND Counter for water exchange<14 THEN 0 else (Recirculation rate 1b*Unit converter: Liters per m3*Oxygen gap)+(Extra oxygen required *Energy switch) *The flow DO addition trough aeration represents the process of adding oxygen to the water.*	Milligrams per month (mg/mo)
Initialization of DO = PULSE(Oxygen Solubility Sea Water*Water demand*Unit converter: Liters per m3, 1,Time per cohort in module) *Before a new cohort is introduced in the system the concentration of dissolved oxygen will be initialized to optimal levels.*	Milligrams per month (mg/mo)
DO consumption = if Counter for water exchange>=13 AND Counter for water exchange<14 THEN 0 ELSE (Oxygen demand per kg feed: Fish * Feeding rate + Feeding rate * Oxygen demand per kg feed: Biofilter) *The consumption of dissolved oxygen is estimated based on feeding rate.*	Milligrams per month (mg/mo)
Water exchange effect on DO = if Counter for water exchange>=13 AND Counter for water exchange<14 THEN Dissolved oxygen : DO/DT else 0 *With a water exchange, all the water in the fish rearing tank is removed, and so the stock of dissolved oxygen will be emptied - represented by the outflow "water exchange effect on DO".*	Milligrams per month (mg/mo)
Extra oxygen required = (Oxygen demand per kg feed: Fish*Feeding rate+ Feeding rate*Oxygen demand per kg feed: Biofilter) *Additional oxygen needs to be added to the fish rearing tank in order to make up for the oxygen consumed by the fish and the biofilter.*	Milligrams per month (mg/mo)
DO concentration = if Dissolved oxygen : DO<=0 OR Water volume fish tanks in liters<=0 then 0 else (Dissolved oxygen : DO/Water volume fish tanks in liters) *The concentration of dissolved oxygen is calculated through dividing the stock of oxygen with the total water volume in the fish rearing tank.*	Milligrams per liter (mg/liter)
Oxygen gap = Oxygen Solubility Sea Water- DO concentration	Milligrams per liter (mg/liter)

The oxygen gap is the difference between the water solubility and the current concentration of dissolved oxygen.	
Effect of DO concentration on biomass = GRAPH(DO concentration) (0.00, 0.00), (1.00, 0.00), (2.00, 0.00), (3.00, 0.0667), (4.00, 0.786), (5.00, 0.958), (6.00, 0.986), (7.00, 1.00), (8.00, 1.00), (9.00, 1.00), (10.0, 1.00), (11.0, 1.00), (12.0, 1.00), (13.0, 0.958), (14.0, 0.814), (15.0, 0.632), (16.0, 0.439), (17.0, 0.242), (18.0, 0.105), (19.0, 0.00), (20.0, 0.00) *The effect of dissolved oxygen concentrations is modeled as graphical function, feeding back to sector 2, affecting the biomass growth and mortality.*	Unitless
Oxygen Solubility Sea Water = GRAPH(Temperature in fish rearing tank) (0.00, 11.2), (5.00, 9.90), (10.0, 8.80), (15.0, 7.90), (20.0, 7.20), (25.0, 6.60), (30.0, 6.10) *The oxygen solubility in sea water depends on the water temperature.*	Milligrams per liter (mg/l)
Oxygen solubility Fresh water = GRAPH(Temperature in fish rearing tank) (0.00, 14.6), (1.00, 14.2), (2.00, 13.8), (3.00, 13.5), (4.00, 13.1), (5.00, 12.8), (6.00, 12.4), (7.00, 12.1), (8.00, 11.8), (9.00, 11.6), (10.0, 11.3), (11.0, 11.0), (12.0, 10.8), (13.0, 10.5), (14.0, 10.3), (15.0, 10.1), (16.0, 9.87), (17.0, 9.67), (18.0, 9.47), (19.0, 9.28), (20.0, 9.09), (21.0, 8.92), (22.0, 8.74), (23.0, 8.58), (24.0, 8.42), (25.0, 8.26), (26.0, 8.11), (27.0, 7.97), (28.0, 7.83), (29.0, 7.69), (30.0, 7.56) *The oxygen solubility in fresh water depends on the water temperature.*	Milligrams per liter (mg/l)

Table 13. *Parameter Settings in Sector 3: Dissolved Oxygen.*

Parameter value	**Initial**	**Units**
Oxygen demand per kg feed: Fish	500 000	Milligram per kg (mg/kg)
Oxygen demand per kg feed: Biofilter	120 000	Milligram per kg (mg/kg)

