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A Comparison between Surface and Underwater Feeding Technology with Respect to Feed Waste

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Comfort is the enemy of progress
- P.T. Barnum

Abstract

Due to the technological development within the fish farming industry, new feeding technologies are being developed — however, little documentation concerning the sustainability of different innovations exist. This thesis explores different feeding technologies in aquaculture to compare their feed waste production with the use of a mathematical model of the feeding process.

Factors that are considered relevant during a feeding process are discussed together with challenges of feeding farmed fish. Two feeding technologies that currently are attempting to address these challenges are presented. First, the conventional surface rotor spreader is introduced, followed by a subsea feeder. The comparison is made possible by using an already existing mathematical pellet distribution model made by SINTEF Ocean for the surface rotor spreader. The model is altered to include the feed distribution pattern of a subsea feeder. It is of interest to see how the subsea feeder measures up to the surface rotor spreader. That is why two of the subsea design parameters, the feeding depth, and the bottom ring radius, are investigated. Both parameters are simulated three times with different values for three different water current profiles: uniform current, linear decreasing moderate current, and linear decreasing strong current. A behaviour related parameter, the local fish density threshold, FD_{thresh}, is also simulated with two arbitrarily chosen values to show how important this parameter is to the overall model. To have a starting point for the simulation, a realistic feeding regime is developed and simulated in conjunction with operators at a fish farm.

The parameter study in this thesis reveals that the surface rotor spreader is the more sustainable option regarding feed waste, but it is uncertain if this is actually true in reality. For this model to produce more realistic results, it will be necessary for each fish farmer to implement local data from their fish farms. Further work must also be done to improve the model accuracy. The outcome of the comparison might change when the above is reviewed.

Sammendrag

Den teknologiske utviklingen innen akvakultur har en eksponentiell vekst og det utvikles stadig nye løsninger. Blant dem finner man nye fôringsteknologier som skal bidra til å løse utfordringer industrien står ovenfor. Undersøkelser viser at der er lite informasjon å hente når det kommer til hvor bærekraftige disse innovasjonene er. Denne masteroppgaven tar for seg hvilken fôringsteknologi i fiskeoppdrett som er mest miljøvennlig med tanke på fôrspill ved hjelp av en pelletdistribusjonsmodell.

I begynnelsen av avhandlingen vil faktorer som anses som relevante under en fôringsprosess diskuteres, etterfulgt av utfordringene som følger med det å mate oppdrettsfisk. Deretter introduseres den konvensjonelle overflaterotorsprederen og en undervannsfôrer. Sammenligningen av disse fôringsteknologiene er muliggjort ved å bruke en allerede eksisterende matematisk pelletdistribusjonsmodell laget av SINTEF Ocean. Denne ble i utgangspunktet laget for å måle fôrspill fra den konvensjonelle overflaterotorsprederen, men modellen har blitt endret slik at fôrfordelingsmønsteret fra en undervannsfôrer er inkludert. For å sammenligne mengden fôrspill fra de to fôringsteknologiene blir to av designparametrene til undervannsfôreren, fôringsdybden og bunnringradiusen, undersøkt. Begge parametrene simuleres tre ganger med forskjellige verdier for tre forskjellige vannstrømsprofiler: jevn strøm, lineær avtagende moderat strøm og lineær avtagende sterk strøm. En adferdsrelatert parameter, den lokale fisketetthetgrensen, FD_{thresh}, simuleres også med to vilkårlige verdier for tilfellet med uniform støm for å vise hvor viktig denne parameteren er for den overordnede modellen. For å ha et utgangspunkt for simuleringene har det blitt utviklet et realistisk fôringsregime i samarbeid med fôroperatører fra et oppdrettsfirma.

Parameterstudiet i denne avhandlingen viser at overflatesprederen er det mer bærekraftige alternativet med tanke på fôrspill, men det er ikke gitt at dette er sant i virkeligheten. For at denne modellen skal gi mer realistiske resultater, vil det være nødvendig for hver oppdretter å implementere lokale data fra sine oppdrettsanlegg. Modellen må også forbedres slik at den når et akseptabelt detaljnivå. Resultatet av sammenligningen kan dermed få et annet utfall hvis overnevnte gjennomføres.

Preface

This master thesis is the final project in the five-year Master's program in Marine Technology and is the course *TMR4930 - Marine Technology, master thesis* at the Department of Marine Technology at the Norwegian University of Science and Technology, NTNU. The master thesis is written by me, Vår Emilie Kjærnes, with the help and input from Martin Føre and Morten Omholt Alver at NTNU. Supervisor for this thesis is Pål Lader and weighting is 30 ECTS. The work done in this thesis is to be seen as a continuance of the project thesis that was written during spring 2018. Chapters 1 and 2 are partly taken from the project thesis. The duration of the master thesis was 20 weeks.

The work was carried out during the autumn semester of 2018 and the topic was chosen out of personal interest. There is currently no documentation as to whether the comparison performed here exists elsewhere. The motivation for writing about the sustainability of feeding technologies comes from my previous work experience where I worked as a feed operator. I see a great need for better monitoring equipment for those who feed fish remotely and more sustainable operations regarding feed waste in aquaculture.

Vår E. Kj

Vår Emilie Kjærnes

30.01.2019, Trondheim

Date

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Contents

List of Tables

List of Figures

Chapter 1

Introduction

The world is in need of fast-growing food production to feed the increasing population on earth, which is estimated to reach 9 billion people by 2050 [63]. Not only is the food production a rising concern, but climate change and environmental issues are as well. The question arises of how it is possible to produce more food and at the same time cutting environmental harm caused by food production. Due to the fact that the aquaculture industry has less need for land areas, the increase in fish production has been proposed as a possible solution for solving the food challenges in the world [28].

The Norwegian aquaculture industry is a fast-growing business, yet volatile and capital intensive. Today, most of the Norwegian coastline is inhabited by fish farming companies who produce about 1.3 million tonnes of fish every year, where about 95% of it is exported [78, 54]. It is estimated that the industry in Norway alone will grow by a factor of five within 2050 [65]. If the small nation of Norway is contributing to feeding the world population, it is crucial that it is done efficiently and sustainably.

Over the years, the focus has been and still is, on the production of top quality fish, but times are changing. Despite production efficiency improving with better techniques and technology, fish farmers are always looking for more sustainable options that can benefit their stock and the environment. Different solutions have been introduced that address various challenges in fish farming, and one that will be researched in this project is the subsea feeder regarding the feed waste contamination from Norwegian fish farms.

Providing food to farmed fish is known as the process of feeding, and the subsea feeder is one technology that serves this purpose. Invented to make the salmon swim deeper in the sea cage and thus reduce the number of sea lice. Diminishing sea lice infections can lower sea lice treatment costs and avoid problems with reduced growth, in addition to increased mortality [3, 8]. However, feeding fish deeper will influence the feed waste situation. No documentation currently exist on the effect the subsea feeder has on the environment compared to a conventional surface spreader. It is only a matter of time before stricter rules and regulations are introduced to safeguard the environment, which will give the industry incentives to develop new technology standards [53].

In Norway, it is not allowed to pollute according to the Pollution Control Act, unless one has received permission from the authorities. Pollution permits for aquaculture are regulated under the Aquaculture Act and Pollution Control Act. The permit contains specific requirements and limits on how much a fish farm can contaminate including requirements for the limitation of feed spills [66, 64]. Too much feed waste creates a negligent operation that is harmful to the environment. Open sea cages are not designed to collect discharge throughout a production cycle but are based on the fact that the emissions are diluted and converted in the recipient. Emissions should, therefore, not be larger than what nature manages to process over time.

Today, feed for farmed fish accounts for over 50% of production costs [11]. It is inevitable that a portion of the feed ends up on the seabed and pollutes the marine environment. Feeding more efficiently to reduce feed waste is a constant focus, but having complete control of the feeding process is an ongoing challenge. Feed contamination occurs due to the operator's lack of sufficient monitoring tools and data. Other limitations include current feeding technology, as well as environmental factors [53].

For a feeding process to be successful concerning feed waste, both the technology and environment must interact efficiently. Thus, this thesis discusses the necessary background information needed to feed farmed fish and analyses under what circumstances the different feeding technologies pollute the least.

1.1 Objective

The objective of this master thesis is to look into two different feeding technologies in sea-based farming covering a conventional rotor spreader and the newer invention called a subsea feeder. The focus is to understand the situation of feeding fish and the technologies concerning this topic. The goal is to compare the subsea feeder technology against the conventional surface spreader with regard to feed waste by conducting a parameter study. Gaining such knowledge is useful when the production of farmed fish is expected to grow, meaning the industry is dependent on feeding being done efficiently and sustainably. It is beneficial to know under what circumstances both technologies perform well. The main focus areas in this thesis are as follows:

- Provide a clear description of the factors influencing a feeding scenario in aquaculture
- Explain the main challenges with feeding
- Give a detailed description of the working mechanisms of the feeding technologies
- Use an existing feed distribution model and extend it to comprise both feeding technologies
- Conclude under what circumstances which technology is more sustainable regarding feed waste

1.2 Limitations

Due to lack of data, the inputs for the parameter study are mainly based on expert opinions. Experiments and testing are still being done to the subsea feeder, and a more detailed analysis might be possible at a later stage.

1.3 Thesis Structure

The work presented in this thesis is a result of five main steps covering the literature review of feeding parameters and challenges, feeding technology descriptions, feed distribution model configuration and description, simulation setup, and analysis and evaluation of the simulation outcome.

The first chapter gives a short introduction to aquaculture and why this topic is of importance. The second chapter explains the different variables that play a role in the entire feeding scenario of farmed fish. The main challenges the aquaculture industry is faced with concerning feeding fish and why they need to be addressed is also included in this chapter. In the third chapter, the feed distribution model for both technologies are explained, followed by the individual model uncertainties. The fourth chapter comprise of the simulation setup and results. Chapter five covers the discussion, and lastly, a conclusion is presented followed by propositions for further work.

1.4 Background

The following sections in this chapter explain the importance of aquaculture and why this thesis focuses on feeding technologies and feed waste within the fish farming industry.

1.4.1 The Need for Aquaculture

Aquaculture is defined as "the cultivation of aquatic organisms in controlled aquatic environments for any commercial, recreational or public purpose" [58]. It broadly encompasses all forms of cultural production of fish and other aquatic organisms for food and other purposes [33].

Aquaculture is an important source of income, nutrition, food and livelihoods for people around the world [18]. The awareness around healthy food, in addition to rising incomes makes the production of fish more and more attractive [16]. The Food and Agriculture Organization (FAO) states that the yield from the wild catch is not to be increased further for it to be sustainable. Management of the wild stocks is, therefore, necessary to maintain their viability. Thus, Aquaculture should fill the the gap between sustainable harvest of wild stocks and the demand for fish. In 2014 the world per capita fish supply reached new heights. It hit a new record of 20 kg due to the exponential growth in Aquaculture, which is now providing half of the human consumption of fish worldwide. Aquaculture management is constantly improving together with the technology that targets the industry, making the production more cost-efficient and sustainable [27].

Even though challenges still exist, fish continues to be one of the most traded goods worldwide [14]. More than half of the fish exports originate in developing countries, meaning value is created where it is most needed. Newer research created in cooperation with civil society representatives, industry, international organizations, and high-level experts worldwide all underline the tremendous potential of inland waters and oceans [27].

1.4.2 Feeding Fish Correctly

Preventing lice infestations and feeding fish are both main priorities in open sea fish production. It is a constant focus to feed fish efficiently to boost growth, and at the same time shortening the production cycle. In other words, efficient feeding leads to a shorter sea-phase and high-quality products [53].

Fish farmers feed their stock in the best way possible to prevent the scenarios of either providing too little feed or too much feed. Although operators actively try to avoid overfeeding or underfeeding, both situations still happen. Reduced fish welfare or polluted surroundings are some of the outcomes of unsustainable feeding [53].

Chapter 2

Literature Review

The following chapter will mainly consist of findings made in the project thesis conducted prior to this master thesis. It involves the parameters which can influence the feeding scenario and the behaviour of fish. Additionally, it includes what feeding challenges fish farmers are faced with. The last part covers a short description of a typical fish farm layout, followed by the feeding technologies.

2.1 The Complexity of Feeding Fish

Feeding farmed fish is not as straight forward as one might think. There are multiple factors which need to be considered before the feed operator can turn on the switch that initiates the meal. Salmon, which is the dominating farmed species in Norway and the featured species in this literature study, responds to a large scope of different environmental variables within the sea cage environment [49]. This includes factors such as salinity, temperature, dissolved oxygen, chemical treatments used for production, artificial light and water currents. The majority of these factors are highly inconstant in both space and time. The greatest differences happen in the vertical direction along the water column. The composition of the above mentioned factors can decide what the preferred swimming depths and densities are, along with the species internal motivational factors such as perceived threats and hunger. They can even override the other environmental and internal drivers affecting their behavioural response that determine the swimming depths. Trade-offs in behaviour due to environmental factors exist on all levels along the water column, which result in different stocking densities. Statistics show that densities in sea cages can vary from 1.5 to 5 times, and in extreme cases even up to 20 times their stocked density [69].

In order to ensure better prediction of behaviour, overall understanding of the interaction between the key environmental variables affecting the fish is needed. With this information, modifications can be done to enhance welfare and feeding regimes [53].

Farmed salmon have limited living space, and it is desirable to control the environmental factors that affect this space. Their artificial environment is aimed at appealing to the species preferences to optimize their position in the sea cage [69]. When designing equipment and deciding upon management practices for the industry, biology has to be the core focus for it to be successful. The goal is to utilize the species adaptive capabilities and avoid triggering unwanted behaviour in order to improve the production efficiency and fish welfare [51].

2.2 Feeding Motivation and Response

Most of the fish farms in Norway feed their salmonoids by distributing feed pellets on the water surface [41]. This is done with the use of conventional rotor feed spreaders, which is also referred to as the pneumatic rotor spreader, or other variations with similar technology [53, 51]. When feed is rationed at the surface layers, salmon tend to react by displaying various combinations of vertical and horizontal movements, changing their swimming velocity and depth [69]. Their reaction rate to food is naturally determined by their hunger level and this level can be predicted when looking at the salmonoid's vertical position in the sea cage prior to a meal [41]. It has been documented that when their hunger level rise, they ascend to the surface towards the feeding area. When satiated, salmon gradually descend due to the decline in feeding motivation [21, 41, 29, 39]. If the meal ends before all of the salmonoids are satiated, the remaining hungry fish stay at the surface. A study published by Fernö et al. in 1995 came to the conclusion that fish that is fed small batches throughout a day generally had a higher probability to remain at the surface, than fish fed more intensively, which returned to deeper depths after a meal [29]. The study also observed that fish behaved as they were anticipating food prior to a meal. One hour before the meal was about to start, fish started to ascend to the surface. Multiple farmers have confirmed this behavioural pattern [69, 53]. This is however not the only observed trigger to increased activity levels prior to feeding. It has been reported that the arrival of the feed boat, footsteps of the farm operators and the start of the feeding systems, such as the rattling of pellets in the feed pipes, have caused anticipatory behaviour [69]. Research done by Lamb, C.F. (2001) and Spruijt et al. (2001) indicate that fish can be taught to have this anticipatory behaviour, which is said to arouse appetite responses. The reason being that it leads to positive emotional enhancement of the meal and thereby increases welfare and feeding motivation. [50, 86].

Several studies have hypotheses that disclose the movement of salmon in correlation with seasons. From winter to summer, salmon is seen ascending more often to the surface in sea cages [71, 43, 42]. It is said this behaviour is due to the increase in hunger levels as the season changes. A study of Smith et al. (1993) recorded a rise in appetite during spring, that was not dependent on temperature, indicating that seasonal movements to shallower waters could be a sign of increased appetite [84]. However, if this is the case, these findings prove that it is not enough to base the feed-ration calculations solely on one environmental factor - temperature, because the fish is then easily underfed [53].

2.3 Feeding Parameters

2.3.1 Temperature

Salmon as a species have an alternating temperature, which means it adapts to its environment [22]. When high water temperatures occur, the internal processes in the fish will go faster, increasing metabolic processes such as food intake, growth, digestion, circulation, bioenergetical re-acclimation processes and the range for activity. The opposite happens when it gets colder in the sea [69]. It is especially during the late summer months most of the growth happens because the ocean is at its warmest. Proper utilization of the rise in temperature is essential for farms with poikilotherm fish [53]. The figure below indicates the temperature differences that occurred at a Norwegian fish farm location during the year 2007. July was excluded form the data for an unkown reason [69].

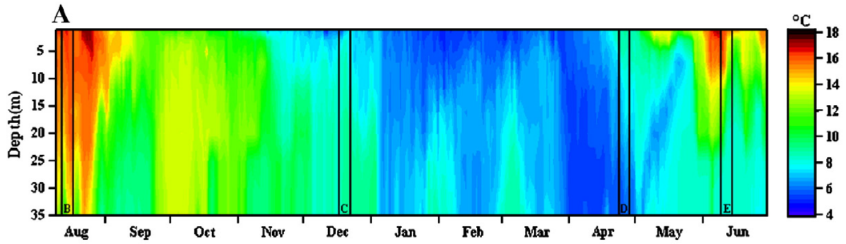


Figure 2.1: Temperature variation throughout a year [87]

In sea cages, temperatures vary from the surface to the bottom of the net, as indicated in Figure 2.1. The net can be as deep as 50 m depending on the cage dimensions and location. The temperatures that are season dependent show that during winter, the temperature profiles correlate positively with depth, but in summer they are inconsistent. The highest temperatures occur most frequently at mid-cage [39]. This can be seen in Figure 2.2, which displays the temperature-depth relation for some dates in June in the first image, where the warmest temperatures seem to lie around 7 m [69].

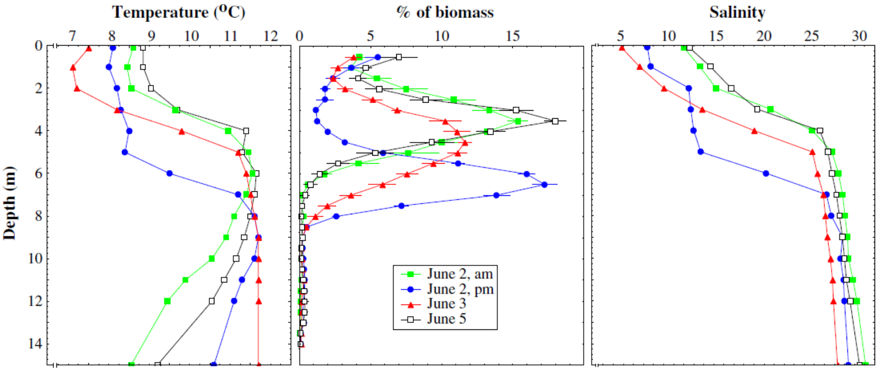


Figure 2.2: Temperature, biomass and salinity in relation to depth [68]

Measurements of different environmental values show that salmon is clearly governed by the temperature of its surroundings [51]. The overall term for its way of interacting with their environments is called behavioural thermoregulation, which means it prefers the highest accessible temperature and avert colder temperatures [38]. The vertical position of the fish in the sea cage is thereby decided in relation to temperature, meaning they will be where the highest temperatures can be found [46]. A study published by Johansson et al. in 2006 proves that temperature influence the preferred swimming depth and the density of salmon. Salmon avoids water warmer than 17°C [40].

As one can understand from the information given above, the temperature is critical to fish farming since it affects fish welfare and growth. When feeding fish, information about the current temperature level is needed to form a picture of the biological state of salmon. When temperatures are high, one can expect an increase in appetite, and when it is cold, the opposite behaviour is more realistic. If the feed doses do not meet the hunger demands of the fish, it will have multiple consequences. The scenario of overfeeding can occur, meaning too much feed is distributed in the sea cage. Consequently, the feed will pass through the sea cage and pollute the surroundings. Cameras often detect this before too much feed leaves the cage, but the visibility is weather-dependent. Not understanding the situation also indicates substantial economic losses for the fish farming company. Operators handling the feeding process need to experience and gain knowledge about the behavioural pattern of the fish they are feeding. Another case is underfeeding, which means that deficient feed is available to the fish. The hunger is present and the fish is not saturated. Underfeeding can lead to a loss in growth, which again affects the production. Either of these two scenarios is unwanted by the company and weakens different sustainability goals. Even though there are more than just one variable needed to get the correct overview of the situation, the temperature is a natural place to start [53].

2.3.2 Salinity

Salinity is an important factor for fish welfare and also for their appetite [56]. The term is defined as the amount of dissolved salt ($Na^{+}Cl^{-}$) in grams per kilogram of water [88]. The ratios between the amounts of the main dissolved substances in seawater are almost constant. At greater depths, salinity is uniform across large areas, but at the surface, there are significant geographic differences; It depends on the relationship between evaporation and freshwater supply during precipitation as well as drainage and calving of ice from rural areas [69].

A large number of farming sites that are located in fjords and close to the shore near mouths of rivers can be exposed to freshwater runoff [74]. If this is the case, a brackish layer of variable salinity and thickness develops [69]. For illustrative purposes, data collected from the same farm as in section 2.3.1, also displays the difference in salinity with depth, see image to the right in Figure 2.2. Here, the salinity concentrations are higher further down the water column. It can indicate that brackish water is present closer to the surface. The salt level in brackish water is lower than in seawater, and if this happens close to or at a farm location, it affects the behaviour of salmon depending on the time of year [69]. Publications by Oppedal et al. from 2001 indicate that when spring arrives, salmon tend to rise to the surface because they get a lower salinity preference. It stays like this until early autumn due to their instinct to spawn [71, 68].

Salmon can adapt to the surrounding salinity level, meaning that in freshwater the amount of energy the fish needs for osmoregulation is reduced. However, this depends on ocean temperatures, where lower temperatures cause slower acclimation processes relative to higher temperatures [34]. The composition of salinity, temperature and social factors, determine the preferred sea cage position of salmon in stratified waters [69]. These variables directly affect feeding strategies because if the preferred position is known, one can make sure that the feed is deployed at the location most accessible to the fish [51].

2.3.3 Oxygen

Dissolved oxygen (DO) levels vary greatly within a sea cage environment [87]. It is important to keep track of this variable since it affects fish welfare and growth together with the factors mentioned above [89]. A study has shown that stocking densities of Atlantic salmon within a sea cage are dependent on the DO levels, which vary greatly both with space and time. Seasonal variations in DO levels are also known to farmers. It is important to take this into account when deciding upon a feeding regime. Figure 2.3 displays the seasonal variations in DO levels measured at a farm over a year. Some periods lack data and are therefore left blank [69]. When looking at the color bar, red defines the lowest DO level, and it occurs clearly in late September, but also somewhat in November. This data differs with each farming location, cage dimensions, and total biomass, but it is included as a representation of how oxygen saturation can vary in a sea cage.

Another interesting discovery is that the amount of consumed oxygen differs with depth, meaning that higher densities in certain areas can have lower DO levels [89]. Figure 2.4 compares a point outside the cage with a point in the center of a cage. As indicated, the DO levels are clearly different and much higher on the outside at the reference point. Hypoxic conditions as low as 30% saturation can be observed in the right image, and cases like this have even been recorded to last up to one hour. This case can correlate with the total water flow through the cage or high fish densities [69].

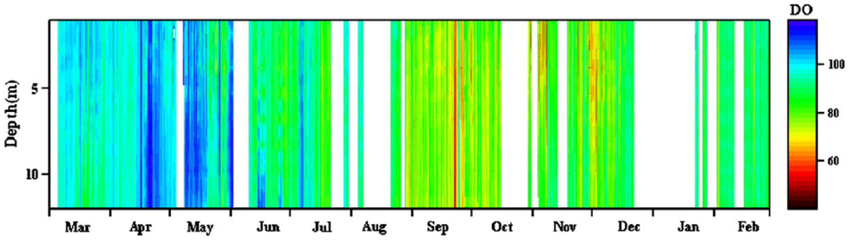


Figure 2.3: Oxygen variation data from a sea cage measured from March 2008 to March 2009 [47]

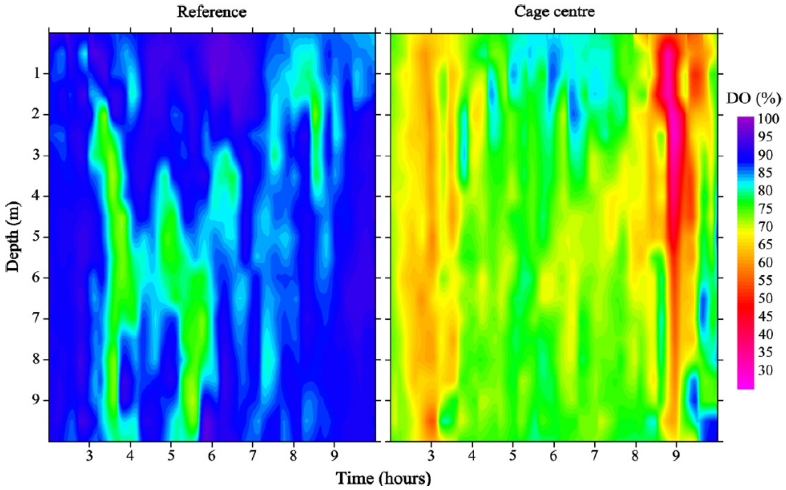


Figure 2.4: Oxygen variation from a farm in September in 2008 [89]

Multiple environmental factors influence the supplement of oxygen, such as wind, tidal currents, and light, which contribute to the mixing of oxygen [20, 19]. Primarily, oxygen in water stems from the mixing of atmospheric pressure and photosynthesis. The amount of dissolved oxygen is determined by the composition of salinity, temperature, and barometric pressure. An increase in one of the first two variables will decrease the amount of dissolved oxygen, whilst an increase in barometric pressure will increase the DO level [89].

High mixing happens in a sea cage when waves are present, but with small waves or no waves at all, mixing only appear in the surface layers. However, the key factor which is important for the transport of oxygen and the supply of it is the water current. When the flow rate is insufficient, oxygen levels tend to be low as well. With tidal currents, it is said that DO levels are at its highest right between low tide and high tide [53]. The situation inside the cage is also influenced by the respiration of salmon, which varies with activity and feed intake [40]. Salmon produce energy with the use of oxygen, and this energy is used for activity and food digestion. If salmon does not get sufficient oxygen supply a lot of problems can occur. This means that the situation of hypoxia is present, and the feeding should stop. The fish will not be able to eat when oxygen saturation levels are low. Nonetheless, the fish have various ways to compensate for low DO levels. Cases of increased stroke volume, heartbeat, ram ventilation, ventilation frequency, or by locating other water bodies that contain higher levels of DO can help in this situation. If their compensation methods have no effect, there will be a reduction in growth accordingly [89].

To present to what degree salmon is affected by the decrease in DO levels, a study on this topic is summarized in the following paragraph. The study was performed by SINTEF Fisheries and Aquaculture in 2008, where the case of full-feeding salmon in seawater with the temperature of 16°C was investigated [13]. The tests were executed with fluctuating hypoxic levels. The first test was performed with a DO level of 70%, which led to reduced appetite. With a level of 60% saturation increased skin lesions, and acute anaerobic metabolism was initiated. This stage is of great importance since anaerobic metabolism leads to lower energy production, which again affects growth, immune function, and feed-uptake [69]. 50% saturation led to increased stress levels, reduced growth and a decrease in feed conversion. The last test with 40% saturation led to mortality and poor osmoregulation [13]. The outcome of the study resulted in different threshold levels for Atlantic salmon to maintain oxygen uptake rates. The average size of the fish was 400g, and they were held in seawater of different temperatures; 18°C, 12°C and 6°C with DO levels of 60%, 40% and 30% respectively [69].

Results from another study done by Mette Remen in 2012 indicate that salmon growth is reduced if the oxygen level falls below 70% at 16 °C and that physiological stress occurs at a DO level $< 60\%$. The fish's ability to adapt to new DO levels does not change the limit values, but the negative effects decrease over time as a result of the stress response being down-regulated and that the salmon eats more in periods of good oxygen conditions. However, the temperature of the water is important for the limits: the critical oxygen saturation increased exponentially when the temperature increased from 6 to 18°C [75].

Even though DO levels are important for fish welfare and production parameters, scarce information exists on how salmon behaves with sub-optimal oxygen levels within sea cages. It has been documented that salmon tend to move vertically in the sea cage to stay out of hypoxic zones, but if this is an action deliberately done due to the DO levels remains unresolved [69].

2.3.4 Light

The swimming pattern of salmon is, next to other environmental parameters and the feeding method, controlled by the everyday light intensity [21, 29, 71, 39, 73]. Salmon are in the category of positively phototactic animals, meaning that they seek out sources with their preferred light intensity which display their favored swimming pattern [42, 43, 70]. Their observed behaviour indicates that salmon tend to swim deeper during the day, but ascend closer to the surface at night. Research also concludes that the fish utilizes the sea cage space to a more significant extent during night time, in addition to having slower swimming velocities, see Figure 2.5 [71, 25, 46]. Early research done on the preferred light intensities of salmon shows that they avoid high light intensities during the first half of the year and that some specific intensities are favored [71, 69, 39]. Later studies, however, have found clear indications that the vertical distribution of fish in the sea cage due to light intensities are overruled by temperature [51].

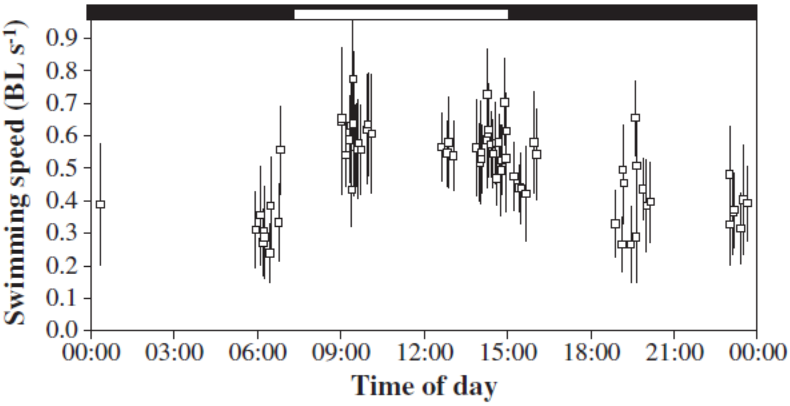


Figure 2.5: Variations in swimming velocities during a day [46]

Technology has made it possible to implement artificial lights in sea cages, altering the seasonal swimming pattern of salmon [71, 72]. The lights can be mounted on the surface, or further down the water column. They were invented with the purpose of minimizing boat traffic hazards, increasing the aesthetics of farms, prevent maturation and boost growth, while providing the fish with effective illumination at multiple depths [43, 42, 70, 30]. The study of Oppedal et al. (2010) includes tests that analyze salmon's attraction to submerged and surface light sources. The results from the different tests indicated that salmon are attracted to the sources. The stocking densities turned out to be lower around a submerged light source in comparison to the surface mounted lights. During the night, salmon densities tended to be at its highest at the depth level with the highest light intensity [69]. Consequently, stocking densities can, therefore, be lower above and below the depth with the highest level of light intensity, which again could theoretically make it possible to influence the swimming depth of salmon at night by deciding the position of the light deployment [43, 42]. When light sources are deployed at different depths, it widens the range of peak light intensity. Thus, the fish is spread throughout the sea cage volume. When lamps are located mid-cage they produce an even illumination that is normally distributed, making the fish position themselves on both sides of the lamps. Light sources close to the surface or the bottom produce a strong light gradient in the vertical direction which can lead to unwanted crowding [69].

As salmon are visual predators, light is important for them when they are being fed [30]. This is why typical feeding scenarios at commercial fish farms take place during the day [53]. When light levels fall, school structures break up, and fish ascend to the surface [69]. Multiple fish species have this behavioural pattern because during the day it is assumed that many fish species swim deeper to avoid predators on the surface, in addition to staying clear of harmful UV-light [29]. At night they have the freedom to move more freely. However, predicting certain behavioural patterns are risky due to the extent of the involved variables. Knowing exactly how the fish behaves under different conditions is still a big question mark for technology suppliers since understanding the biology of fish is not always straight forward [51].

2.3.5 Water Currents

Fish farmers are interested in finding the best possible location for their farms. When a promising location is found, several environmental surveys must be carried out before the fish farm can be installed and accepted. The surveys are done according to the Norwegian Standard for Marine fish farms - Requirements for design, dimensioning, production, installation and operation (NS9415) [60]. Conducting current measurements is a part of the surveys, but are also frequently carried out for monitoring purposes. Monitoring a site during operation is a requirement by the Norwegian government to make sure that discharge from the fish farms is within regulations.

A location with favorable current conditions is of great importance because it may prevent illness and the pollution from fish farms might be reduced [69, 53]. Three water current levels are of particular interest when a potential fish farm is being assessed; The bottom current, the current close to the bottom of the cage and the surface current, which is also referred to as the exchange current. Sufficient current conditions at the bottom of the fish cage will prevent the accumulation of food at the cage bottom, but also at the seabed. It is therefore referred to as the dispersal current. The seabed current prevents the lack of oxygen close to the bottom of the sea. It is not desirable to have any areas that lack oxygen in the vicinity of the fish cage, and food accumulation might create this scenario. Fish feed must be removed regularly from the fish cage environment if this situation occurs [31].

During a feeding process, it can be helpful to have information about the water currents. However, few fish farmers have water current data available for operators monitoring the feeding process. A fish farmer wants to maximize the feed's travel time through the sea cage to give the fish time to consume it. If the currents are too high, the feed is likely to disappear through the net walls before it gets eaten, which leads to feed waste. Too slow currents do affect the appetite of fish since DO levels are most likely low, meaning the fish will not eat even though the pellets are available to them [53].

There are three current types which are important when evaluating a location according to NS9415; The tidal current, the wind-induced current, and the turbidity current. Tidal currents can have a great impact on the feeding process because they can be very strong [60]. For example, if a fish farm is located close to a fjord orifice, then the tidal current will be at its strongest in between high tide and low tide. During high tide and low tide, there will be no current [45].

The next current is the wind-induced current. When the wind blows over the ocean, a part of the wind energy is transferred to the sea surface, which contributes to the mixing of the water masses. The rest creates wind-induced water currents. If the ocean is approximately homogeneous in density, larger parts of the wind energy will be used for mixing and less to create wind-induced water currents. The wind-induced current is strongest at the surface and decreases with depth [60].

The last current is the turbidity current. A current is created when there are density differences present. Water will flow from different density zones to create equilibrium. The same happens when the water level is different. A river that flows into a fjord creates a stratified outward current at the surface. The coastal current along the Norwegian coast is another example of a turbidity current. The topography in an area will be of major importance. When a given amount of water flows north along the coast, between islets and sheaves or inwards into the fjords and encounters obstacles in the form of shallow waters or narrow channels, the current velocity will from a continuity perspective increase to allow the same volume to pass. This is in contrast to the tidal current where the water level difference on either side of the channel determines the flow rate. The turbidity current, like the tidal current, is relatively constant with the depth. The frequency and velocity of these currents can usually only be determined by direct current measurements [60].

Having detailed information about the water currents at the fish farm locations can make production more efficient. The feeding strategy can be adjusted to fit the water current pattern, and fish welfare might increase [53].

The change in current velocities from outside a fish cage to the inside of it is another aspect that needs to be addressed. Due to the net mesh of the fish cage, water flow is restricted and cause reduced current velocities inside the cage in comparison to currents outside of the cage. Biofouling causes further restrictions on the water flow through the net walls, decreasing the current velocities even more. Such perturbations of current patterns in and around cages are likely to impact the underwater spatial distribution of pellets. It also influences the water exchange to and from a cage, which might have consequences for the oxygen supply within a cage. Especially if several cages are placed together [11]. However, schooling densities inside a cage can remain unchanged even if water currents outside are very high [69]. If strong currents inside the cage occur, it can have the ability to change swimming velocities, schooling structure, depths and directions for salmon, see Figure 2.6. Experiments also show that higher current velocities inside a cage can lead to the fish being forced into the net wall due to exhaustion of their anaerobic capacity [85]. This scenario is illustrated in picture C in Figure 2.6.

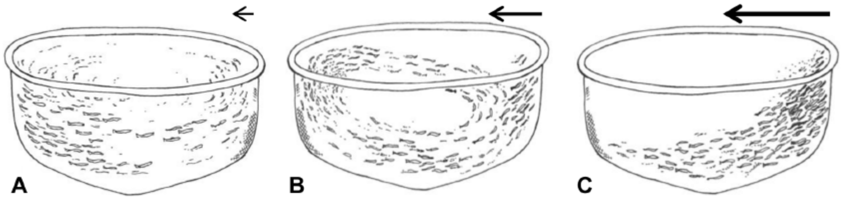


Figure 2.6: Three observed swimming structures (A - circular movement, B - circle and on current, C - standing on current) [24]

Oppedal et al. (2010) have a hypothesis which claims that salmon change their vertical position within the sea cage according to the water currents [69]. Their vertical position can also be affected by available swimming space and sea cage deformations, which alters the cage volume. Full-scale tests done at two different farms showed that current velocities between $0.13-0.35$ m/s caused a decrease in cage volume between 20-40%. The sea cage bottom was pushed upwards accordingly [85]. It is also said that water currents can show serious differences in velocities along the water column. Therefore, there is a complex inter-connection between swimming velocities, packing densities, cage deformations and high currents that one has to understand to ensure better fish welfare and proper feeding [51].

2.3.6 Location

The location of a fish farm can affect the feeding regime in various ways. Fjords, sounds, and bays can be realistic locations, and with them, the above mentioned environmental variables differ [39]. Coastal areas are known to be more exposed to strong and variable currents. Also, water levels change due to wind-driven upwelling causing colder water to rise to the surface. This water contains lower oxygen saturation, which is not beneficial for production. Farms in fjords, however, are not exposed to upwelling in the same way, but they are more affected by the seasonal variations to a greater extent. This means the vertical water layers varies with temperature, salinity, water currents, and oxygen [69].

The existing standard NS9415, is used to determine where and how farmers can set up their production locations. The purpose of the standard is to reduce the risk of escapes due to technical failure and misuse of aquaculture facilities. The standard describes the requirements for the physical design of floating fish farms and how the physical design must be documented. The standard also includes calculation and design rules for such facilities. In addition, testing of different environmental variables, such as water currents, wind, and the temperature is also required in order to get the location approved [60].

2.3.7 Stocking Densities

Schooling densities of fish are used as benchmarks to set limits for production in aquaculture [73]. However, little information exists to analyze how fluctuating environmental factors affect fish welfare and the stocking densities. Various tests have been done to analyze the effects of fish crowding. The results from the study by Oppedal et al. published in 2011, showed that high densities occur when vertical swimming space is narrowed down due to sub-optimal temperature limits. Additionally, if the schooling densities exceed 30 kg/m^3, it affects the welfare of fish. Consequences such as reduced growth rate, feed intake, feed utilization and an increase in cases of fin erosions, skin lesions and cataracts are plausible [73].