Table 14. *Model Formulations in Sector 4: Feed and Waste Solids.*

Formulations and comments	**Units**
Accumulated sludge(t) = Accumulated sludge(t - dt) + (Waste solids removal rate + Effect of water exchange on waste	Kilograms (kg)

solids) * dt *This stock accumulates the waste solids that have been removed from the system. This stock could be used in the context of an environmental impact analysis.*	
Waste solids removal rate = Recirculation need*Installed capacity of filters *Waste solids are actively removed in the system. The amount of waste removed is determined by the amount of water flowing through the cleaning facilities, and the installed capacity of the filters.*	Kilograms per month (kg/mo)
Effect of water exchange on waste solids = if Counter for water exchange>=13 AND Counter for water exchange<14 THEN Waste solids/DT else 0 *With each water exchange, all waste solids currently in the fish rearing tanks will be removed.*	Kilograms per month (kg/mo)
Waste solids(t) = Waste solids(t - dt) + (Waste solids accumulation rate - Waste solids removal rate - Effect of water exchange on waste solids) * dt *This stock accumulates the waste solids in the system, before they are removed.*	Kilograms (kg)
Waste solids accumulation rate = Pollution fraction per kg feed*Feeding rate *The amount of waste solids ending up in the fish rearing tank depends on the feeding rate. The higher the feeding rate the higher the total amount of waste solids.*	Kilograms per month (kg/mo)
Av feed demand per cohort per month = (Av growth in unit*Feed conversion ratio)/(Time per cohort in module-1) *The demand for feed is based in the total biomass growth per production cycle, times the feed conversion rate, divided by the time the cohort is in the production unit (minus one to remove the month of system cleaning between cohorts).*	Kilogram (kg)
Av growth in unit = (Desired production capacity per unit-(Number of fish per cohort*Initial biomass per fish)) *The average growth in unit is the total biomass change per cohort. It is calculated as the total biomass (the desired production capacity per unit) minus the initial biomass.*	Kilograms (kg)
Concentration of waste solids = if Waste solids<=0 OR Water volume in fish rearing tank<=0 then 0 else((Waste solids)/Water volume in fish rearing tank)	Kilogram per cubic meter (kg/m^3)

The concentration of waste solids is calculated by dividing the stock of waste solids with the water volume in the fish rearing tanks.	
Concentration of waste solids mg per L = Concentration of waste solids*Unit converter: Mg per kg/Unit converter: Liters per m3 *This variable is also expressing the concentration of waste solids, but in milligrams per liter instead of kilogram per cubic meter.*	Milligram per liter (mg/liter)
Expected solids = Waste solids accumulation rate*Filtering months *This variable calculates the amount of "expected" waste solids. It is used in another stage to determine the installed filtering capacity in the system.*	Kilograms (kg)
Feeding rate = if Biomass>0 THEN Av feed demand per cohort per month else 0 *The feeding rate is based on an estimated demand for feed per cohort per month.*	Kilogram per month (kg/mo)
Installed capacity of filters = Expected solids/Water demand*Filtering efficiency *The total filtering capacity is expressed by the variable installed capacity of filters. It is based on the expected concentration of waste solids and a filtering efficiency parameter.*	Kilogram per cubic meter (kg/m^3)

Table 15. *Parameter Settings in Sector 4: Feed and Waste Solids.*

Parameter value	**Initial**	**Units**
Feed conversion ratio	1.1	Unitless
Filtering efficiency *It is assumed that the filters are able to remove 95% of the solid waste in the water when passing through the treatment unit.*	0.95	Unitless
Filtering months *The estimated filter capacity is based on the efficiency per month.*	1	Months (mo)
Pollution fraction per kg feed *A fraction of the feed in the system will end up as*	0.3	Unitless

pollution. There are different estimates of this fraction, ranging from between 0.3 up until 0.6		
Unit converter: Mg per kg *This parameter is used as a unit converter.*	1 000 000	Milligram per kilogram (mg/kg)