Even though a meal can change the swimming depth of salmon, other environmental variables surpasses this urge [21, 41]. It has been observed that when feeding is initiated, the normal schooling pattern breaks down and the majority of fish will swim towards the centralized feed spreader and pellets [41]. This tangled pattern will be restored to the original schooling pattern when the fish is saturated. However, the diffusion of fish in the sea cage is mainly controlled by where the optimal combination of the environmental parameters is located [73]. Through out a year, temperatures in the ocean change. From August to September, the warmest temperatures occur. For salmon, this means that they will distribute themselves on the lower depths to avoid the warmest surface layers at 2-3 m (<17°C). Nonetheless, when fish all seek the same space, the density increases, and consequences follow. In addition to a lower Feed Conversion Rate (FCR), cases of severe hypoxia have a larger chance of occurring and appetite is lost. In winter, the same behavioural pattern exists due to the cold surface layers. Salmon distributes themselves at the positions with the highest temperatures, which are located further down the water column. The period with the most homogenous ocean temperatures is from October to mid-November, and experiments have shown more even distributions of fish in this time interval [29].

It is evident that salmon have preferred swimming depths within their sea cage environment, which can lead to stocking densities up to 17 times the expected fish density. The median values are in the range between 1.1 to 1.7 of the stocking densities. Both depth and fish densities are products of inherent trade-offs with the surrounding environmental factors. Alterations in hours of daylight and temperature profiles throughout a year mainly dictate the trade-offs [73]. In scenarios where fish is forced to swim in undesirable sea cage conditions, their welfare diminishes. It happens if the densities are too high, limiting swimming space, which again negatively affects production parameters. Due to these large variations in environmental factors, appropriate stocking density limits should be set according to location characteristics. Fish will spread more evenly throughout the sea cage environment if thermally homogeneous water is present, composing more desirable swimming space, which can provide proper welfare for higher biomass [73, 69].

At a conventional fish farm in Norway, the water column usually indicates more thermally homogeneous conditions which rarely reaches extreme values. This allows for the stocking densities to be higher, and still maintaining sufficient welfare [73, 69].

2.3.8 Genetic Variation

Another factor which is a part of the complexity of feeding fish is the genetic variation. When a farmer places an order for new smolt they are never of the exact same genetic composition. All generations, families, and individuals have a special genetic architecture, which gives them certain traits and preferences. It is an important part of farming because the behaviour of different generations will always differ and is not easy to predict. It is first when they are placed in the sea cage one can determine their true behaviour, which challenges the making of a suitable feeding regime and choosing the correct feeding method, and technology [51, 53].

Some populations and individuals can differ in their preference of habitats [32]. It can be a challenge for management and conservation when developing welfare guidelines and assessing environmental impact. Earlier studies have tried to investigate the differences in behaviour on a genetic basis for farmed salmon. The studies mentioned in Garcia de Leaniz et al. (2007) state that the results are difficult to interpret because there are often many different explanations for the observed variations in salmon behaviour. Despite the difficulties with interpretation, studies have also concluded that certain behavioural traits are inherited and can be said to be adaptive. These traits, for instance, could be their predator avoidance behaviour or their aggression level [32]. High predator avoidance might keep them away from the surface to a greater extent, and high aggression levels can implicate that fighting for food and high feed intake rates are strong characteristics. These are speculations, but one can never know for sure how each generation will turn out.

2.4 Challenges Concerning Feeding

This section will comprise of some of the main challenges that the Norwegian Aquaculture industry is faced with regarding feeding fish. First, difficulties concerning feed waste will be explained, followed by the sea lice situation and lastly, the consequences of downtime. The latter is information gathered at a land-based fish farm feeding central in collaboration with feed operators stationed there.

2.4.1 Feed Waste

Feed waste is defined as uneaten feed leaving the sea cage environment [17]. It is an important problem in the aquaculture industry and has a major impact on the pollution of the local environment, production costs, and cost-effective and sustainable use of natural resources. About 50% of production costs is used on fish feed from hatched eggs to marketable fish meat, making it the most important production input. It is the primary driver for fish growth [11]. About 5-7% of feed is lost from commercial farming sites every year and reducing it would have a significant positive effect on the production, and the environmental and economic aspects of fish farming [11, 79]. Achieving such a reduction is challenging, and more research is needed to better understand the dynamic processes involved in the feeding process [79].

Fish farmers face the challenge of maximizing the growth of fish by letting enough feed be available to the farmed individuals, but at the same time minimizing feed waste [11]. Many solutions have been tested, and new methods are being invented to optimize this part of the production. So far the most efficient method is monitoring of the fish during feeding using underwater cameras [11]. The operators controlling the meals adjust the amount of feed by looking for behavioural cues. These cues are interpreted by each operator individually. Typically, they look for any sign of an increase or a reduction in appetite or behavioural patterns that indicate that the fish is stressed in some way. The main visual cue is, however, when pellets drift by the camera image. Further inspection of the situation is then initiated to see if the feeding should be stopped [53]. The efficiency of this method relies strongly on how the operators interpret the situation, who are prone to make mistakes. Thus, the skills of each operator directly impact the utilization of feed and growth of fish at fish farms [11].

According to Statistics Norway (SSB) about 1.3 million tonnes of salmon are produced annually in Norway, most of which are farmed in open water [78]. Additionally, a total of 1.5 million tonnes of feed is traded every year. As of today, sludge production, which consists of feed waste and feces, is not collected in open seas because no technology exists to serve this purpose. Emissions from sludge are also thought to be within the carrying capacity of the recipient, but it is a controversial topic [1].

Surveys of the bottom fauna underneath the sea cages is a requirement to make sure the emissions are not harming the environment. These surveys are performed regularly. So far there is no solution to how this waste can be exploited and collected efficiently, but it most certainly has a value. Based on assumed feed composition and digestibility as given in the Tables 2.1 - 2.3, it is estimated that the content of energy is 11,785,235 GJ and the accompanying amount of phosphorus is 9,096 tonnes per year in feces and feed waste from sea-based salmon farming [1].

By comparison, an average Norwegian household used 20,230 kWh per year in 2012, which corresponds to 73 GJ (1 kWh equivalent to 3.6 MJ or 0.0036 GJ). Remarkably, the amount of energy in feces and feed from Norwegian salmon farming corresponds to the energy consumption of 160,000 households. In 2013, 15,200 tonnes of phosphorus was dispersed over the Norwegian agricultural areas. Feces and feed from Norwegian salmon farming, however, contain 60% of the amount used in Norwegian agriculture. Thus, exploiting the sludge correctly would be of great benefit to the agriculture industry as well as the aquaculture industry. Some fields of use are biogas production, aquaponics, and fertilizer for agriculture. [1].

Table 2.1: Estimated annual amount of dry matter in sludge from the sea phase in Norwegian salmon production [1]

	Dry matter
Amount in feed, %	94
Apparent digestibility, %	70
Amount sold, tonnes	1,364,880
Amount consumed, tonnes	1,185,340
Amount of feed waste, tonnes	179,540
Amount of feces, tonnes	355,602
Total amount of sludge, tonnes	535,142

Table 2.2: Estimated annual amount of energy in sludge from the sea phase in Norwegian salmon production [1]

	Energy
Amount in feed, MJ/kg	24.5
Amount in MJ/kg dry matter	26.1
Apparent digestibility, $\%$	77
Amount sold, GJ	35,574,000
Amount consumed, GJ	30,894,500
Amount of feed waste, GJ	4,679,500
Amount of feces, GJ	7,105,735
Total amount of sludge, GJ	11,785,235

Table 2.3: Estimated annual amount of phosphorus in sludge from the sea phase in Norwegian salmon production [1]

	Phosphorus
Amount in feed, $\%$	0.9
Amount in $\%$ dry matter	1.0
Apparent digestibility, $\%$	35
Amount sold, tonnes	13,068
Amount consumed, tonnes	11,349
Amount of feed waste, tonnes	1,719
Amount of feces, tonnes	7,377
Total amount of sludge, tonnes	9,096

Exactly knowing how much feed is going to waste in a feeding scenario is difficult to measure because many variables influence the fish behaviour and pellet path. Currents, however, are an important factor when considering feed waste and can be an indicator for feed operators to estimate the loss of feed [10, 53]. To recall the essential facts from section 2.3.5 and 2.3.3; If the currents are too high, the fish will be occupied with using its energy to swim against the current [85]. When fish use their energy to stay in one place, less energy will be available for growth even in a fully-fed state. If the currents are too low the DO levels will decrease, which can harm the fish and feeding should cease [67, 89]. Another important fact that one should consider when feeding fish is that current velocities change along the water column. The ocean currents are affected by wind and density, which alters the different layer velocities. Thus, the current velocities decrease towards the seabed [59]. A study and simulation done by Alver et al. (2004) proves that the pellets drift with the water current at different levels along the water column with a downward motion. Their horizontal movements are due to current, while the gravitational pull causes their vertical movement [10]. This indicates that different velocities at different levels can either increase or decrease the risk of losing feed pellets through the net wall.

2.4.2 Sea Lice

Salmon lice are the most common parasite found on farmed salmon and the biggest disease problem in the industry [12]. For several years now, salmon lice have been treated with oral agents and bath treatments [44]. Severe lice infestations lead to reduced growth, stress, a weakened immune system and in worst case scenario it can have fatal consequences for farmed fish [12]. Norway has important wildlife strains and a significant aquaculture industry. Taking good care of both is important. Aquaculture causes the number of fish in the sea to increase, thus increasing the number of salmon lice hosts. Therefore, the levels of salmon lice in the plants must be kept as low as possible so that the total lice quantities in the sea do not get too large. Salmon lice grow all year, but their growth process accelerates when temperatures rise. The fastest reproduction process takes place in late summer months [48].

Monitoring of salmon lice shows that the numbers are increasing and that in some cases lice have become resistant to the preferred treatment method. Hence, the aquaculture industry is actively working to come up with solutions to prevent lice infestations [53, 51]. Governmental regulations have had a positive effect on the salmon lice control. The salmon lice itself represent little or no threat to the individual farmed salmon's health and well-being as long as the lice level is kept below the limits imposed by the authorities. Treatment is initiated when lice infestations reach the limit of one full grown female lice for every second farmed salmon [12]. However, these regulations do not solve the problem alone and alternative farming methods, including newer technology, are continuously being tested [53, 51].

Salmon lice preventive measures are currently a part of the production cycle. One way to implement this is through medicated feed that is given to the fish over a short time-period [52, 53]. Another and newer solution is to deploy the feed at certain depths to make the fish avoid the water layers with the highest salmon lice density, where the risk of infestations is high [8, 51].

2.4.3 Downtime

Feed operators are entirely dependent on the feed system technology at the farm locations to execute their tasks. The feeding system components do however need maintenance quite frequently due to various reasons. Downtime of one element of the feed system can lead to multiple days where one or numerous cages do not get fed. This means lost growth and potential earnings. One wasted day of feeding during summer, where the fish has it's highest growth rate, can cost the farmer formidable amounts in retrospect. Another common situation in Norway is when the weather is too extreme for the workers to be on site. Some fish cages may have to stay unfed until the weather calms down. This can take up to several days or weeks in the worst case scenario [53].

The most important consequence that comes from frequent downtime on feeding system components is that the sea-phase of the fish is prolonged to reach ideal weight. Increasing time at sea means an increased risk of lice infestations and hence, increased costs in delousing treatments, leading to lower fish welfare and higher mortality rates. Therefore, working efficiently with outdoor workers to prevent downtime or detecting and solving problems that occur is essential. Operators feeding the fish from a land-based remote feeding central can often be limited in their actions if the outside workers at the farming plants do not attend to the failed components in time [53].

2.5 Overview of a Fish Farm Layout

A typical fish farm consists of four main components; the floating elements, the net pens, the feed barge (with the feeding system included) and a mooring system [76]. The cages consist of the first two above mentioned components and can have different designs, but the most common way to farm salmon is in open, cylindrical, floating cages [81, 82]. The other common option is square shaped cages made of steel. This type is becoming rarer due to various reasons, but mostly due to their high rigidity and poor response characteristics to environmental loads [76]. The dimensions of such squared shaped cages range from 20-40 m in width and up to 35 m in depth. For the circular cages, their circumference is often between 90-157 m. Trends have shown an increase in circumference. The largest circumference currently used is 240 m, but exist only in Tasmania. The amount of cages per location varies with the farmers Maximum Allowable Biomass (MAB) licenses and geographical layout, but one can normally find farms that possess between 4 to 16 cages. According to Norwegian regulations, one cage may hold up to 200,000 individuals, which complies with the maximum allowable stocking density of 25 kg/m^3 [81, 53].

The function of the cage components, such as the net pen, is to contain the farmed individuals. The weight system's purpose is to maintain the net pen volume by stretching it and can be found at the bottom of the net either in the form of individual weights or in the form of a ring or with both. Cage volumes vary from 8,000 m^3 up to 60,000 m^3

[76, 53]. Other designs do exist, but in general, the two versions presented above occurs most frequently. The floating elements keep the cage afloat so that no fish can escape and production processes can be carried out [53].

Figure 2.7 shows a typical layout of a cage with a floating element, net pen, and a weight system. The cage system is held together by a mooring system that stretches out over a large area underneath the surface. Figure 2.8 illustrates how the mooring system is laid out.

The last main component is the feed barge [76]. It serves the purpose of storing feed pellets, 3-25mm in diameter, in silos and holds the majority of the feed system parts; Blowers, cooling system, air control system, dosers, multiple valves, generators, and selectors [57]. The feed is transported from the silos to the cage via pipelines. Pipe connections can be up to 1200 m long. To prevent blockage, they are cleaned periodically or when necessary. At the end of the pipeline, there is a connection to a feed spreader located in the middle of the cage [57, 81]. All in all the whole farm is designed to withstand certain levels of environmental impacts, such as wave forces and strong water currents to ensure the safety of workers and the welfare of the farmed individuals [76, 60].

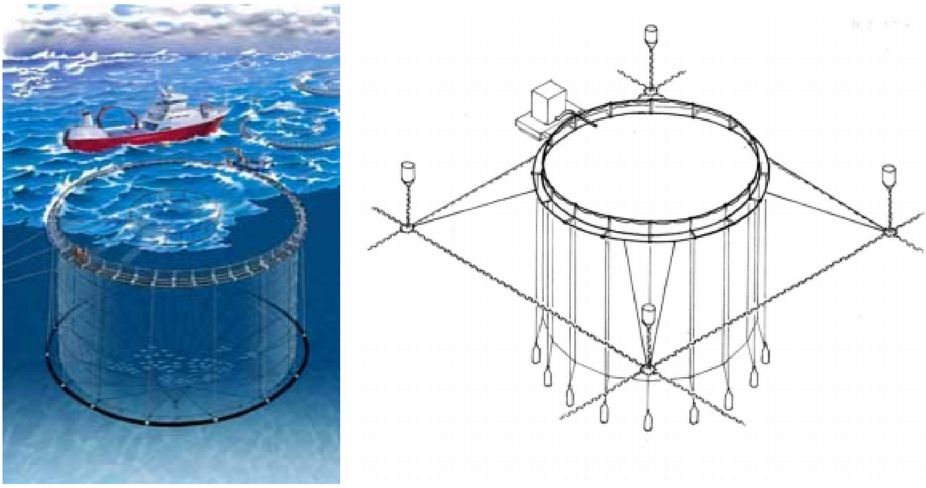


Figure 2.7: A Common Cage Design [76]

2.6 Feed Distribution Technologies

The goal with feeding is to transfer the proper nutrients to the fish to ensure growth and good health without wasting feed. Suppliers and fish farmers both care about how efficient

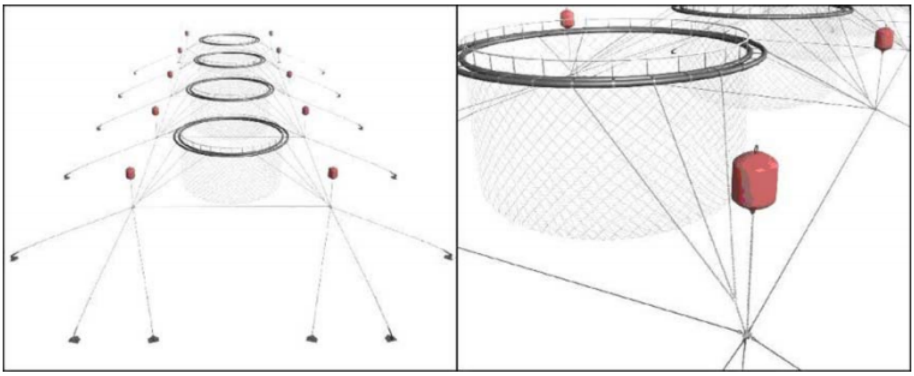


Figure 2.8: An Illustration of the Mooring System [76]

feeding is conducted. When feeding is done efficiently, feed pellets are transported from the feed barge to the cage without being damaged until the fish is satiated. Satisfactory pellet distribution is achieved through correct handling of the feeding system, where parameters such as air pressure and velocity, temperature and dosage are important [57, 53]. Continuous communication with the operators on site is also essential for the production to avoid downtime [53].

Feed spreaders come in various designs, and their main task is to distribute the feed uniformly in the cage. With time, questions have occurred whether certain types of spreaders are performing sufficiently concerning distribution patterns, sustainability and changes in environmental conditions [81, 53].

The majority of fish farmers nowadays use the conventional surface rotor spreader, but of various types [81]. Subsea feeding, on the other hand, has not yet been a priority for farmers. However, ever since the technology became available on the market, it has gained increasing attention [51]. Every fish farmer has a different reason for why they prefer certain systems, but their major concerns are primarily how healthy their stock is and how much the fish is growing. Additional motives for selecting different technologies are keeping the lice numbers to a minimum and reducing feed waste to a certain extent [53].

Every feeding pipe leads to a feed spreader, either over or under water [4]. Since there are multiple variations of such feed spreaders on the market this thesis will only present two types; One standard pneumatic rotor spreader and one subsea feeder [7, 5]. However, the designs of the spreaders are not in focus as the simulations executed in this thesis can be adapted to any design by making alterations to their feed distribution patterns.

2.6.1 The Surface Rotor Spreader

A surface rotor spreader usually consists of a pipe, a flotation device and a submerged counterweight that is perpendicular to the surface. The latter makes sure the spreader is stable and stays upright [81]. Some spreaders do not have counterweights due to different designs [7, 6]. Figure 2.9 displays a common pneumatic rotor spreader. The feed pipe from the feed barge connects to the spreader at the blue flange in the picture. The ball bearing depicted allows the outlet and center pipe to rotate during feeding. The rotation is not specifically controlled by operators. It is the curved shape of the outlet pipe together with the airflow in the pipe that creates the torque about the vertical axis and is the driving force of the pellet distribution [82]. The motion of the spreader distributes the feed pellets in a circular pattern across the surface as they are thrown from the outlet pipe[61].

Due to the absence of moving and electronic components, minimal maintenance, and low investment costs are advantages associated with this technology [80]. However, some operators claim that substantial maintenance is needed when using surface rotor spreaders. Outlet pipes can loosen if the pressure gets too high when the feeding pipe is filled with water due to different circumstances. Spreaders and feed pipes can also get clogged with feed, or the floatation device can get pierced and lose air. Due to various weather conditions, spreaders can also change their position in the cage. Depending on how the operator feeds the fish and utilizes the feeding system, different scenarios requiring maintenance can often occur [53].

When simulating the pellet distribution pattern from a rotor surface spreader, the influence from the surroundings of the spreader must be considered. The main external influencing factors are the wind and waves. Water currents also affect the spreading pattern after the pellets leave the outlet pipe and land on the surface [11].