Table 16. *Model Formulations in Sector 5: Energy.*

Formulations and comments	**Units**
Temperature in fish rearing tank(t) = Temperature in fish rearing tank(t - dt) + (Net change in water temperature in tank - Temperature loss) * dt *The stock representing the temperature in the fish rearing tank is affected by two flows - the net change in temperature and the temperature loss.*	Degrees Celsius (degC)
Net change in water temperature in tank = (Optimal temperature-Temperature in fish rearing tank)*Per month *There is a system in the facility that will heat/cool new water added to the fish rearing tanks, in order to ensure an optimal water temperature. A change in temperature in the fish rearing tank is represented by the flow "net change in water temperature in tank".*	Degrees Celsius per month (degc/mo)
Temperature loss = (0*Per month+STEP(0.5*Temperature in fish rearing tank*Per month,5)+STEP(-0.5*Temperature in fish rearing tank*Per month,9))*Scenario 2 *One assumption in the base-run scenario is that there is no heat exchange between the water in the fish rearing tank and the surrounding environment. In scenario 3 there will however be a heat loss, due to insufficient heating capacity of the system. This loss will lead to a consequent temperature drop in the fish rearing tank, represented by the outflow "temperature loss".*	Degrees Celsius per month (degc/mo)
Energy consumption circulation pumps = (Recirculation rate 1a+Water outtake from source+Recirculation rate 1b+Water exchange outflow*0.25+Water exchange inflow*0.25)*Energy use RAS per m3 *The energy consumption for the circulation pumps is the total amount of energy needed to support all water flows in the unit, per month.*	Kilowatt hours per month (kWh/mo)
Energy consumption for heating or cooling of water = ((Optimal temperature-Temperature of inflowing	Joules per month (j/mo)

water)*(Water outtake from source*Unit converter: Liters per m3)*Specific heat capacity)+(Net change in water temperature in tank*(Water volume in fish rearing tank/Per mo*Unit converter: Liters per m3)*Specific heat capacity*Energy switch) *The energy needed to heat or cool the new water added to the fish rearing tank is given by the equation:* $q = C_p * m * \Delta T$ *Where* q = *amount of heat needed (J)* C_p= *the specific heat capacity of water* m= *mass* ΔT = *change in temperature*	
Energy use light and heat = Total energy need for lighting scheme + Temperature unit converter *This variable is calculating the total energy demand for both temperature regulation and the lighting scheme.*	Joule per month (J/mo)
Hours of light per day = Light*Hr per day*Energy switch *This parameter represents the lighting scheme used in the system, in other words the number of hours of light per day.*	Hours of light per day (hr-light/day)
Hours of light per month = Unit converter: Days per month*Hours of light per day *This variable transfers the hours of light per day to hours of light per month, which is useful since the energy requirements are expressed in terms of energy use per month.*	Hours of light per month (hr-light/mo)
Temperature unit converter = If Energy consumption for heating or cooling of water>0 then (Energy consumption for heating or cooling of water) ELSE -(Energy consumption for heating or cooling of water) *This energy converter makes make sure that the estimated energy use to cool/heat water is non-negative.*	Joules per month (j/mo)
Total Energy use per month : kWh= Energy use light and heat*Unit converter: J to kWh + Energy consumption circulation pumps *This variable calculates the total energy use per month, taking into account the energy needed for heating/cooling of water, provision of light as well as for the circulation pumps.*	Kilowatt hours per month (kWh/mo)
Total energy need for lighting scheme = Energy need per m2 per hour*Land use tanks only: m2*Hours of light per month	Joules per month (J/mo)

The total energy needed for the lighting scheme is based on the total area in the tanks and the number of hours of light per month.	
Effect of light on biomass = GRAPH(Hours of light per day) (0.00, 0.00), (1.85, 0.00), (3.69, 0.0807), (5.54, 0.288), (7.38, 0.484), (9.23, 0.649), (11.1, 0.768), (12.9, 0.849), (14.8, 0.912), (16.6, 0.965), (18.5, 0.993), (20.3, 1.00), (22.2, 1.00), (24.0, 1.00) *The effect of light on biomass is modeled as a graphical function, feeding back to sector 2 where it affects biomass growth and mortality.*	Unitless
Effect of water temperature on biomass = GRAPH(Temperature in fish rearing tank) (0.00, 0.00), (1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.0211), (7.00, 0.0737), (8.00, 0.172), (9.00, 0.295), (10.0, 0.519), (11.0, 0.747), (12.0, 0.944), (13.0, 1.00), (14.0, 1.00), (15.0, 1.00), (16.0, 1.00), (17.0, 0.944), (18.0, 0.6), (19.0, 0.298), (20.0, 0.0246), (21.0, 0.00), (22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00), (26.0, 0.00), (27.0, 0.00), (28.0, 0.00), (29.0, 0.00), (30.0, 0.00) *The effect of water temperature on biomass is modeled as a graphical function, feeding back to sector 2 where it affects biomass growth and mortality.*	Unitless