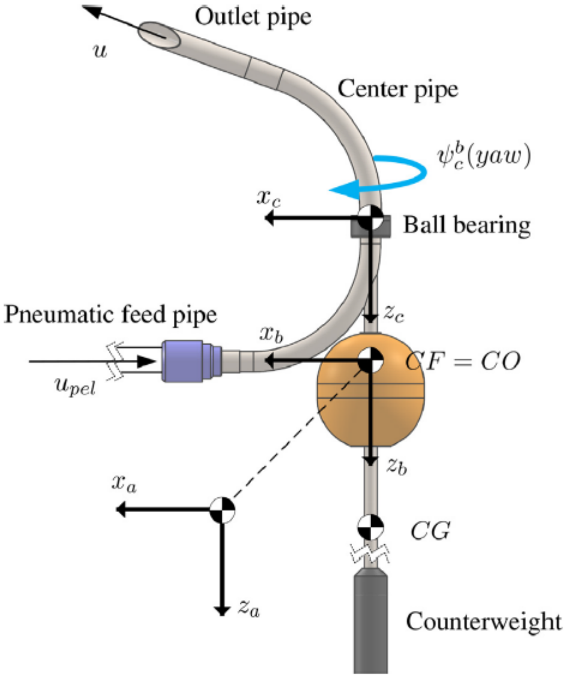


Figure 2.9: Model of the CF90 Double rotary Spreader [81]

For a more detailed description of the establishment of this system, see the study of Skøien et al. (2015,2016) [83, 80].

2.6.2 The Subsea Feeder

The subsea feeder technology is a relatively new invention that is said to be an effective feeding system that boosts growth and better fish welfare. It is not yet an invention that is used by many fish farmers even though equipment suppliers in the industry focus on feeding fish deeper beneath the surface [51]. Some companies, however, are trying out the technology, but to a different extent than others [3]. The main reason for farmers to try out this subsea feeder technology is because the feed is distributed under the surface below the lice belt, which refers to the preferred depths of sea lice (0-6m) [37, 36]. The system enables feeding at a specific depth and can, therefore, save companies costs and time-consuming processes related to delousing. In retrospect, suppliers are finding more advantages to this system than only fighting the lice infestations. Among them are more stable environmental values at the feeding depth, such as water currents, temperature, and oxygen are the parameters mentioned more often than others [51]. Further research is however needed to make any conclusions on this matter. A picture of the AKVA group Subsea Feeder is included for illustrative purposes.

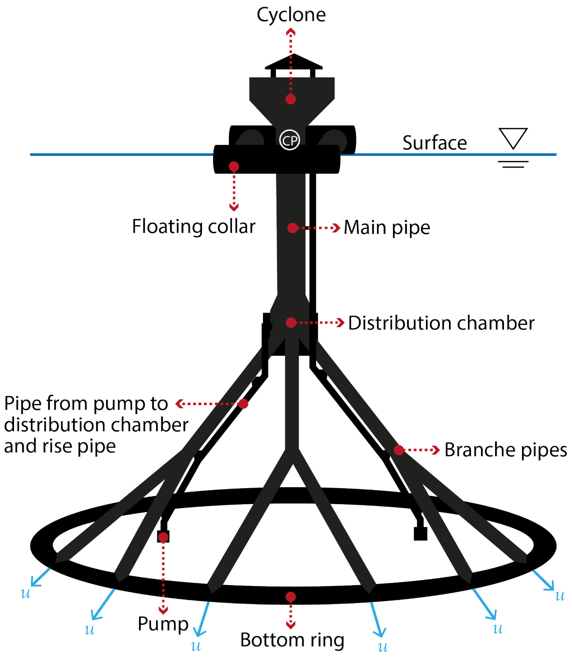


Figure 2.10: AKVA Subsea Feeder

The illustrated feed spreader in Figure 2.10, consists of no moving parts. It is connected to the feed barge in the same manner as the surface spreader, with a pipeline, except that the pipe leads to a cyclone seen above the water surface in the picture. From there water is added via a pump that is placed further down on the spreader and the feed is led down the main pipe. Supply of water makes sure that the pellets maintain a certain velocity, u. At the end of the main tube, the water-pellet mixture reaches a distribution chamber. New amounts of water are added, and the feed is spread into manifolds that lead to the outlet points on the bottom ring (marked with blue arrows in Figure 2.10). Within the bottom ring, there is a chain/wire that keeps the structure stable and perpendicular to the surface [3, 36].

Currently no existing published document covers the specific mathematical reference frames of a subsea feeder. The center point of the spreader, however, is located in the middle of the cyclone in the water plane which coincides with the center of the fish cage.

2.6.3 The Importance of Feed Distribution

Many biological and physical factors determine the success of a feeding operation. External factors such as wind and waves play a major role. However, the environmental factors will mainly affect the pellet dispersal after it leaves the feeder nozzle. Below the surface, the pellets are moved primarily due to current velocities and gravity [73]. In this context, different currents and their corresponding directions can affect the likelihood of pellets drifting out of the cage walls before they get eaten [11].

The feed delivery system is also involved in the production outcome as it determines how well the feed is distributed over the cage surface, and how close to the cage edge the pellets land. The different feed spreader technologies existing in the market create different spreading patterns [11]. It has been documented that the pattern created is dependent on the physical configurations of a single spreader type [62].

The way the feed is dispersed on the surface over time can give clear indications of the fish welfare, growth rate, aggression, and feed loss [82]. In Atlantic salmon, suboptimal feed intake is related to reduced and inefficient growth. Confinement of the amount of feed or the spatial and temporal availability of it should not occur so fish may forage unrestrictedly. The feed availability plays an essential role in achieving efficient production, and a highly localized delivery of feed may lead to monopolization by dominant individuals [81]. However, operators monitoring the feeding processes in Norwegian fish farming want the feed to be somewhat centralized so that the feed pellets can be detected on their monitoring devices. If the pellets are too far apart the pellets are difficult to detect, and it is harder to get an idea of how the fish eat. The feeding process is a constant tradeoff between distribution radius and monitoring quality. There is a lack of flexibility and information that the operator is left with, which shows large potential for improvement [53].

Chapter 3

Model Description

This chapter explains the method used to conduct the feed spreader simulations. First, the reason for choosing this method as basis for the comparison is explained. The second part summarizes the building blocks, which make out the model made by Alver et al. (2004,2016) [10, 11]. Based on this model, an additional part is presented, which comprises of the pellet distribution setup of a subsea feeder.

3.1 Background

Due to the fact that feed make out the greatest single cost factor in Atlantic salmon production, other scientist like Alver et al. (2004,2016) have raised the issue regarding how to maximize the availability of feed for the farmed fish and at the same time minimize feed waste to save costs and prevent environmental harm [11, 10]. The following section shortly summarizes the content of their previously conducted studies.

3.1.1 Previous Studies

The first study concerning the pellet distribution pattern of the pneumatic surface rotor spreader was conducted in 2004. This study derives a two-dimensional mathematical model which describes the short-term spatial distribution of feed pellets in Atlantic salmon sea cages. The pellet distribution pattern is under the influence of gravity, water currents and the presence of fish. Fish are represented by their appetite, which depends on their gut fullness and population structure. Feeding rates and feed intake are both influenced by their size distribution. Feed waste and feed distribution is simulated during longer feeding periods or single meals under various physical conditions. Different pellet sizes, pellet release rates, feeding frequencies and fish size distributions are also taken into account. Behavioural characteristics are not explicitly modeled. Atlantic salmon is used as the modeled species, but it is possible to adapt the model to other species as well as long as they feed on sinking particles in the water column. The model is compared to experimental data with respect to feed intake and wastage rate, and shows good agreement. Its main application is to help minimize the feed waste from salmon cages, thus optimizing feed use. Conclusively, the study states that the average feeding depth during meals, which is part of the model output, could be a key factor in detecting the reduction in appetite of fish. Furthermore, this information can be used to determine if the feeding should be reduced or stopped to minimize feed waste. It could be done by monitoring the average fish depth during a meal [10].

A later study, published by Alver et al. in 2016, have improved the applicability and realism of the original model from 2004 by introducing the third dimension as a part of the model representation. The reason being that the initial model is not well suited for representing the circular cages that is now the industry standard in Atlantic salmon production. Additionally, a detailed description of the surface pellet distribution is difficult to represent in 2D. The latest simulation is more realistic in terms of cage geometries and pellet diffusion rates, which ensures that the model accurately describes the dynamics of pellets over a variety of sizes and depths. This model is based on the same parameters as the original model, but with some adjustments and validation applied to the horizontal and vertical pellet diffusion process. A new feed input module is also added to realistically represent the feed distribution over the cage surface. The full dynamics of the new model shows improved fit with the measurement data compared to the original model [11].

3.2 The Initial Model

This section comprises of the different mathematical steps that makes out the pneumatic rotor spreader simulation model, where some parts also apply to the subsea feeder. An overview of all parameters mentioned in this chapter can be found in Table 3.1. The information about the initial model is taken from the studies conducted by Alver et al. (2004,2016) [11, 10].

3.2.1 Cage Discretization

The cage model is discretized along the three spatial dimensions. Two of the axis are defined horizontally, and one is defined in the vertical direction. The different axes have assigned subscripts, i, j and k, that refer to the discretized intervals, respectively. Where $i \in \{1, ..., i_{max}\}, j \in \{1, ..., j_{max}\}$, and $k \in \{1, ..., k_{max}\}$. The model's accuracy increases with the number of finite elements. The resolution is therefore a trade-off between computational load and accuracy. Figure 3.1 illustrates the discretized model with cells. One cell has the dimensions Δx along the x-axis, Δy along the y-axis and Δz along the vertical z-axis. Figure 3.2 displays a closeup of the model's origin and axes.

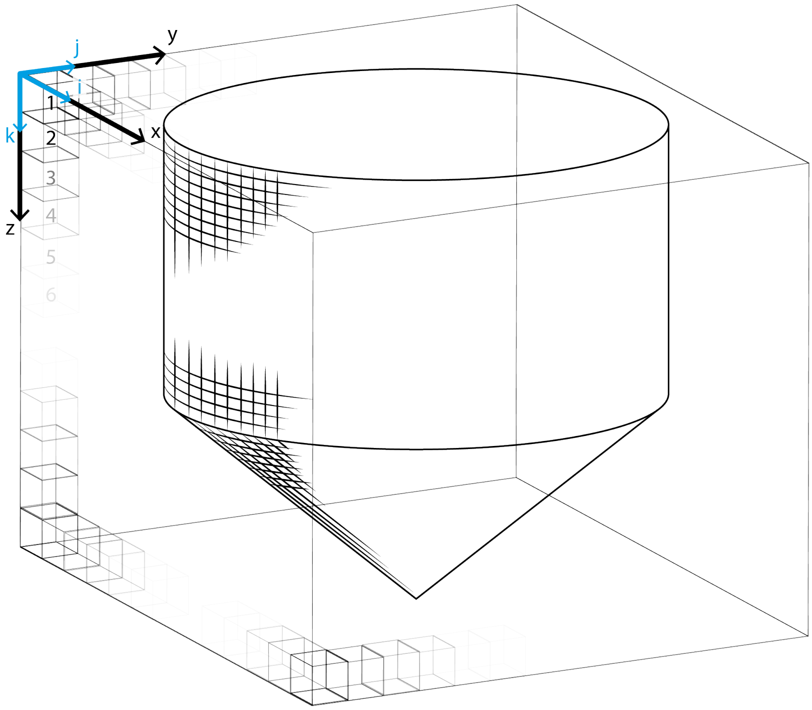


Figure 3.1: Model discretization

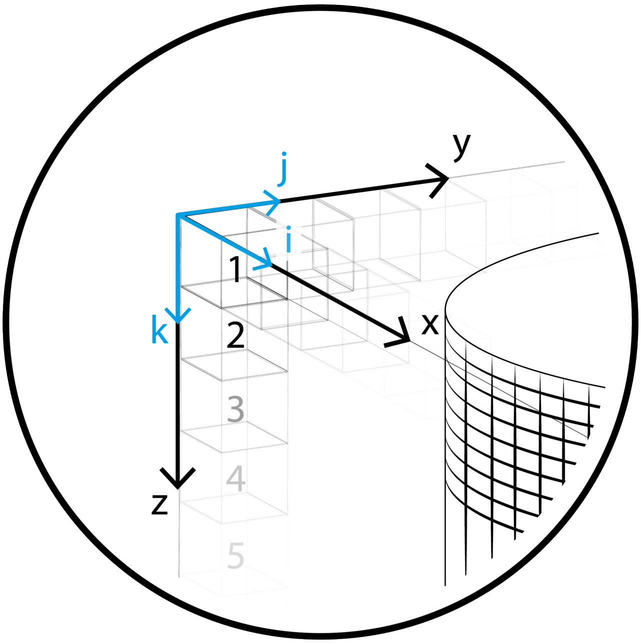


Figure 3.2: Model discretization closeup

The model is easily implemented in a computer as a cubic array of cells. The actual shape of the cage is represented with a binary cubic cell array, where the value 1 means that a cell is inside the cage, and the value 0 defines a cell outside the cage. The pellet transport equation, see 3.2.2, is integrated over the entire cubic cell array, but it is only the cells inside the cage that are considered when the feed waste and ingestion rates are calculated.

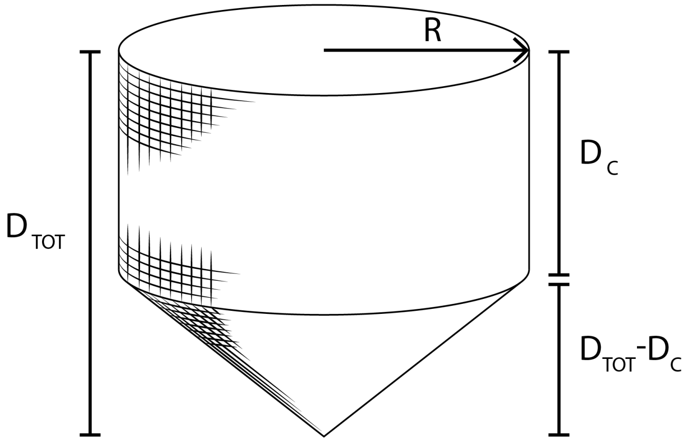


Figure 3.3: Model main dimensions (made by author)

The shape of the modeled cage is designed to fit the industry standard, see Figure 3.3. A circular cylinder is used for the upper part of the cage net. It has a defined radius, R, and height, D_c. The lower part of the net cage has a conical shape where its base matches the circumference of the cylinder, see cage in Figure 3.1. The tip of the cone points towards the seabed, and the two parts make out the total depth of the cage, D_{tot}. The conical part of the cage has a height of $D_{tot} - D_c$. Cells with their center inside of the cylindrical-conical form are considered to be a part of the cage. Extra width is added to the model to improve the accuracy of the model. In this study an extra 4 m is added to each side in the horizontal plane. See Figure 3.4.

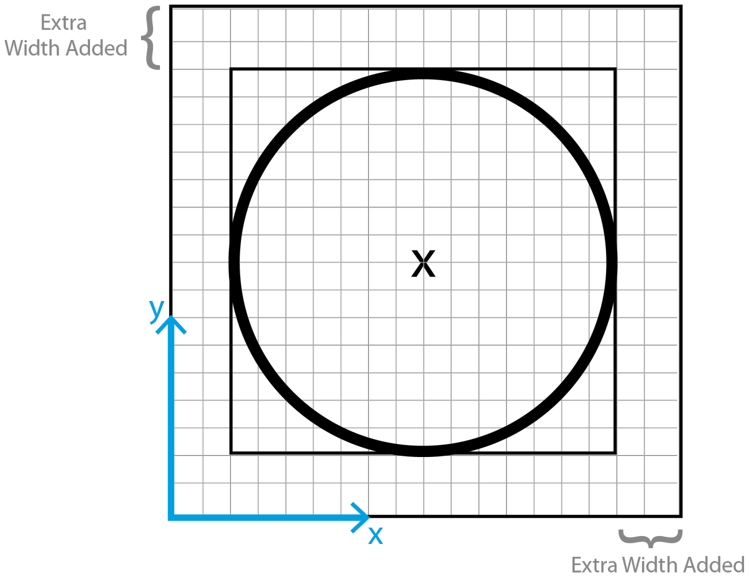


Figure 3.4: Model overview of the horizontal plane

3.2.2 Pellet Transport Equation in 3D

The pellets are modeled as a spatial concentration rather than being considered individually. Every farming location is influenced by local water currents and in almost all cases there is a horizontal current through all cages that varies with direction and velocity. During the feeding process, these currents will cause a general drift of the feed pellets along the water column. The main variables to consider when looking at a feed particle are how close it is to the cage bottom, and how far it is to the cage net wall to which it is drifting in the horizontal direction. Its horizontal movements can be described as the motion caused by the present water current, and its vertical movement due to gravity. This simplification reduces the computational load significantly [10].

For the surface feeder, pellets will be dispersed over a part of the cage surface. After entering the water, each pellet will move due to the influence of a seemingly random component and a deterministic component. The deterministic component comprises of the water current and gravity. The pellet will sink vertically with a certain velocity by balancing the immersed weight of the pellet and the force of resistance from the water. The sinking velocity will depend on the shape of the pellet and its specific weight. This is easy to determine experimentally for a specific feed type [10]. The sinking velocity for each pellet size used in this paper is set equal to the measured velocities found during experiments conducted for the CREATE project [9, 79].

The main horizontal movement of the pellets are caused by the water current. The assumption is made that the horizontal drift will be equal to the measurable water current. The random component affecting the pellet motion is caused by disturbances from the fish, and by waves and whirls in the water. The combined motion is complex, and is regarded as the random motion that spread the feed particles [10]. Waves and whirls are therefore not explicitly modeled. The Coriolis effect is also not considered [9].

Diffusion of pellets is assumed to be omnidirectional. The pellet movement can be viewed as the limit of a random walk with the time step approaching zero. This mathematical behaviour for the distribution of pellets represents the diffusion [77].

The full 3D pellet transport equation, which calculates feed waste, can be written as follows:

$$\frac{\partial c}{\partial t} + v_{\mathrm{x}}\frac{\partial c}{\partial x} + v_{\mathrm{y}}\frac{\partial c}{\partial y} + (v_{\mathrm{z}} + u_v)\frac{\partial c}{\partial z} + k\left(\frac{\partial^2}{\partial^2 x}c + \frac{\partial^2}{\partial^2 y}c + \frac{\partial^2}{\partial^2 z}c\right) = u - f_I \tag{3.1}$$

Here, $c(x, y, z)$ represents the *local feed concentration* with the spatial coordinates x, y and z. The *water current* components are represented as $v_x(x, y, z)$, $v_y(x, y, z)$ and $v_z(x, y, z)$ along the horizontal axes and vertical axis. The *sinking velocity* of feed pellets is defined as u_v, $u(x, y, z)$ represents the *feed addition* and k represents the *diffusivity*. The last parameter is the *local feed ingestion*, f_I [11].

The inside of each cell is said to have a uniformly distributed concentration, which is a characteristic of the discretization scheme used. The local feed concentration change rate is given by the sum of what is added to the cell minus what leaves the cell, in addition to how much feed is eaten by the fish. The feed concentration equation can be expressed as follows:

$$\dot{\mathrm{c}} = f_{\mathrm{A(i,j,k)}} + f_{\mathrm{D(i,j,k)}} + u_{\mathrm{(i,j,k)}} - f_{I\mathrm{(i,j,k)}} \tag{3.2}$$

The two terms after the equal sign that occur in (3.2) is the change due to advection, f_{A} and the change due to diffusion, f_{D}. Both terms depend on the amount of feed in a cell, i,j and k, as well as all bordering cells. Detailed information about the advection and diffusion term can be found in Alver et al. (2016) [11]. f_I and u are the feed ingestion and feed supply in every cell. Some cells will be bordering the cage walls or the surface, which indicates that some terms in f_{A} and f_{D} will be outside or above the cage grid. Thus, boundary conditions for these scenarios are established:

$$\begin{aligned} c_{i,0} &\equiv c_{0,1}, \quad & c_{i+1,1} &\equiv 0 \\ c_{0,j} &\equiv 0, \quad & c_{i,n+1} &\equiv 0 \end{aligned} \tag{3.3}$$

The first boundary condition above state a no-flux boundary condition to the upper boundary by giving the outside concentration the same value as the one below the surface. Implementing this rule means no diffusion can take place up through the surface. The remaining boundary conditions define the feed concentration outside of the cage walls and below the cage to be equal to zero. It is assumed that feed leaving the cage will disappear immediately. The rules regarding the diffusion of feed through the net walls and the bottom of the cage introduce some error that can be reduced by implementing more layers of cells outside of the cage in the model, see Figure 3.4. Thus, the error inside the area of interest is reduced [10].