Table 17. *Parameter Settings in Sector 5: Energy.*

Parameter value	**Initial**	**Units**
Energy need per m2 per hour	3.49*(3600)	Joule per hour of light per square meter (j/hr-light-m^2)
Energy switch *The energy switch could potentially be used for extreme condition testing, hence evaluation if the system responds to a power outage in the way expected.*	1	Unitless
Energy use RAS per m3 *The energy needed to move one cubic meter of water using the circulation pumps in the system.*	0.31	Kilowatt hours per cubic meter (kWh/m^3)
Hr per day	24	Hours per day (hr/day)
Light	1	Light
Optimal temperature	15	Degrees Celsius (degC)
Temperature of inflowing water	6	Degrees Celsius (degC)

Per month	1	Per month (1/mo)
Scenario 2 *This is a switch to simulate Scenario 2*	1	Unitless
Specific heat capacity *The specific heat capacity of water*	4 186	Joules per kilogram per Degree Celsius (j/kg-degC)
Unit converter: Days per month	365/12	Days per month (day/mo)
Unit converter: J to kWh	2.77777778*10^(-7)	kWh/j

Table 18. *Model Formulations in Sector 6: Carbon Dioxide.*

Formulations and comments	**Units**
CO2(t) = CO2(t - dt) + (CO2 accumulation rate - CO2 removal rate - Effect of water exchange on CO2) * dt *This stock contains the accumulated CO_2 in the fish rearing tank.*	Milligrams (mg)
CO2 accumulation rate = CO2 production per mg O2 consumed*DO consumption *The CO_2 accumulation rate is estimated based on the oxygen consumption of the fish.*	Milligram per month (mg/mo)
CO2 removal rate = if Gap between actual and safe CO2 level>=0 THEN (Gap between actual and safe CO2 level*Recirculation rate 1b*1000)+CO2 accumulation rate else CO2 accumulation rate *CO_2 is actively removed from the fish rearing tank, a process represented by the outflow "CO2 removal rate".*	Milligram per month (mg/mo)
Effect of water exchange on CO2 = if Counter for water exchange>=13 AND Counter for water exchange<14 THEN CO2/DT else 0 When the water in the fish rearing tank is exchanged the stock of CO_2 will be fully emptied.	Milligram per month (mg/mo)
Concentration CO2 = if CO2<=0 OR Water volume fish tanks in liters<=0 then 0 else CO2/Water volume fish tanks in liters *The concentration of CO_2 depends on the accumulated CO_2 and the total water volume in the tank.*	Milligrams per liter (mg/l)
Gap between actual and safe CO2 level = Concentration CO2-Maximum safe CO2 concentration *The difference between the safe concentration of CO_2 and*	Milligrams per liter (mg/l)

the actual concentration is represented by this variable.	
Oxygen consumption fish = if Counter for water exchange>=13 AND Counter for water exchange<14 THEN 0 ELSE (Oxygen demand per kg feed: Fish*Feeding rate) *The carbon dioxide released into the system is estimated based on the respiration of the fish.*	Milligram per month (mg/mo)
Effect of CO2 concentration on biomass = GRAPH(Concentration CO2) (0.00, 1.00), (11.1, 1.00), (22.2, 1.00), (33.3, 0.944), (44.4, 0.818), (55.6, 0.607), (66.7, 0.382), (77.8, 0.218), (88.9, 0.0947), (100, 0.00) *The effect of CO$_2$-concentrations is modeled as a graphical function, feeding back to sector 2 where it affects biomass growth and mortality.*	Unitless

Table 19. *Parameter Settings in Sector 6: Carbon Dioxide.*

Parameter value	**Initial**	**Units**
CO2 production per mg O2 consumed	0.96	Unitless
Maximum safe CO2 concentration	20	Milligram per liter (mg/l)

Table 20. *Model Formulations in Sector 7: Biofilter and Nitrification*.

Formulations and comments	**Units**
Capacity of Nitrobacter(t) = Capacity of Nitrobacter(t - dt) + (Growth rate of biofilter Nitrobacter - Mortality rate of biofilter Nitrobacter) * dt *The capacity of nitrobacter, one of the types of nitrifying bacteria making up the biofilter, is here measured in milligrams.*	Milligrams (mg)
Growth rate of biofilter Nitrobacter = (Desired capacity Nitrobacter-Capacity of Nitrobacter)/Time to activate biofilter *The growth rate of the nitrobacter is determined by the desired capacity of the biofilter and the time it takes to activate the biofilter.*	Milligrams per month (mg/mo)
Mortality rate of biofilter Nitrobacter = Fractional mortality rate Nitrobacter*Capacity of Nitrobacter *The mortality rate of the nitrobacter is determined by the mortality fraction.*	Milligrams per month (mg/mo)
Capacity of Nitrosomonas(t) = Capacity of Nitrosomonas(t - dt) + (Growth rate of biofilter Nitrosomonas - Mortality rate	Milligrams

Nitrosomonas) * dt *The capacity of nitrosomonas, one of the types of nitrifying bacteria making up the biofilter, is here measured in milligrams.*	
Growth rate of biofilter Nitrosomonas = (Desired capacity of Nitrosomonas-Capacity of Nitrosomonas)/Time to activate biofilter *The growth rate of the nitrosomonas is determined by the desired capacity of the biofilter and the time it takes to activate the biofilter.*	Milligram per month (mg/mo)
Mortality rate Nitrosomonas = Fractional mortality rate Nitrosomonas*Capacity of Nitrosomonas *The mortality rate of the nitrosomonas is determined by the mortality fraction.*	Milligram per month (mg/mo)
Nitrite(t) = Nitrite(t - dt) + (Ammonia to nitrite rate - Nitrite to nitrate rate - Effect of water exchange on nitrite) * dt *This stock contains the accumulated nitrite in the system.*	Milligrams (mg)
Ammonia to nitrite rate = Ammonia conversion rate *Nitrite will accumulate as the biofilter converts ammonia to nitrite.*	Milligrams per month (mg/mo)
Nitrite to nitrate rate = Nitrite Conversion rate *Nitrite will be converted to nitrate by the biofilter.*	Milligrams per month (mg/mo)
Effect of water exchange on nitrite = if Counter for water exchange>=13 AND Counter for water exchange<14 THEN Nitrite/DT else 0 *With a water exchange the stock of nitrite is completely emptied.*	Milligrams per month (mg/mo)
Unionized ammonia(t) = Unionized ammonia(t - dt) + (Addition of unionized ammonia - Ammonia to nitrite rate - Effect of water exchange on ammonia) * dt *This stock represents the accumulated unionized ammonia in the system.*	Milligrams (mg)
Addition of unionized ammonia = Fraction unionized*Feeding rate*Addition of ammonia per kg feed *The accumulation rate of unionized ammonia in the system is estimated based on the feeding rate.*	Milligrams per month (mg/mo)
Ammonia to nitrite rate =	Milligrams per month (mg/mo)

Ammonia conversion rate *The nitrifying bacteria in the biofilter convert ammonia into nitrite.*	
Effect of water exchange on ammonia = if Counter for water exchange>=13 AND Counter for water exchange<14 THEN Unionized ammonia/DT else 0 *With a water exchange the stock of unionized ammonia is completely emptied.*	Milligrams per month (mg/mo)
Ammonia conversion rate = (Capacity of Nitrosomonas/Biofilter months)*Effect of pH in treatment tanks on biofilter functioning *The ammonia conversion ratio the amount of unionized ammonia the biofilter is capable of converting per month. In case of a change in pH, the functioning of the biofilter might be inhibited, hence affecting the ammonia conversion ratio.*	Milligrams per month (mg/mg)
Biofilter capacity gap: ammonia = if (Concentration of Unionized ammonia module 1-Maximum unionized ammonia concentration)>0 then (Concentration of Unionized ammonia module 1-Maximum unionized ammonia concentration) else 0 *In case the concentration of unionized ammonia is above the maximum "safe level", then the biofilter capacity is insufficient.*	Milligrams per liter (mg/l)
Biofilter capacity gap: nitrite = if (Concentration of Nitrite-Maximum nitrite concentration)> 0 then (Concentration of Nitrite-Maximum nitrite concentration) else 0 *In case the concentration of nitrite is above the maximum "safe level", then the biofilter capacity is insufficient.*	Milligrams per liter (mg/l)
Concentration of Nitrite = if Nitrite<=0 OR Water volume fish tanks in liters<=0 THEN 0 else (Nitrite/Water volume fish tanks in liters) *The concentration of nitrite in the system depends on the accumulated nitrite and on the total water volume in the fish rearing tanks.*	Milligrams per liter (mg/l)
Concentration of Unionized ammonia module 1 = if Unionized ammonia<=0 OR Water volume fish tanks in liters<=0 then 0 else (Unionized ammonia/Water volume fish tanks in liters) *The concentration of unionized ammonia in the system depends on the accumulated unionized ammonia and on the total water volume in the fish rearing tanks.*	Milligrams per liter (mg/l)