3.2.3 Modelling the Feed Input from the Surface Rotor Spreader

The dispersion of feed in the cage has a significant effect on feed wastage. Pellet distribution patterns can cause low or high local feed concentrations. If the spreader has a higher dispersion of feed it will lead to a low local feed concentration. The model accounts for this scenario by distributing the feed more evenly between the size classes of fish. The opposite occurs if the dispersion leads to a higher local concentration of feed. This is however, only tested for the surface rotor spreader [11].

Oehme et al. conducted a study in 2012 that investigated the actual distribution pattern of a pneumatic rotor spreader. They figured out that the dispersion of distance travelled by single pellets resembled a skewed normal distribution. It was discovered that the standard deviation and mean of this distribution varied with the angle relative to the forward direction of the spreader, as well as with the tilt of the spreader nozzle (pointing downwards or horizontally) and air velocity. The variation in pellet size had no significant effect on the distribution pattern [62].

In order to model the spread pattern for a surface rotor spreader a parameterised probability distribution is introduced. This is a normal distribution function dependent on the angle relative to the forward motion of the spreader (ψ), distance to the spreader (d) and airvelocity (v_{air}).

$$P(v_{air}, d, \psi) = \frac{1}{X_2\sqrt{2\pi}} exp\left(-\frac{(d' - X_1)^2}{2X_2^2}\right) \tag{3.4}$$

X_1 represents the mean value, and X_2 the standard deviation. Both determined by the air velocity and direction according to the following functions:

$$X_1 = (p_1 + p_2 v_{air}) p_{1,tilt} \left(1 - \frac{\psi}{180}\right) + (p_3 + v_{air} p_4) p_{2,tilt} \frac{\psi}{180} \tag{3.5}$$

$$X_2 = (p_1 + p_2 v_{air}) p_5 p_{1,tilt} \left(1 - \frac{\psi}{180}\right) + (p_3 + v_{air} p_4) p_6 p_{2,tilt} \frac{\psi}{180} \tag{3.6}$$

$$p_{1,tilt} = \begin{cases} 1: & \text{for tilt up} \\ p_7: & \text{for tilt down} \end{cases} \tag{3.7}$$

$$p_{2,tilt} = \begin{cases} 1: & \text{for tilt up} \\ p_8: & \text{for tilt down} \end{cases} \tag{3.8}$$

The parameters $p_1 - p_8$ represent the different distribution patterns in the forward ($\psi = 0$) and backward ($\psi = 180$) directions of the spreader. To determine the weighted average between the different patterns in the forward and backward directions, $\psi \in [0, 180]$ is used. Angles in between are found by interpolation. The resulting distribution pattern, which is established with the variable, d', illustrates the skewed pellet dispersal. d' is set equal to the distance from the spreader d to the power of p_9.

$$d' = d^{p_9} \tag{3.9}$$

The result is a probability distribution parameterized by $p_1 - p_9$. It describes the distribution for a single type of spreader for both tilt states and at all angles. Spread patterns calculated over a 2D surface are shaped like circles and with a more skewed pattern when the spreader is tilted up compared to when it is tilted down. The simulation of the distribution pattern for a pneumatic rotor spreader has been compared to observations and was found to match the measured patterns closely [11].

3.2.4 Representing the Fish

In a real life fish farming scenario there are fish of different sizes in every cage, which can be said to be approximated as a normal distribution. However, such a distribution is difficult to model exactly and a simplification is made. The variation in the fish population is accounted for in the model by dividing the total fish population, consisting of N individuals, into sets of super-individuals. Each group of super-individuals represent a certain number of fish (N_m), where all individuals within a group have the same body weight (W_m) and stomach content capacity (V_m) [11]. The number of groups is arbitrarily selected and in this paper set equal to 7. By increasing the number of groups, the population will be more precise [9].

The simulation time is considered to be short-term, which creates the assumption that the body weight (W_m) will stay constant. The only dynamic variable of the fish is the stomach content (V_m). The spatial positions of the individual fish are not explicitly modeled, but their feed intake is computed by assuming that they accumulate similarly to how the feed is dispersed throughout the cage.

3.2.5 Feed Ingestion

Many factors affect the feed intake rate. The model is designed to treat the distribution of pellets in time and space, by analyzing how the feed spreads and disappears in the cage, and how much feed is available. The feed availability and its distribution pattern will influence the feed ingestion rate and the competition for food between fish. Light levels and other visibility related factors are not currently a part of the model [10].

The stomach content equation is based on the assumption that the stomach emptying rate is proportional to the stomach content, and dependent on the water temperature. The equation can be defined as follows:

$$\dot{V}_m = w_{fm} - a_1 T^{a_2} V_m \tag{3.10}$$

The *feed ingestion* is represented by w_{fm} and the *stomach emptying rate* is defined by the second term in the equation. a_1 and a_2 are constants and T is the water temperature. The feed intake rate term is calculated as the product of multiple factors.

$$w_{fm} = P_w w_0 p_c p_{am} p_{hm} \tag{3.11}$$

P_w defines the weight of each pellet, and the remaining factors are defined below:

$$w_0 = \left(T_h + \frac{k_{T_s} N P_w}{c_T} \right)^{-1} \tag{3.12}$$

w_0 represents the *maximum feed intake rate* and is limited by the search and handling time per pellet, T_h. c_T stands for the total amount of feed in the cage and k_{T_s} is a constant.

The p_{am} factor in the feed intake rate equation 3.11 is the *appetite factor*. It is dependent on the relative stomach fullness of the fish:

$$p_{am} = \begin{cases} 0.50 - \dfrac{0.57(V_{rm} - 0.3)}{V_{rm} - 0.2} & \text{if } V_{rm} > 0.3 \\ 0.50 + \dfrac{0.67(0.3 - V_{rm})}{0.4 - V_{rm}} & \text{if } V_{rm} \leq 0.3 \end{cases} \tag{3.13}$$

V_{rm} represents the relative stomach fullness and this value is calculated based on the model developed by Burley and Vigg, where they found the maximum stomach volume of coho salmon (*Oncorhynchus kisutch*) [23].

$$V_{rm} = \frac{V_m}{0.0007 W_m^{1.3796}} \tag{3.14}$$

In order to improve this part of the model, it would be useful to know the maximum stomach volume of Atlantic salmon. As far as the author knows, no published research exists on this topic.

The next factor in equation (3.11) is the *confusion factor*, p_c. Confusion occurs due to the increasing local fish density in the areas where the feed concentration is high. Under the assumption that the fish distribute themselves according to the feed, an expression is formulated for p_c, that depends on how well the pellets are spread within the cage (ρ)[11].

$$p_c = \rho^{b_1} \tag{3.15}$$

Where b_1 is a constant, and $\rho \in [0, 1]$. $\rho = 0$ indicates that all the pellets are concentrated within a single cell and $\rho = 1$ means that all cells have the same amount of feed. Alver et al. (2016) decided that ρ should be calculated based on the potential concentrations of fish in the cage. Due to the assumption made earlier about how the fish distribute themselves according to the feed, it is clear that the feed dictates how the fish will be dispersed throughout the cage volume. If the fish densities exceed a certain threshold for a significant proportion of the population, then the feed is considered to be poorly distributed. The model should in this case use a low ρ value [11].

This can be formulated mathematically by first determining the relative feed concentration in each cell within the cage. This can be expressed as $c_{i,j,k}/c_T$ for cell (i,j,k), where c_T is the total amount of feed in the cage. If the feed spread dictates the fish distribution, then the biomass of fish in a cell can be represented by $W_{i,j,k} = W_{Total} \cdot c_{i,j,k}/c_T$. The fish density in a cell ($FD_{i,j,k}$) in kg/m^3 is found by dividing $W_{i,j,k}/\Delta x \Delta y \Delta z$. A function $f(FD)$ is defined, which gives a local density value (ρ) based on the fish density in a cell.

$$f(FD) = \begin{cases} 1: & \text{for } FD < FD_{tresh} \\ 1 - \frac{FD - FD_{tresh}}{FD_{tresh}} & \text{for } FD_{tresh} < FD < 2 \cdot FD_{tresh} \\ 0: & \text{for } FD > 2 \cdot FD_{tresh} \end{cases} \tag{3.16}$$

The parameter FD_{tresh} represents the maximum fish density that does not cause a reduction in ρ. The ρ factor is defined as the average of local values, weighted by the density of the fish. With this definition, a ρ value is chosen that relates to the actual fish density, and which retains its meaning for all population sizes and cage dimensions.

$$\rho = \sum_{i,j,k} \frac{W_{i,j,k} f(FD_{i,j,k})}{W_{Total}} \tag{3.17}$$

The last factor in the feed intake rate equation (3.11) is the *hierarchy factor*, p_{hm}. It represents the scenario where larger fish outperform smaller fish by gaining preferential access to food during feeding.

$$p_{hm} = \left(\frac{W_m}{W_{max}} \right)^{f_a f_d} \tag{3.18}$$

W_{max} defines the body weight of the largest fish in the population. f_a represents the weighted average of the appetite of the fish, where the largest fish is weighted most. The factor f_d is added to weaken the hierarchical effect when the feed is more evenly distributed since a higher concentration of feed leads to monopolization of dominant fish.

$$f_a = \frac{1}{W_{Total}} \sum_{m=1}^{m_{max}} N_m p_{am} W_m \tag{3.19}$$

$$f_d = \rho^{-b_2} \tag{3.20}$$

Where b_2 is a constant and W_{Total} is the total biomass of fish in the cage. The hierarchical factor, p_{hm}, will be equal to 1 for the group of largest fish. The remaining groups of fish will have $p_{hm} < 1$. With time the fish will be more satiated and p_{hm} will approach 1 for all groups, which weakens the hierarchical effect.

The *total feed intake* for the entire population can be defined as:

$$w_{f\mathrm{T}} = \sum_{m_1}^{m_{max}} N_m w_{fm} \tag{3.21}$$

The relative feed distribution intake is assumed to be equal to the relative feed distribution, which makes it possible to calculate the *ingestion rate* in cell (*i,j,k*):

$$f_{I(i,j,k)} = \frac{c_{i,j,k}}{c_T} w_{f\mathrm{T}} \tag{3.22}$$

Table 3.1: Overview of state variables, controlled variables, parameters and disturbances (uncontrollable inputs) [11]

Symbol	Value	Unit	Type	Description
a_1	5.2591×10^{-6}		Parameter	Parameter for gut evacuation rate
a_2	0.7639		Parameter	Parameter for gut evacuation rate
b_1	0.4		Parameter	Parameter for confusion factor
b_2	0.5		Parameter	Parameter for hierarchy factor
$c_{i,j,k}$		g	State variable	Amount of feed in cell (i,j,k)
Δx	1	m	Parameter	Cell size in x direction
Δy	1	m	Parameter	Cell size in y direction
Δz	1	m	Parameter	Cell size in z direction
D_c		m	Parameter	Depth of cylindrical part of cage
D_{tot}		m	Parameter	Total depth of cage
i_{max}			Parameter	Number of cells in x direction
j_{max}			Parameter	Number of cells in y direction
k_{max}			Parameter	Number of cells in z direction
k_{max}	0.1	m^2s^{-1}	Parameter	Diffusitivity constant
k_{ref}	1.2×10^{-4}		Parameter	k value for reference pellet diameter
k_{T_s}	1		Parameter	Parameter for maximum feed intake rate
m_{max}	7		Parameter	Number of fish size groups
N			State variable	Total number of fish
N_m			State variable	Number of fish in group m
P_s	3-12	mm	Parameter	Feed pellet diameter
$P_{s,ref}$	6	mm	Parameter	Reference feed pellet diameter
P_w	0.22	g	Parameter	Weight per feed pellet
R		m	Parameter	Radius of cage
T		$^{\circ}C$	Disturbance	Water temperature
T_h	12	s	Parameter	Handling time per pellet
Θ	0.2		Parameter	Calibration factor for k
U	1	BLs^{-1}	Parameter	Swimming velocity of fish
u_v	0.1	ms^{-1}	Parameter	Sinking velocity of pellets
V_m		g	State variable	Stomach content of fish in group m
W_m		g	State variable	Average weight of fish in group m

3.3 Expanding the Initial Model

This part of the model description comprises of the subsea feeder model, which is implemented into the initial model. Remaining model steps such as pellet transportation, cage discretization, feed intake, and fish representation, will be identical for both spreaders.

3.3.1 Modeling the Feed Input from the Subsea Feeder

The subsea feeder that the author has become the most familiar with is the AKVA Subsea Feeder [3, 5]. This system is therefore used as an example to define a feed distribution pattern below the surface. The main information used as a reference from the Akva Subsea

Feeder is presented in Table 3.2.

Table 3.2: Akva Subsea Feeder Main Parameters [5]

Feeding depth	7-8 m
Number of outlets	12
Circumference of bottom ring	17 m
Radius of bottom ring	2.7 m

It is desirable to make the model as generic as possible. In this case, this is done by letting the cage depth, cage radius, feeding depth, number of feeding nozzles and the circumference of the bottom ring be changeable. The shape of the distribution pattern is not changeable and will stay ring shaped for both spreaders. Other parameters can also be changed, but these are not explicitly targeting the design of the marine structure and will, therefore, be mentioned later in Chapter 4.

The goal with the subsea feed distribution model is to determine the feed concentration in each cell (i,j,k) at the depth where feed is deployed. This is done by first creating a 2D cell array, which covers the horizontal area of the entire model, meaning the x,y-plane as illustrated in 3.4. The next step is to find the coordinates of the subsea feeder outlets, which are located along the bottom ring of the subsea feeder. It is realistic to assume that a uniform feed distribution is wanted, meaning evenly placed feed outlets.

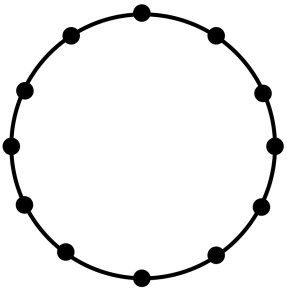


Figure 3.5: Subsea feeder bottom ring outlet distribution

All outlets are spread along the bottom ring with the angle interval:

$$\theta(i) = \frac{2\pi}{\text{Number of outlets}} \cdot i$$

Where $i \in 1, ..., i_{max}$ represent the total number of outlets and θ is the angle between the line from the centre of the circle to the point and the x-axis, see Figure 3.6. The outlet coordinates can be found by using the cylindrical coordinate system [90]:

$$x = x_0 + r\cos\theta \tag{3.23}$$

$$y = y_0 + r\sin\theta \tag{3.24}$$

Where x_0 and y_0 are the coordinates of the subsea feeder center point that coincides with the center of the fish cage. r is the radius of the bottom ring of the subsea feeder.

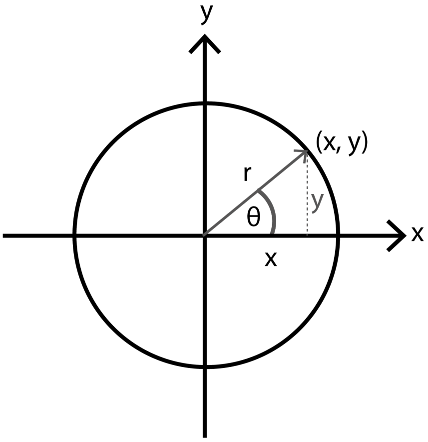


Figure 3.6: Circle Coordinates [26]

When the outlet coordinates are established, the values for x and y are rounded up to find their corresponding cells in the 2D cell array covering the feeding plane. This step might introduce some error to the exact location of the feeding outlet. The cells assigned to the outlet coordinates are then given a normalized concentration value, meaning that the total concentration for all cells shall be equal to 1 (See Figure 3.7).

$$\text{Concentration} = \frac{1}{\text{Number of outlets}} \tag{3.25}$$

The cells containing the normalized concentration is then implemented into the global cubic array, which covers the complete 3D model. By doing this, the feeding depth can be decided manually and the actual amount of feed in the cage can be set by multiplying the feed concentration in the feeding layer with the actual dosage.

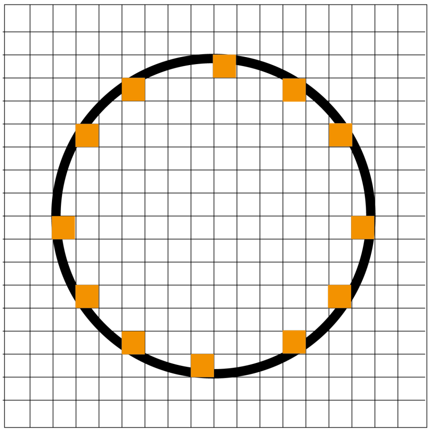


Figure 3.7: Subsea feeding plane containing cells with feed concentration

3.4 Establishing the Current Profiles

Choosing a suitable location for a fish farm is a comprehensive process. Environmental considerations are crucial and of particular interest are the current conditions along the water column [31]. In a feeding situation it is of great importance to the operators to see how the water currents affect the pellet distribution. Fish farms that are more exposed to stronger surface currents can be more difficult to feed. Operators find it difficult to tell how fast the pellets are leaving the cage due to drift. Additionally, it is hard to tell from looking at monitoring devices if the fish population is able to eat when currents are strong. The time it takes for the fish to detect and eat the pellets might become too short, and feed will be lost to the surroundings. Another drawback is that strong water currents can cause the fish to become stressed, which again reduces fish welfare [53].

In the initial model only calm weather conditions are considered. However, to simulate the scenario where surface currents are somewhat stronger, which is a common situation for fish farmers, three different current profiles have been established. The current profiles are based on the findings of Yosef Ashkenazy published in 2017 on wind-induced currents and information given to the author by Morten Omholt Alver, see Figure 3.8[15, 9]. Yosef Ashkenazy discovered that the wind's variability on deep ocean currents cause the water currents to decrease linearly with depth (z) and only vanishes at the seabed. The surface current velocity depends therefore linearly on the ocean depth [15]. Since fish farm locations are required to have a certain current velocity requirement above the seabed, the current profiles are given a linear part and an uniform part [31, 60]. The current velocity is only studied in the x-direction (horizontally) and will decrease with the depth of the cage. The current velocities are considered to be stationary, meaning that the current velocity at each water layer will stay constant with time. In addition, it can be realistic to assume that the current velocity is halved from the surface to the bottom of the cylindrical part of the net, but this can vary a lot between farming locations [9].