Desired capacity Nitrobacter = Excess nitrite+Ammonia to nitrite rate *The desired capacity of the nitrobacter is the sum of the excess nitrite in the system and the monthly ammonia to nitrate conversion rate.*	Milligram (mg)
Desired capacity of Nitrosomonas = Excess ammonia+Addition of unionized ammonia *The desired capacity of the nitrosomonas is the sum of the accumulated unionized ammonia above “safe levels” and the accumulation rate of unionized ammonia.*	Milligram (mg)
Excess ammonia = Biofilter capacity gap: ammonia*Water volume fish tanks in liters *The excess ammonia in the system is the total amount of ammonia above the recommended level.*	Milligram (mg)
Excess nitrite = Biofilter capacity gap: nitrite*Water volume fish tanks in liters *The excess nitrite in the system is the total amount of nitrite above the recommended level.*	Milligrams (mg)
Initital capacity nitrosomas = Av feed demand per cohort per month*Fraction unionized*Addition of ammonia per kg feed *The biofilter is assumed to be activated before the first cohort is introduced in the system. The biofilter capacity is based on feeding rate.*	Milligrams (mg)
Nitrite Conversion rate = Capacity of Nitrobacter/Biofilter months*Effect of pH in treatment tanks on biofilter functioning *The amount of nitrite converted to nitrate per month is determined by the capacity of the nitrobacter. These nitrifying bacteria are not functional over a wide range of pH-values, therefore there is an effect of pH included in the equation - capturing the effect of a change in pH on biofilter functioning.*	Milligram per month (mg/mo)
Effect of nitrite on biomass = GRAPH(Concentration of Nitrite) (0.00, 1.00), (0.1, 1.00), (0.2, 0.979), (0.3, 0.495), (0.4, 0.333), (0.5, 0.147), (0.6, 0.00), (0.7, 0.00), (0.8, 0.00), (0.9, 0.00), (1.00, 0.00) *The effect of nitrite on biomass is modeled as a graphical function, feeding back into sector 2 where it affects the biomass growth and mortality.*	Unitless
Effect of pH in treatment tanks on biofilter functioning = GRAPH(pH in treatment tanks) (0.00, 0.00), (0.483, 0.00), (0.966, 0.00), (1.45,	Unitless

0.00), (1.93, 0.00), (2.41, 0.00), (2.90, 0.00), (3.38, 0.00), (3.86, 0.00), (4.34, 0.00), (4.83, 0.00), (5.31, 0.00), (5.79, 0.00), (6.28, 0.00), (6.76, 1.00), (7.24, 1.00), (7.72, 1.00), (8.21, 1.00), (8.69, 1.00), (9.17, 1.00), (9.66, 0.5), (10.1, 0.5), (10.6, 0.5), (11.1, 0.5), (11.6, 0.5), (12.1, 0.5), (12.6, 0.5), (13.0, 0.5), (13.5, 0.5), (14.0, 0.5) *The effect of pH on the biofilter functioning is modeled as a graphical function.*	
Effect of unionized ammonia on biomass = GRAPH(Concentration of Unionized ammonia module 1) (0.00, 1.00), (0.0267, 1.00), (0.0533, 0.919), (0.08, 0.73), (0.107, 0.358), (0.133, 0.189), (0.16, 0.109), (0.187, 0.0702), (0.213, 0.0456), (0.24, 0.0246), (0.267, 0.00), (0.293, 0.00), (0.32, 0.00), (0.347, 0.00), (0.373, 0.00), (0.4, 0.00) *The effect of unionized ammonia on biomass is modeled as a graphical function, feeding back into sector 2 where it affects the biomass growth and mortality.*	Unitless
Fraction unionized = GRAPH(pH in fish rearing tanks) (7.00, 0.003), (7.20, 0.0047), (7.40, 0.0074), (7.60, 0.0117), (7.80, 0.0184), (8.00, 0.0288), (8.20, 0.0449), (8.40, 0.0693), (8.60, 0.106), (8.80, 0.158), (9.00, 0.229), (9.20, 0.32), (9.40, 0.427), (9.60, 0.541), (9.80, 0.652), (10.0, 0.748), (10.2, 0.825) *The fraction unionized ammonia depends on the pH-level in the water.*	Unitless

Table 21. *Parameter Settings in Sector 7: Biofilter and Nitrification.*

Parameter value	**Initial**	**Units**
Addition of ammonia per kg feed	22 000	Milligrams (mg)
Biofilter months *This parameter is used to calculate the biofilter conversion capacity, specifying the time period of analysis.*	1	Months (mo)
Fractional mortality rate Nitrosomonas	0.01	Per month (1/mo)
Fractional mortality rate Nitrobacter	0.01	Per month (1/mo)
Maximum nitrite concentration	0.1	Milligrams per liter (mg/l)
Maximum unionized ammonia concentration	0.0125	Milligrams per liter (mg/l)
pH in treatment tanks	7	Unitless
Time to activate biofilter	0.4	Months (mo)

Table 22. *Model Formulations in Sector 8: The Financial Sector*

Formulations and comments	**Units**
Accumulated expenses per cohort(t) = Accumulated expenses per cohort(t - dt) + (Total expenses per month - Expenses reset) * dt *This stock accumulates the monthly expenses in the system, and resets to zero after one production cycle.*	Norwegian kronor (NOK)
Total expenses per month = if Counter for water exchange>=13 AND Counter for water exchange<14 THEN 0 else Fixed costs+Direct costs *The total expenses per month includes both fixed and direct costs.*	Norwegian kronor per month (NOK/mo)
Expenses reset = if Counter for water exchange=13.00 THEN Accumulated expenses per cohort/DT else 0 *This outflow fully empties the stock accumulated expenses per cohort after each production cycle.*	Norwegian kronor per month (NOK/mo)
Direct costs = (Feeding rate*Feed price per kg)+Total cost oxygen *Direct costs are made up by the total cost for feed per month and the total cost for producing oxygen (in-house production is assumed).*	Norwegian kronor per month (NOK/mo)
Fixed costs = Total Energy use per month : kWh*Electricity price per kWh+(Cost salt solution*Water outtake from source)+Labor cost per production unit inc taxes *Fixed costs include the cost of energy, salt solution and labor.*	Norwegian kronor per month (NOK/mo)
EBIT = PULSE((Revenue per cohort-Total expenses per cohort),13,13)*DT *EBIT is one of the central economic performance indicators included in the model.*	Norwegian kronor (NOK)
Labor cost per production unit inc taxes = Total employees per production unit*Monthly salary per employee *The labor cost depends on the number of employees per production unit and their monthly salary.*	Norwegian kronor per month (NOK/mo)
One time costs per cohort = One time fixed costs+One time direct costs *One-time costs include both fixed and direct costs.*	Norwegian kronor (NOK)

One time direct costs = Number of fish per cohort*Cost per smolt *The one time direct cost included in this model is the cost for smolts.*	Norwegian kronor (NOK)
One time fixed costs = Cost insurance*Desired production capacity per unit *The one time fixed cost included in this model is the cost for insurance.*	Norwegian kronor (NOK)
Production cost per kg = if Biomass<=0 or (Accumulated expenses per cohort+ One-time costs per cohort) <=0 then 0 ELSE PULSE((Accumulated expenses per cohort+ One-time costs per cohort)/Biomass*0.25,13,13) *The production cost per kilogram is the total accumulated expenses per cohort, divided by the total amount of biomass produced during that production cycle.*	Norwegian kronor per kilogram (NOK/kg)
Revenue per cohort = PULSE((Live weight to HOG conversion*Market price salmon*Biomass)*DT,13,13) *The revenue per cohort is based on the total amount of biomass sent to the market (converted to HOG) and the market price of salmon.*	Norwegian kronor (NOK)
Total cost oxygen = ((DO addition trough aeration+Initialization of DO)/Unit converter: Mg per kg)*Cost oxygen *The monthly cost of oxygen depends on the amount of oxygen added through aeration and initialization of oxygen before a new cohort enters the system.*	Norwegian kronor per month (NOK/mo)
Total EBIT = EBIT*Cohorts per year*Mortgage time *The total EBIT is based on the yearly production over an extended period (determined by the mortgage time).*	Norwegian kronor (NOK)
Total employees per production unit = (Minimum employees/Nr of production units)+(Desired production capacity per unit/Additional employees based on production) *The minimum number of employees (regardless of the size of the facility) is divided with the number of production units. Then the additional employees required for the production in one unit is added, in order to get the total number of employees per production unit.*	Employees (employee)
Total expenses per cohort = PULSE((Accumulated expenses per cohort+ One-time costs per cohort),13,13)*DT	Norwegian kronor (NOK)

The total expenses per cohort are the accumulated expenses plus the one-time costs per cohort.	
Total loan coverage = PULSE((Total EBIT/(Interest rate^ Mortgage time))*DT,13,13) *The total loan coverage is calculated based on the total EBIT, the mortgage time and the interest rate. It is assumed that the whole loan is paid back the last year of the mortgage time.*	Norwegian kronor (NOK)