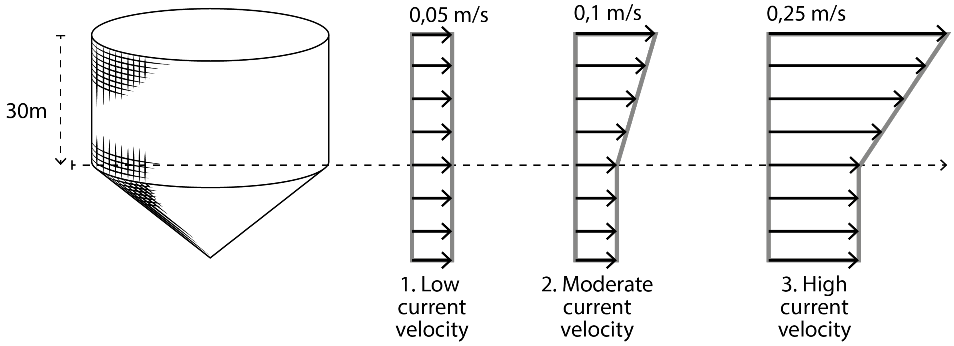


Figure 3.8: Current Profiles

The profile to the left in Figure 3.8 represents a uniform current profile (1) where the current velocity along the water column stays constant at 0.05 m/s. The profile in the middle represent a simplified moderate current profile (2). Here the surface current is set to 0.1 m/s. It decreases linearly down to the bottom of the cylindrical part of the cage. From there on it stays constant with a value of 0.05 m/s. The last current profile, pictured on the right, indicates a case with a stronger surface current (3). It is made in the same way as the moderate current profile, except that the surface current velocity is higher with a value of 0.25 m/s. After it reaches the bottom of the cylindrical part of the net, the current velocity stays constant at 0.125 m/s. The approach for calculating the decreasing current velocity for the different current profiles until they reach the bottom of the cylindrical part of the net is as follows:

$$\begin{aligned}
\text{Uniform current velocity} &= 0.05 \text{ m/s} \\
\text{Linear decreasing moderate current velocity} &= 0.1 - \left(\frac{0.05}{\text{Depth of cage cylinder}+1}\right) \cdot k \cdot dz \\
\text{Linear decreasing high current velocity} &= 0.25 - \left(\frac{0.125}{\text{Depth of cage cylinder}+1}\right) \cdot k \cdot dz
\end{aligned}$$

Where *k* represents the water level and *dz* the model resolution in the vertical direction. One extra layer is added to the depth of the cylindrical part of the cage so that the pellets can diffuse past the bottom of it.

3.5 Model Uncertainties

The initial feed distribution model containing the two feed spreader models have several underlying assumptions that are important to keep in mind.

3.5.1 Surface Spreader Distribution Model

It is fairly easy to predict the spreading of pellets, but the behaviour of fish on the other hand, is a more complicated task. The most obvious simplification done regarding the behavioural characteristics of fish is that their motion and location are not expressed explicitly. They are assumed to distribute themselves according to the pellet dispersal. This means that the modeled fish have no preferences for certain parts along the water column. However, locating the position of fish can introduce a number of new uncertain parameters if included in the model and is said to not improve the model's predictive power [10]. Another limitation to the representation of the fish is the population itself. The modeled population is only an approximation of a realistic normal distribution with regard to weight, stomach content and number of fish in each group. Modelling more sets of sub-individuals with smaller deviations might increase the accuracy of the model.

One uncertainty that stands out in the model is that the fish appetite solely depends on their stomach fullness. Realistically, the appetite of fish is dependent on several parameters that are not included in the model. However, the appetite is not seen as a limitation in the model. Oxygen levels, light intensities and feeding history are some of these factors. Different light intensities occur throughout the day, but changes also with depth. Since salmon are visual predators, their feeding behaviour is strongly influenced by the light intensity. The model does not take light intensities into account, but it is possible to implement it if desired.

Another parameter that can be important to the behavioural characteristics of fish is the previous feeding history. If the fish were fed a long time ago, their appetite can be high, and if they were fed a short while back, their response might be low. The model resets the appetite with every simulation to always see the response of hungry fish. This can introduce some error in the results if multiple meals are intended. Feed intake rates and feed wastage rates will vary depending how the feeding regime is set up. For instance, younger fish are fed multiple times a day and fish closer to slaughter weight will normally be fed only once during the day. Additionally, operators claim to have observed that if the fish get multiple meals a day, their interest in pellets can decrease with each meal [53]. In other words, their response time might increase with this type of feeding regime. The model can be adapted to fit a feeding regime that allows multiple meals, but this is not done in this study.

Oxygen levels also affect the feeding behaviour of fish, see section 2.3.3. If the DO levels can be implemented in the model, it could improve the modeled behavioural characteristics of fish. However, DO levels are dependent on water currents, which means that the level of detail regarding water currents needs to be higher as well. The initial model assumes calm weather conditions. This means that the rotor spreader is stable at the surface and is not affected by waves, strong winds or strong currents (>0.5-0.8 m/s [60]). Basically, the water currents are assumed to be invariant with depth, ranging from 0.03-0.20 m/s, which defines the acceptable current velocities at a fish farm [10].

After adjusting the model to fit both spreader types, alterations are made to the water current velocity assumption. For the three current profiles, only one indicates that the current velocity is invariant with depth, see Figure 3.8 (1). The other two decrease linearly to the bottom of the cylindrical part of the cage and stay constant after that. The modeled water currents work in the horizontal direction only and are assumed to provide sufficient oxygen supply to the fish in the model. These wind-induced inspired current profiles are not based on collected current data from a farming location and are therefore set on assumption to demonstrate different surface water current scenarios. This part of the model will need realistic current profiles based on individual farming locations to make the complete model more accurate for the location in question.

The model does not reflect how the distribution pattern is affected by various wind velocities. The experimental data used to compare the results from the simulation, was collected during calm weather conditions [62]. The wind effect was intentionally excluded from the model as it can introduce a certain amount of inaccuracy to the pellet distribution pattern if wind velocities are high. The model can be corrected to include wind effects by adding a bias to the surface spread pattern. It is recommended to compare this solution to experimental data that contains both wind conditions and the horizontal distribution to ensure its accuracy [11].

According to the previous studies the advection effects, which express the movement of pellets between cells due to water currents, has not been validated. This might represent some uncertainty in terms of the general performance of the model. The detailed description of the advection term can be found in Alver et al. from 2016 [11]. It is assumed that the pellets are given a bias in movement velocity equal to the current velocity when affected by water currents. Since pellets are relatively small in weight and volume, this seems like a realistic assumption. Furthermore, if water currents were to vary rapidly, there may be transient deviations in the effect the current has on the pellet velocity. However, it is not considered to be an important contribution factor.

The feed concentration within a cell is dependent on the local rate of change. This is given by the sum of the transports into the cell minus the transports out of the cell, in addition to the feed eaten by the fish. The feed inside each cell is also assumed to be uniformly distributed, which in reality might not be the case. When feed drift outside the cage, it is immediately assumed that it disappears. This introduces some error, which is reduced by adding more more layers of cells outside the modeled cage.

If more parameters, like the ones mentioned above, are correctly implemented in the model, it could improve the model's response to changes in the feeding regime or to different geographical locations. It is important to mention that all parameters that influence a feeding scenario and the behaviour of fish can be different for each farming location, meaning that the model would need local data to be as accurate for a given location as possible.

3.5.2 Subsea Feeder Distribution Model

The initial model, which only used to consider a surface rotor spreader, has various simplifications that applies to the subsea feeder model as well. The only exception is the wind effect on the surface distribution pattern since the subsea feed dispersal will not be influenced directly by wind forces. All behavioural characteristics of fish and the current profiles are also a part of the uncertainties in the subsea model.

There is one simplification in particular that must be mentioned because it introduces a certain amount of error to the underwater distribution pattern. The Akva Subsea Feeder from AKVAgroup on which the model is based, see section 2.10, is designed to distribute the pellets at a certain angle and with a specific velocity.

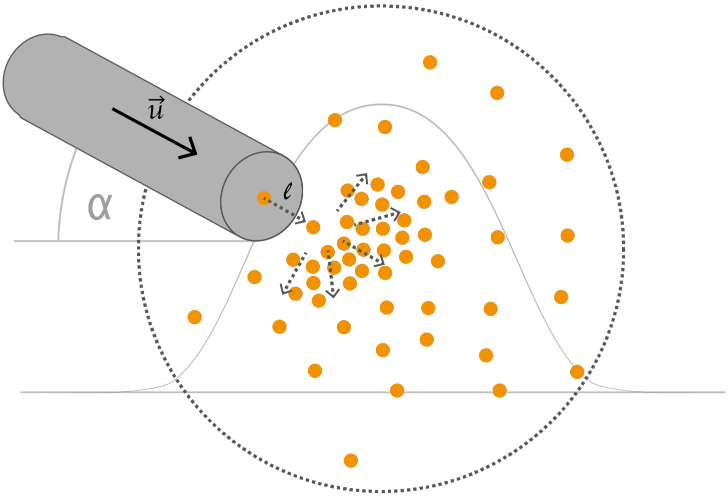


Figure 3.9: Actual pellet distribution at the subsea feeder outlet

Figure 3.9 illustrates how the actual pellet distribution will look like. Pellets leaving the outlets will be slowed down due to the mass of water on the outside of the spreader structure. In reality, this means that the distribution of pellets actually starts at a distance l from the spreader outlet with a certain angle α, and at t = 0 the pellet will have a velocity u. It is a realistic assumption that the dispersal of pellets will resemble a normal distribution, but it is difficult to assume the area the distribution will cover. If the dispersal area is as big as a cell than it needs to be considered in the simulation. To identify the scope of this distribution area it would be necessary to collect experimental data.

The model does not take the actual feeding distribution at the outlet into account and assumes that the pellets will suddenly appear at a determined water layer at given coordinates. Pellets will fall perpendicular to the subsea bottom ring as illustrated in Figure 3.10. The velocity of pellets at the outlet is ignored, and the only factors influencing the pellets motion after it theoretically leaves the nozzle comprises of gravity and current velocities. The actual feed distribution, on the other hand, would look something like Figure 3.11.

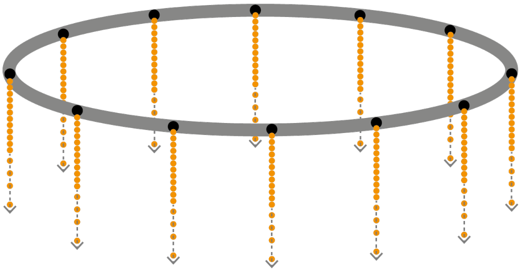


Figure 3.10: Modeled subsea feed distribution at the beginning of each simulation

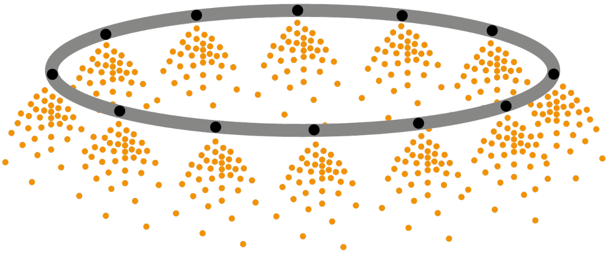


Figure 3.11: Actual subsea feed distribution

Diffusion and advection is also a part of the subsea model. The model also assumes that the subsea feeder is operating during calm weather conditions, but in reality the subsea feeder will be exposed to stronger environmental forces. This can cause the spreader to rotate about the x and y axis [36]. The motion of the subsea structure can have a large impact on the underwater distribution pattern. It introduces therefore a significant uncertainty to the results because most fish farms along the Norwegian coast are prone to more extreme weather conditions.

The last uncertainty worth mentioning is how the outlet coordinates are set up. Since the coordinates have to be rounded up to fit into the model grid, it might introduce an error to where exactly the feed is deployed. However, this error is considered small and is therefore not taken into account. Also, it is not a certainty that all subsea outlets release the same amount of feed. Experiments and tests are needed to verify if this is indeed the case.

Chapter 4

Feed Waste Simulation

This chapter covers the feed waste simulations for both the surface rotor spreader and the subsea feeder with their accompanying results. First, all parameters that can be altered in the model with their corresponding range will be presented. A selection of those parameters is chosen for further analysis. The remaining parameters will stay constant throughout the simulations. A specific feeding regime given by the fish farming company Nordlaks Oppdrett AS is presented as a basis for the comparison. Three current profile cases will be tested for all the design parameters. The behavioural parameter FD_{thresh}, which represents the fish density threshold, is only tested for the case with a uniform and low current velocity. Changing this value will show how sensitive the fish is to crowding, which affects their ability to catch pellets. Also, this value connects the feed waste calculation with the behavioural part of the model.

4.1 Model Parameters

All model parameters are within a given range. How the range is determined can depend on industry standards, production goals, and biological and environmental factors. The parameters presented in Tables 4.1-4.3 below are changeable in the model. The surface spreader design parameters can also be altered, but they stay constant throughout the parameter study and are not presented.

Table 4.1: Simulation Parameter Options: Subsea Spreader and Fish Cage

Parameters	Subsea feeding depth	Subsea radius	Number of Outlets	Cage radius	Cage depth
Min	7 m	2,7 m	1	9,5 m	10 m
Max	15 m	12,5 m	30	25 m	50 m

The AKVA Subsea Feeder depth is set to be equal to 7 m and to test how the subsea feeding depth can influence feed waste, an arbitrary maximum feeding depth of 15 m is set [3]. The bottom ring radius of the AKVA subsea feeder is as presented in Table 3.2 equal to 2.7 m, which is chosen to be the minimum value for the bottom ring radius range. The maximum radius is set equal to half of the largest fish cage radius currently used in fish farm production in Norway, which is approximately 25 m. Thus, the arbitrarily chosen maximum value for the bottom ring radius becomes 12.5 m. The spreader must have at least one outlet, and the random value of 30 outlet points is set as the upper limit. The fish cage radius and depth range are dependent on the industry standards [55].

Table 4.2: Simulation Parameter Options: Environmental and Biological

Parameters	Current velocities	Temperature	Number of Fish	Fish weight	Weight deviation	FD_{tresh}
Min	0.05 m/s	2 $^{\circ}C$	0	100 g	0 g	25 kg/m^3
Max	0.25 m/s	17 $^{\circ}C$	200000	6000 g	300 g	75 kg/m^3

Water current velocity limits are collected from the Norwegian Standard NS9415 [60]. Temperature values are based on findings in Oppdal et al. (2010), where the fish were observed to avoid areas with a higher temperature than 17°C [69]. Operators at Nordlaks Oppdrett AS state that feeding should be done with caution when the temperature gets below 2°C [53]. The fish number range is set according to the Aquaculture law [55]. Fish weights are based on data published by Havforskningsinstituttet, in addition to talking to representatives at Nordlaks Oppdrett AS [35, 53]. Weight deviations are set based on experimental data [9]. The lower limit of FD_{thresh} is set based on fish welfare criteria and the upper limit was chosen to be 75 kg/m^3 after speaking with Morten Omholt Alver [9].

Table 4.3: Simulation Parameter Options: Feeding Regime and Model Grid Configurations

Parameters	Pellet size	Feed dosage	Simulation time	dxy	dz
Min	3 mm	3 kg/min	20 min	0.5 m	0.5 m
Max	12 mm	50 kg/min	240 min	1 m	1 m

Pellet sizes can be as big as 25 mm in diameter, but this thesis only operates with the sizes 3 mm, 9 mm and 12 mm [11]. The feed dose range is set based on the maximum capacity of the subsea spreader, which is at 50 kg/min. According to the product specifications of the AKVA Rotor Surface Feeder, the minimum dose needed for the system to work is 3 kg/min, but this is dependent on the feed pipe length [2]. Similar information for the subsea feeder was not found, and the minimum dose for the surface feeder was used as the lower dosage limit. Simulations can go on for as long as the user desires, but normally a meal can last from 20-240 min depending on the hunger level of the fish population [53]. The last two columns in Table 4.3 defines the model resolution. Cells of 1 m^3 are said to be large so to improve the model accuracy one can reduce the cell sizes. In this case, a lower limit of 0.5 m is suggested, but it will increase computation time [9].

4.2 Simulation Parameter Selection

To limit the data set, only a few parameters from Table 4.1 to 4.3 are chosen for further investigation. Parameters that stay constant and the ones used for further investigation are presented in the tables below.

Table 4.4: Investigated Model Parameters

Simulation Parameters Used	Unit
Subsea feeding depth	m
Subsea bottom ring radius	m
Local fish density threshold FD_{thresh}	kg/m^3

Table 4.5: Constant Model Parameters

Constant Parameters	Unit
Pellet size	mm
Feed dosage	g/s
Temperature	°C
Weight deviation	g
Number of fish	[-]
Fish weight	g
Cage depth	m
Cage radius	m
Subsea outlets	[-]
Resolution (dxy,dz)	m
Simulation time	s

Two of the subsea feeder design parameters are chosen for the parameter study because it is desirable to examine how the characteristics of the structure influence feed waste. Figure 4.1 depict the design parameters that will be investigated in the following simulations.

The fish density threshold FD_{thresh} is a part of the selection as well because it is important to demonstrate how the behavioural part of the model influences the feed waste results.

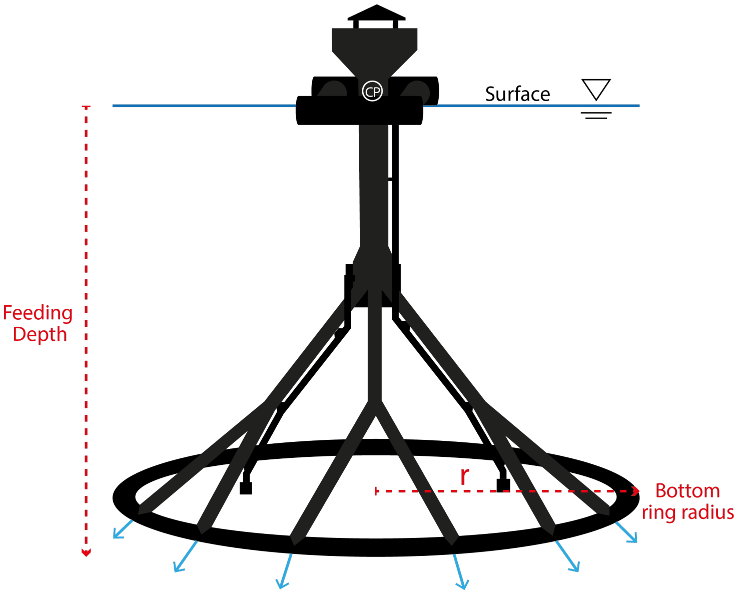


Figure 4.1: Illustration of investigated subsea feeder design parameters

4.3 Realistic Feeding Regime

To have a starting point and a base for the feeding technology comparison, a realistic feeding regime has been developed in collaboration with feed operators at Nordlaks Oppdrett AS. The realistic feeding regime is referred to as the realistic feeding scenario (RFS) further on in this thesis.

It is important to mention that the simulated cage comprises of two parts as mentioned in 3.2.1. The cylindrical part is set to 30 m, and the conical part is equal to 15 m. The chosen depth was agreed upon with the operators from Nordlaks Oppdrett AS [53].

The model grid stays the same for all simulations with *dxy* and *dz* both equal 1 m. The value of the last parameter FD_{thresh} determines how sensitive the fish population is to crowding. If the density of fish gets too high, their appetite is decreased. However, to the author's knowledge, no published documentation states what this crowding limit is and thus, the arbitrary value of 75 kg/m^3 is set.