Table 23. *Parameter Settings in Sector 8: The Financial Sector.*

Parameter value	**Initial**	**Units**
Additional employees based on production *When production increases, extra employees are needed. It is estimated that one extra employee is hired per additional 200 000 kilograms biomass produced.*	200 000	Unitless
Cohorts per year *A continuous flow of revenue requires biomass to be sent to the market several times per year. In this model it is assumed that one cohort is sent to market every month, giving a total of 12 cohorts per year reaching harvestable size.*	12	Per year (1/year)
Cost insurance	0.2	Norwegian kronor per kilogram (NOK/kg)
Cost oxygen	1	Norwegian kronor per kilogram (NOK/kg)
Cost per smolt	8	Norwegian kronor per kilogram (NOK/kg)
Cost salt solution	0.2	Norwegian kronor per Cubic meter (NOK/m^3)
Electricity price per kWh	0.8	Norwegian kronor per kilowatt hour (NOK/kWh)
Feed price per kg	11	Norwegian kronor per kilogram (NOK/kg)
Interest rate	1.04	Unitless
Live weight to HOG conversion	0.84	Unitless
Market price salmon	30	Norwegian kronor per kilogram (NOK/kg)
Minimum employees	5	Employees

		(employee)
Monthly salary per employee	600000/12	Norwegian kronor per month per employee (NOK/mo-employee)
Mortgage time	5	Years (yr)
Nr of production units	12	Unitless
Policy: Reduce costs	1	Unitless

Table 24. *Model Formulations in Sector 9: Resource Use for Production.*

Formulations and comments	**Units**
Accumulated energy use per cohort(t) = Accumulated energy use per cohort(t - dt) + (Energy use - Energy reset) * dt *This stock is accumulating the monthly energy use for every production cycle. When a cohort leaves the system the stock is fully emptied, before the next cohort is introduced.*	Kilowatt hours (kWh)
Energy use = Total Energy use per month : kWh *The total energy use per cohort is depending on the monthly energy use for production.*	Kilowatt hours per month (kWh/mo)
Energy reset = if Counter for water exchange>=13 AND Counter for water exchange<14 THEN Accumulated energy use per cohort/DT else 0 *This flow fully empties the stock "accumulated energy use per cohort" after each production cycle.*	Kilowatt hours per month (kWh/mo)
Accumulated water use per cohort(t) = Accumulated water use per cohort(t - dt) + (Water use - Water reset) * dt *This stock accumulates the monthly water use for production.*	Cubic meters (m^3)
Water use = Water outtake from source *The water use for production is made up by the new water introduced into the system each month.*	Cubic meters per month (m^3/mo)
Water reset = if Counter for water exchange>=13 AND Counter for water exchange<14 THEN (Accumulated water use per cohort)/DT else 0 *After each production cycle the stock containing the accumulated water use is fully emptied, before the next cohort is introduced in the system.*	Cubic meters per month (m^3/mo)
Energy use per kg biomass =	Kilowatt hour per kilogram (kWh/kg)

if Accumulated energy use per cohort<=0 OR Biomass<=0 then 0 ELSE PULSE((Accumulated energy use per cohort)/(Biomass)*dt,13,13) *The energy use per kilogram biomass produced serves as an environmental impact indicator.*	
Energy use per kg edible = if Accumulated energy use per cohort = 0 or Biomass =0 then 0 else PULSE((Accumulated energy use per cohort)/(Biomass*0.68)*dt,13,13) *Another way of looking at the resource use for production is to estimate the energy need per kilogram edible biomass. It is estimated that 0.68 kilogram meat is edible per kilogram biomass produced.*	Kilowatt hour per kilogram (kWh/kg)
Water use per kg biomass = if Biomass <=0 or Accumulated water use per cohort<=0 then 0 else PULSE((Accumulated water use per cohort*Unit converter: Liters per m3)/(Biomass)*dt,13,13) *The water use per kilogram biomass produced can be used as an environmental impact indicator.*	Liters per kilogram (l/kg)
Water use per kg edible = if Biomass<=0 or Accumulated water use per cohort<=0 then 0 ELSE PULSE((Accumulated water use per cohort*Unit converter: Liters per m3)/(Biomass*0.68)*dt,13,13) *Another way of looking at the resource use for production is to estimate the water need per kilogram edible biomass. It is estimated that 0.68 kilogram meat is edible per kilogram biomass produced.*	Liters per kilogram (l/kg)