Table 4.6: Investigated Model Parameters

Simulation Parameters Used	Value
Subsea feeding depth	7 m
Subsea bottom ring radius	2,7 m
Local fish density thr. FD_{thresh}	75 kg/m^3

Table 4.7: Constant Model Parameters

Constant Parameters	Value
Pellet size	9 mm
Feed dosage	300 g/s
Temperature	14 °C
Weight deviation	300 g
Number of fish	150 000
Fish weight	1500 g
Cage depth	45 m
Cage radius	25 m
Subsea outlets	12
Resolution (dxy,dz)	1 m
Simulation time	3600 s

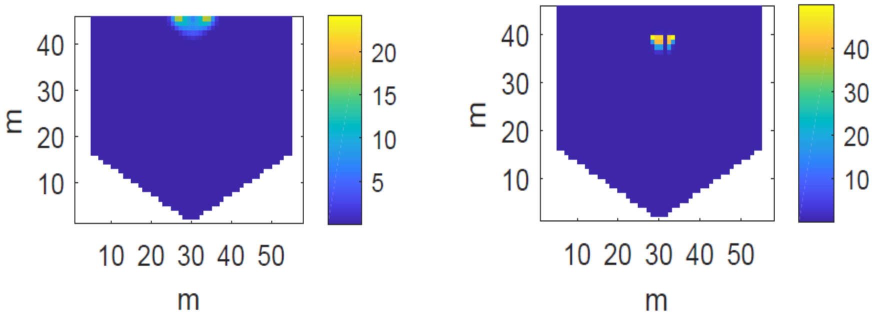
The realistic feeding regime presented above is simulated for all three current profiles, which give the following results:

Table 4.8: Feed waste results from the realistic feeding scenario (RFS) with various current profiles

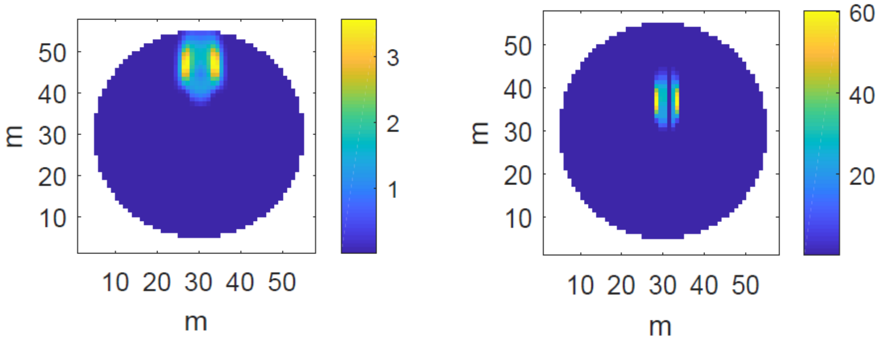
Simulation	1	2	3
Current Profile	uniform	linear decreasing	linear decreasing
Current Velocity	low	moderate	high
Feed waste from surface spreader (%)	1.28	1.22	1.12
Feed waste from subsea feeder (%)	2.93	2.77	4.1

The simulations in Table 4.8 show the feed waste percentage for each current profile case for both spreaders. The results indicate that the surface rotor spreader produces the least feed waste for all three current profiles. The lowest feed waste occurs in the last simulation, where the feed waste percentage is 1.12%. By increasing the current velocity, the feed waste is reduced for the surface spreader. The subsea feeder, on the other hand, produces less feed waste from simulation 1 to 2, but rises again in the last simulation.

One might expect that the feed waste from the surface spreader would increase with a rise in surface current velocity because of the reduced pellet travel distance to the cage walls, but this is not necessarily the case. If the feed distribution is sufficiently modeled and its dispersal area is small compared to the fish cage dimensions, then increasing the current velocity need not cause more feed spills, but can rather help spread the feed even better, which can increase fish feed ingestion. In this case, it means that the value of the local fish density-dependent variable ρ is increased in the model, creating a rise in w_{fm}, see equation 3.11 and 3.21. However, by looking at the static simulation plots in Figure 4.2, which illustrate the feed dispersal for both spreaders at time step equal 3600s, it can be questioned whether the feed waste results are realistic.



(a) Vertical simulation plot of the surface feeder (b) Vertical simulation plot of the subsea feeder

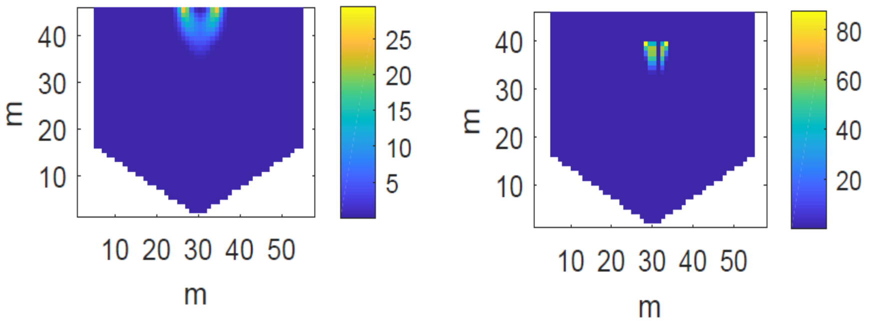


(c) Horizontal simulation plot of the surface feeder (d) Horizontal simulation plot of the subsea feeder

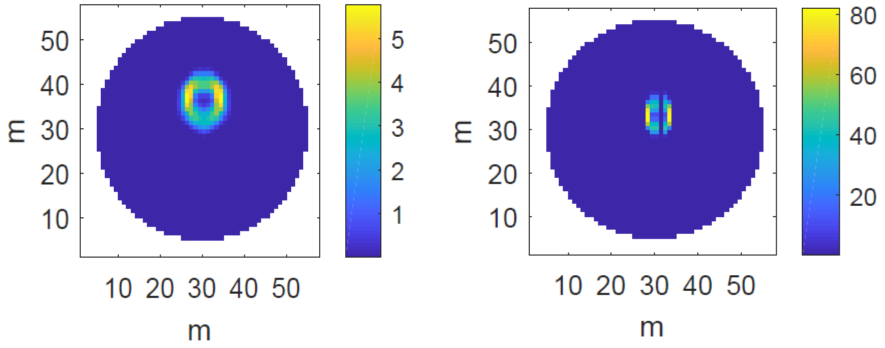
Figure 4.2: Simulation plot of the realistic feeding scenario at t = 3600s with high current velocity where the color bar represents the feed concentration in grams/cell

Based on what is visible in the plots (a,b,c,d) in Figure 4.2, it looks like the feed deployed by the surface spreader in plot (c) almost reaches the outskirts of the fish cage when the surface current velocity is high. One might think that this would mean that more feed is lost to the surroundings. The same plot does, however, indicate low feed concentration values by examining the color bar, which displays the concentration of feed in grams/cell. Yellow means the highest density recorded. By comparing the pellet concentration (grams/cell) in the images belonging to the surface spreader to the left (a,c) with the plots belonging to the subsea feeder to the right (b,d), it is evident that the subsea feeder deploys feed that is significantly more locally concentrated. This may be a reason why the feed waste from the subsea feeder is higher in this case, and also higher in the other simulations compared to the surface feeder. Cells that have a high feed density means that the local density-dependent ρ value in the model is closer to 0, decreasing the feed ingestion in w_{fm} (see equation 3.11). More pellets will then fall by the fish and sink to the seabed. This is a realistic scenario because high fish density acts as a stressor and influences the appetite of fish [85].

Another reason for the high feed waste percentages for the subsea feeder, is because the feed is deployed deeper in the cage. Pellets are given a shorter traveling time due to their reduced distance to the cage bottom.



(a) Vertical simulation plot of the surface feeder (b) Vertical simulation plot of the subsea feeder



(c) Horizontal simulation plot of the surface feeder (d) Horizontal simulation plot of the subsea feeder

Figure 4.3: Simulation plot of the realistic feeding scenario at t = 3600s with moderate current velocity where the color bar represents the feed concentration in grams/cell

The reduction in feed waste in the second simulation observed in Table 4.8 for the subsea feeder is unclear, see Plot 4.3 (b and d). It might be due to the same reason as for the decrease in feed waste from the surface feeder, where slightly higher current velocities cause a better feed dispersal, and thus, increasing the feed intake. However, claiming this is contradicting the likely reason why the feed waste is increased in the last simulation when looking at the plot 4.2 (b and d). There, the feed is said to be more locally concentrated, causing a reduction in feed intake and a rise in feed waste. The moderate current plot (4.3), however, display an even higher local concentration of feed than for the high current velocity case when examining the color bar in (b) and (d). Based on these observations, it is a chance that this part of the model contains an error.

The simulation plot for the low current velocity case at t = 3600s is depicted in Appendix A, Figure A.1, in addition to the development of feed waste and feed ingestion over time for the realistic feeding regime with all the different current profile cases, see Appendix B. The graphs that show the feed ingestion and feed waste development over time confirm the assumption that the local ρ value is higher for the subsea feeder in comparison to the surface feeder, see Figure C.1 and Figure C.2. It takes more time for the feed ingestion to stabilize during the subsea feeder simulations than for the surface feeder simulations.

4.4 Current Profile Cases

The two subsea spreader design parameters from the investigated model parameters list in Section 4.2 are simulated three times with values that are representative for their range and unequal to the same parameter in the realistic feeding scenario (RFS) presented in Section 4.3. For every simulation, all other parameters except the one being tested, stay unchanged. Each parameter simulation set is run for the different current profile cases; low, moderate and high current velocity. The creation of these current profiles is explained in Section 3.4.

The low current velocity case is pictured in Figure 3.8, see (1). This case is testing what percentage of feed waste occurs when a constant current velocity of 0.05 m/s along the water column is used.

The moderate current velocity case is pictured in Figure 3.8, see (2). This case investigates what percentage of feed waste occurs when a surface velocity of 0.1 m/s gradually decreases with depth until it reaches the bottom of the cylindrical part of the net. From there on it stays constant at 0.05 m/s.

The high current velocity case is pictured in Figure 3.8, see (3). This case investigates what percentage of feed waste occurs when a surface velocity of 0.25 m/s gradually decreases with depth until it reaches the bottom of the cylindrical part of the net. From there on it stays constant at 0.125 m/s.

The local fish density FD_{thresh} is only simulated with two other values for the uniform profile current case with low current velocity to illustrate the effect of this parameter on the feed waste outcome.

4.5 Simulation Results

4.5.1 Subsea Feeding Depth

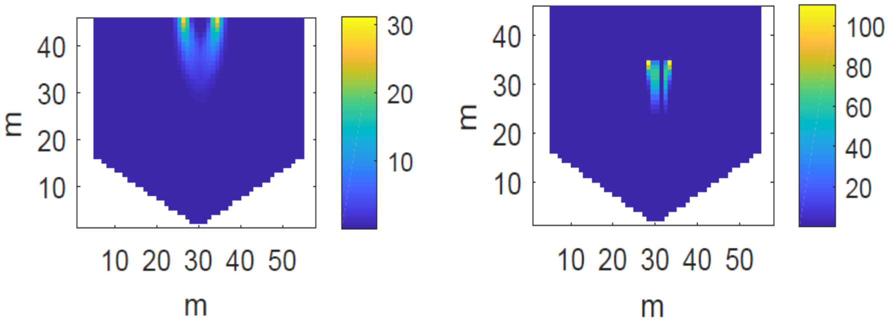
Table 4.9: Feed waste results gained from simulating the realistic feeding scenario (RFS) with various subsea feeding depths

Current Profiles	uniform				linear decreasing				linear decreasing			
Current Velocity	low				moderate				high			
Simulation	RFS	1	2	3	RFS	1	2	3	RFS	1	2	3
Subsea Feeding Depth [m]	7	10	12	15	7	10	12	15	7	10	12	15
Feed Waste Surface (%)	1.28	1.28	1.28	1.28	1.22	1.22	1.22	1.22	1.12	1.12	1.12	1.12
Feed Waste Subsea (%)	2.93	3.23	3.55	4.39	2.77	3.08	3.39	4.28	4.1	3.75	3.77	4.72

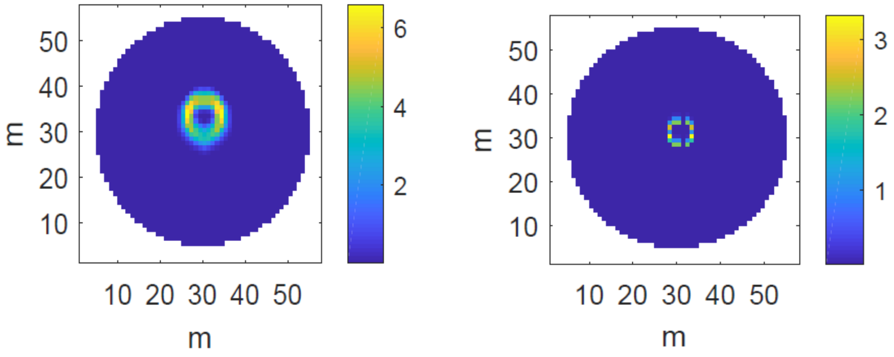
The simulations in Table 4.9 show how the feed waste from the subsea feeder changes with various feeding depths. The feed waste results from the surface feeder stays the same as in the realistic feeding scenario (RFS) because no changes are made to its setup, see Table 4.8.

The first thing one can see from the table above is that all subsea feeder simulations for the first two cases (low and moderate current velocity) give higher feed waste outcomes compared to the realistic feeding scenario (RFS). The last current profile case (high current velocity) show that the feed waste from the realistic feeding scenario (RFS) lies between the results from the 10 m and 15 m simulations. General for all simulations done for the subsea feeding depth parameter, is that feed spills are increased when the pellets are deployed deeper in the cage. The reason is likely that lower feeding depths create a shorter distance from the feeder outlets to the cage bottom, and more pellets will disappear through the net.

The subsea feeder feed waste results in the first case (low current velocity) are higher than the results in the second case (moderate current velocity). By looking at the static simulation plots (t = 3600s) of the pellet distribution for these two cases with a subsea feeding depth equal to 12 m, see Figure 4.4 and 4.5, it is clear that the local feed concentration is higher for the first case when inspecting the color bar for each plot, see Figure 4.4. High feed concentration leads to lowered feed intake.



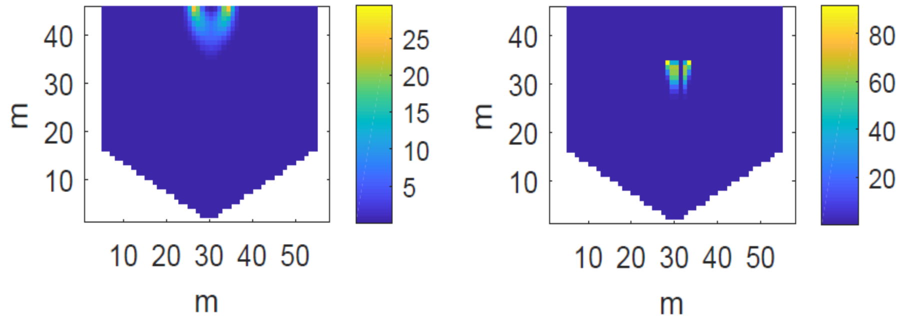
(a) Vertical simulation plot of the surface feeder (b) Vertical simulation plot of the subsea feeder



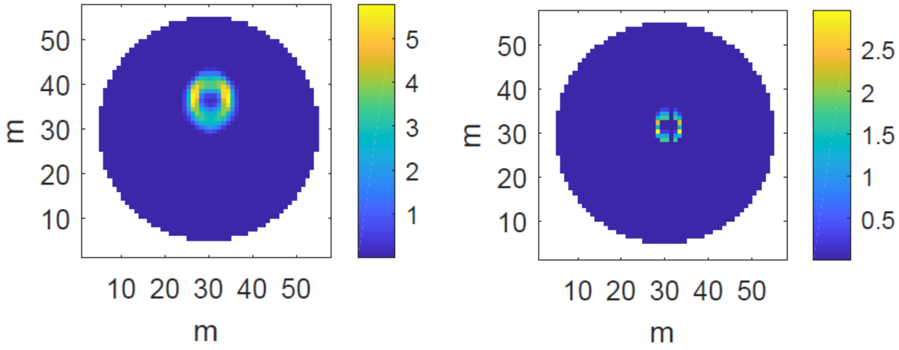
(c) Horizontal simulation plot of the surface feeder (d) Horizontal simulation plot of the subsea feeder

Figure 4.4: Simulation plot of both feed spreaders with subsea feeding depth equal to 12 m at time step t = 3600s with low current velocity. The color bar represents the feed concentration in grams/cell

From what is visible in Figure 4.4 (b,d) and 4.5 (b,d), it can seem like the increasing current velocity in the second case (moderate current velocity), see Figure 4.5, causes a rise in diffusion rates, that lower the local feed concentrations (grams/cell). This results in a feed waste reduction compared to the first case (low current velocity), see Figure 4.4. However, the same uncertainty arises here as it did for the second simulation in Table 4.8.



(a) Vertical simulation plot of the surface feeder (b) Vertical simulation plot of the subsea feeder



(c) Horizontal simulation plot of the surface feeder (d) Horizontal simulation plot of the subsea feeder

Figure 4.5: Simulation plot of both feed spreaders with subsea feeding depth equal to 12 m at time step t = 3600s with moderate current velocity. The color bar represents the feed concentration in grams/cell

Since two of the current profiles are linearly decreasing, it would mean that the deeper one feeds, the lower the current velocity. In the third case (high current velocity) in Table 4.9 it may seem like the subsea feeding depth for the first and second simulation reduces the feed waste due to the improved current velocity conditions compared to the realistic feeding scenario (RFS). Realistically, the feed waste result might be a trade-off between the distance to the cage bottom and the current velocity, as well as the feed concentration, which influences the feed intake. That is why the third simulation for the high current velocity case in Table 4.9 is higher than the realistic feeding scenario (RFS). By looking at the temporal simulation plots for the high current velocity case in Table 4.9 where the subsea feeding depth is equal 12 m (Figure 4.6) and 15 m (Figure 4.7), it looks like the feed is dispersed even better for the 15 m simulation (Figure 4.7). The assumption is based on an observation made in Figure 4.7, where the feed ingestion stabilizes within a shorter period of time compared to how the feed ingestion stabilizes for the 12 m simulation in Figure 4.6. However, it is likely that a feeding depth of 15 m will cause the pellets to reach the outskirts of the cage faster than for the 12 m simulation. It is more realistic to think that feeding at a greater depth will lead to more feed waste.

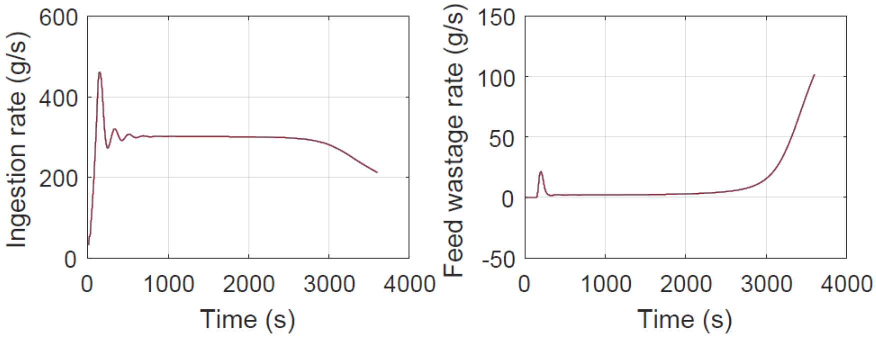


Figure 4.6: Temporal simulation plot of the subsea feeder with a feeding depth equal to 12 m and with a high current velocity

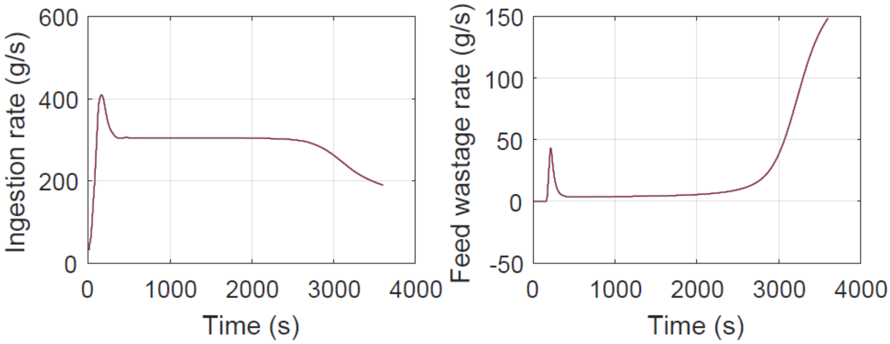


Figure 4.7: Temporal simulation plot of the subsea feeder with a feeding depth equal to 15 m and with a high current velocity

4.5.2 Subsea Bottom Ring Radius

Table 4.10: Feed waste results gained from simulating the realistic feeding scenario (RFS) with different sizes of the bottom ring radius of the subsea feeder

Current Profiles	uniform				linear decreasing				linear decreasing			
Current velocity	low				moderate				high			
Simulation	RFS	1	2	3	RFS	1	2	3	RFS	1	2	3
Bottom Ring Radius [m]	2.7	5	8	12.5	2.7	5	8	12.5	2.7	5	8	12.5
Feed Waste Surface (%)	1.28	1.28	1.28	1.28	1.22	1.22	1.22	1.22	1.12	1.12	1.12	1.12
Feed Waste Subsea (%)	2.93	2.27	2.06	2	2.77	2.1	1.88	1.81	4.1	1.99	1.66	1.59

Table 4.10 shows that increasing the subsea bottom ring radius more than 2.7 m, which is the case for the RFS, give better feeding results. Even though changing the subsea bottom ring radius improves the feed waste outcome, it does not out conquer the surface spreader results.

When examining the feed waste results in Table 4.10, it is visible that the low current velocity case displays higher feed waste values compared to the moderate current velocity case. An interesting finding is however, that the high current velocity case contains the lowest subsea feed waste percentage overall.

By expanding the subsea bottom ring radius, the feed distribution area is increased, which likely lowers the feed concentration, and thus the fish density as well. In addition, if the current velocity is increased, the feed dispersal area will be enlarged even further. This happens in every simulation for this parameter, but most of all for the third simulation in the third current velocity case, where the feed waste for the subsea feeder is lowered to 1.59%. By comparing the third simulation in the low current velocity case with the third simulation in the high current velocity case in Table 4.10, it is obvious that the fish population have a more stable feed ingestion rates when comparing their respective simulation curves in Figure 4.8 and Figure 4.9. The local fish density variable ρ is closer to 1 in this case.

It can be questioned if the feed waste outcome of 1.59% is realistic. First of all, having a subsea bottom ring radius that is 12.5 m is not an option today, but if it was, the feed would be deployed considerably close to the cage walls. Slightly higher current velocities than tested here could instead of spreading the feed to the fish farmers advantage cause even more feed waste.

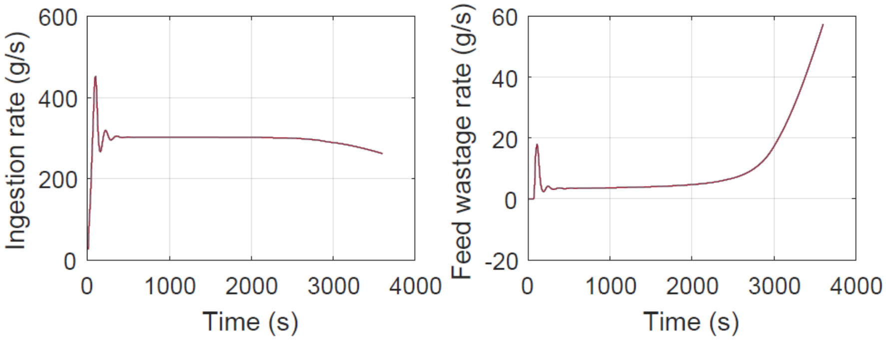


Figure 4.8: Temporal simulation plot of the subsea feeder with a bottom ring radius equal to 12.5 m and with a high current velocity

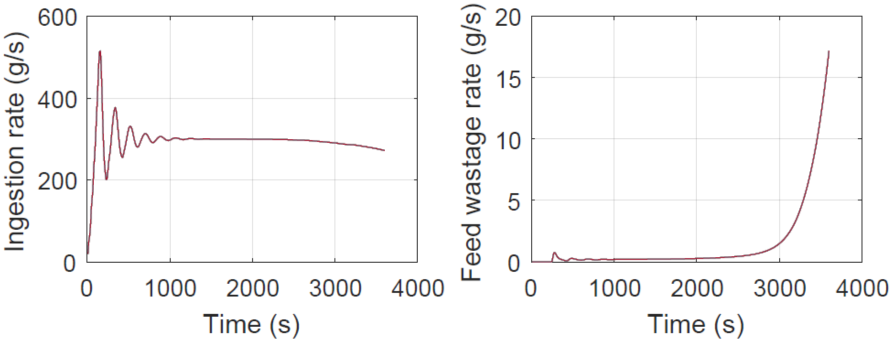


Figure 4.9: Temporal simulation plot of the subsea feeder with a bottom ring radius equal to 12.5 m and with a low current velocity

The static simulation plot of the subsea bottom ring radius equal to 12.5 m at time step 3600s, which displays the best feed waste result can be found in Appendix E.

4.5.3 Variations of FD_{thresh} with Uniform and Low Current Velocity

Table 4.11: Feed waste results with two different values of the local variable FD_{thresh} and uniform current

Simulation	1	2
Local Fish Density Threshold FD_{thresh}	25	100
Feed Waste Surface (%)	2.75	1.08
Feed Waste Subsea (%)	55.01	2.29

The realistic feeding scenario in Table 4.8 is examined for two different values of the behaviour-related parameter FD_{thresh}. This parameter determines how sensitive the fish is to crowding, meaning the fish density threshold that does not cause a reduction in appetite. The local factor ρ is dependent on FD_{thresh}, see equations 3.16 and 3.17.

The first observation that is made, is that the feed waste from the subsea feeder in the first simulation is extremely high compared to the surface spreader. By looking at the feed ingestion and feed waste curves from this simulation in Figure 4.10, it is clear that a significant share of the fish population is experiencing crowding over the given limit. This assumption is made by looking at the shape of both graphs, where the feed waste stays at an almost constant high level, and the feed ingestion rate stay around half of what can be observed for the first surface feeder simulation depicted in Figure 4.11. Additionally, the value of ρ is seemingly significantly closer to 0 due to the high feed concentration that encloses the bottom ring of the subsea feeder.

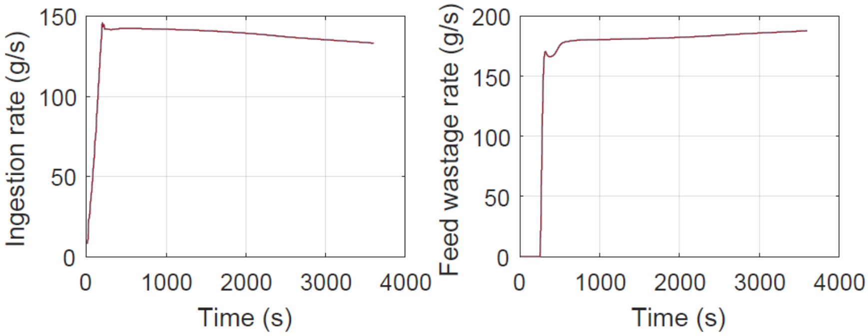


Figure 4.10: Temporal simulation plot of the subsea feeder with a fish density limit of FD_{thresh} = 25 kg/m^3 and with a low current velocity

Looking at the simulation plots in Figure 4.11 for the surface feeder, a slightly higher ρ value is likely present. The feed ingestion rate is significantly higher than the feed wastage rate, which can only be explained with a more even feed distribution. It seems like a smaller share of the fish population is exceeding the crowding threshold. This explains the low feed waste percentage for the surface spreader in the first simulation.

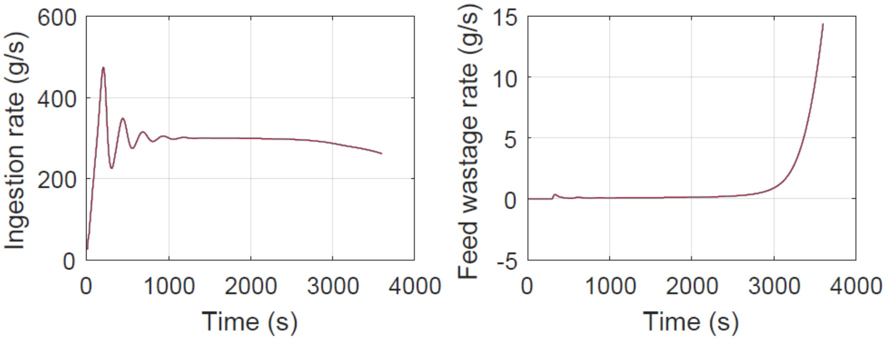


Figure 4.11: Temporal simulation plot of the surface feeder with a fish density limit of FD_{thresh} = 25 kg/m^3 and with a low current velocity

For the second simulation, an arbitrary FD_{thresh} value of 100 kg/m^3 was tested to see what happens if the threshold were to be even higher than in the realistic feeding scenario. The subsea feeder result is presented in Figure 4.12 and the surface feeder result is depicted in Figure 4.13.

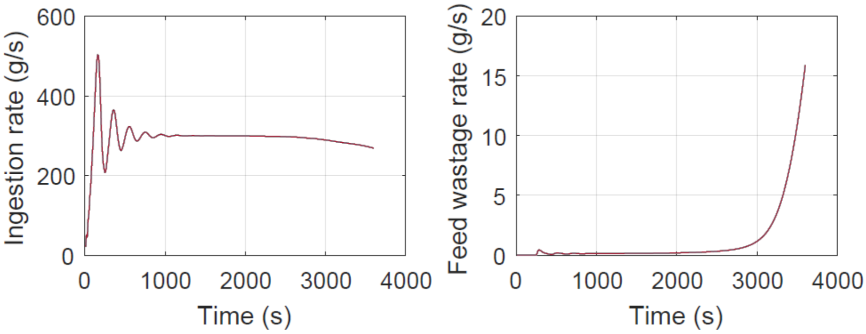


Figure 4.12: Temporal simulation plot of the subsea feeder with a fish density limit of FD_{thresh} = 100 kg/m^3 and with a low current velocity

The graph above is almost identical to the graph 4.11. The same observations are made here.

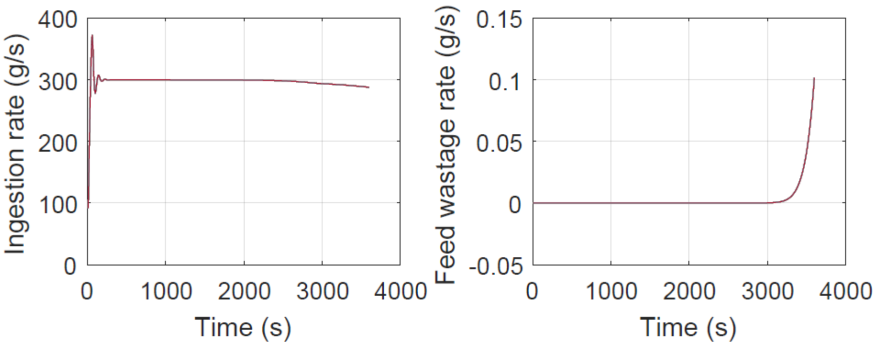


Figure 4.13: Temporal simulation plot of the surface feeder with a fish density limit of FD_{thresh} = 100 kg/m^3 and with a low current velocity

The surface feeder results depicted in Figure 4.13 illustrate how fast the feed ingestion stabilizes when the density threshold, FD_{thresh}, is increased. Basically, raising this limit means that the fish can get to the pellets faster than before. Increasing this value too much might create an unrealistic representation of the actual situation.

Chapter 5

Discussion

The following chapter discusses the results gained from the parameter study conducted in chapter 4 and implements them in an overall context. The second part of this chapter covers the reliability of the model, as well as the potential sources of error.

5.1 Parameter Study

The parameter study performed in this thesis aims to show which feeding technology provides the lowest emission of feed for different current profiles. Three parameters have been examined: the feeding depth and bottom radius of the subsea feeder, and finally the behaviour-related fish density threshold FD_{thresh}. All parameters remained the same as in the realistic feeding scenario, except the ones being tested. The design parameters were investigated for all three current profiles, while FD_{thresh} was only tested for the case with a uniform current profile.

5.1.1 Subsea Feeding Depth

Subsea feeder

To summarize the findings from the investigation of the varying feeding depths, it can be said that feeding fish deeper than 7 m will most likely cause more feed waste compared to surface feeding. By looking at the difference in feed waste percentage between the various current profiles, a decrease in feed waste from the subsea feeder is observed for the case with moderate current velocity compared to the other two cases. The same situation is observed in the realistic feeding scenario. An explanation is assumed to be that the current velocity helps spread the feed over a larger area. The fish distribution assumption in the model then allows for more fish to eat the pellets faster. Realistically, such a scenario can occur if the current velocity is not too strong and if the feed distribution area does not exceed the cage dimensions. However, if the ratio between the spreading radius and the cage radius is smaller and the current is strong, then this will most likely increase feed spills. Another possibility for this outcome is that the model contains an error.

A reduction in feed waste was observed for the subsea feeder during the case with the linear decreasing strong surface current. The results indicate that the feed spill is reduced with a feeding depth of 10 m and 12 m compared to the realistic feeding scenario where the feeding depth is equal to 7 m. The results in Table 4.9 were 3,75%, 3,77% and 4,1% respectively. For the other current cases, the realistic feeding scenario had the better results. It is realistic to assume that this situation can occur because the higher up the feed is deployed, the stronger the current. Based on this, one might think that the lower you feed, the feed waste should be reduced. Feeding closer to the bottom of the cage would mean a shorter traveling time for the pellets in the cage. This theory is confirmed in the observation made for the feeding depth of 15 m, which gave 4,75% feed waste. Thus, finding the optimal combination of depth and current velocity is desirable, but the environment is unpredictable and inconsistent, which makes it difficult to achieve.

It is challenging to know how far down one can actually feed regarding the preferences and behaviour pattern of fish. Salmon has different patterns of behaviour for each season. Some of these may be more beneficial for the subsea feeder compared to the surface spreader. During times with unfavorable temperatures, meaning above 17°C or below 2°, the fish tend to swim lower in the cage. Outside of these periods, fish might swim higher, benefiting the surface spreader [51].

In reality, feeding far down in the cage might be disadvantageous as this can lead to poor utilization of the cage volume, shorter residence time for pellets in the cage, and that the fish does not detect the feed because the majority of the population is elsewhere in the cage. However, it can be assumed that, if the season triggers the right behaviour and the feeding depth causes a reduction in lice infestations, and at the same time boosts growth, subsea feeding might be more beneficial than surface feeding. Considering the environmental impact that comes from feed spills compared to unsustainable delousing treatments, one might discover that feed waste is less harmful. If the fish population is less exposed to lice, its production time at sea can be reduced, saving the fish farmer significant delousing expenses and the environment for chemical emissions due to delousing treatments, but this is only an assumtion.

Surface spreader

The feed waste results from the surface spreader simulations turned out better than for the subsea feeder in every simulation. No design parameters for the surface feeder were tested, only the current profiles made out a difference. This is seen in Table 4.8. By increasing the current velocity, the feed waste from the surface spreader was reduced. The feed dispersal is assumed to be locally concentrated to a certain extent, but on a lower level than for the subsea feeder due to its parameterised probability distribution [11]. All current velocities below 0.25 m/s in the simulations cause an increased feed dispersal area at the surface. This might be the case in real life, but if the surface current velocity increases even further, the pellets would most likely disappear before the fish could to catch them. There is a fine line to when the current velocity becomes unfavorable. The results gained from these simulations also depend heavily on the behavioural part of the model, which entails numerous uncertainties. Further experiments and simulation tests are recommended in this case to verify this hypothesis.

5.1.2 Subsea Bottom Ring Radius

The results gained from changing the bottom ring radius of the subsea feeder indicates that the larger the feed distribution area, the lower the feed waste. However, the surface spreader proved to be the best option regarding feed waste compared to the results attained with varying the subsea bottom ring radius. No variations were made to the surface spreader results and they remained unchanged from the realistic feeding scenario and the subsea feeding depth simulations.

Feed from the subsea feeder is distributed from given points in the 3D model space, which causes pellets to gather about these points, which increases the feed concentration. By looking at the pellet distribution on the surface, it is clear that the distribution setup for the surface feeder, which is based on a normal distribution of pellets, creates a lower pellet concentration. In the latter case, more cells will contain a feed concentration at the beginning of the simulation, which means that more fish can be fed at the same time due to the fish distribution assumption. By increasing the bottom ring radius and the current velocity, the pellets will get more evenly distributed because more cells will be filled with feed due to diffusion and advection to neighbouring cells. This explains the best subsea feeder result of 1.56% in Table 4.10. However, increasing the subsea bottom ring radius up to 12.5

m is currently not an option as a structure of this scale would, for instance, be difficult to handle for the outdoor operators and it would be a costly purchase compared to current systems. Also, if the current velocities were to be even higher than the maximum surface current tested in this paper, then this structure might produce significant amounts of feed waste due to its distance to the cage walls. Another challenge would be the environmental forces that would affect the movements of the structure, which could cause damage to the fish cage and other accompanying systems. The results achieved through testing of the bottom ring radius parameter are thus unrealistic to a certain extent. The main observation that one should pay attention to is, however, that the feed distribution area has a significant influence on the feed waste.

5.1.3 Local Fish Density Threshold FD_{thresh}

The fish density threshold parameter, FD_{thresh}, is an important factor in the model, but it also brings a lot of uncertainty to the feed waste results. After testing the realistic feeding scenario with different values of FD_{thresh}, it was clear that a large share of the fish population in the subsea feeder simulations experience crowding to a greater extent than they do for the surface spreader. The feed concentration is higher at the subsea feeder outlets, which according to the fish distribution assumption, increases the density of fish as well. By looking at the different feed distribution setups for both spreaders in Chapter 3, it makes this observation believable.

It is a known fact that salmon is an easily stressed species and high fish densities trigger this unwanted behaviour [85]. By increasing the fish density threshold, the model allows for fish to gain better access the feed, that will saturate them faster. A significantly high FD_{thresh} value would create a scenario where the fish would detect and eat pellets in an abnormally and unrealistically fast pace. Thus, if the fish density is chosen arbitrarily, as it is in this paper, all feed waste results cannot be trusted. To the authors knowledge no documentation exist on this topic that can define a suitable limit for the fish density threshold.

5.2 Model Reliability and Sources of Error

5.2.1 Subsea Feed Distribution Pattern

The subsea distribution pattern is represented in the model as a simplified version of reality. As mentioned in section 3.5, this introduces some error that might influence the feed waste results. To improve this part of the model, it would be necessary to know the exact water mass velocity in the subsea manifolds, which lead to the outlets. Having this information would make it possible to calculate the distribution area about each outlet, and determine if this makes out a difference in the feed ingestion or feed waste. Also, it may be beneficial to include the exit angle of the feed outlets to ensure that the pellets are distributed in the correct water layer. This paper disregards the exit velocity and angle at the subsea outlets because they are assumed to have little to no effect on the feed waste results due to the cage dimension and model resolution.

An assumption that is made in the model, which may give misleading results, is how the present water current causes the pellet movements. During the simulations, the stationary water currents are only modeled in the x-direction but vary with depth. This might create unrealistic pellet movements because more factors influence their transportation path. For instance, water currents exist in all directions, not only one, and current velocities change over time [60, 31]. Waves have an impact as well. Fish movements can create whirls in the water, causing pellets to be pushed upwards in some cases. The latter is disregarded in the model because it is assumed to make out a minimal difference in the outcome. Increasing the level of detail when it comes to what influences the pellet migration, however, can legitimate the feed waste outcome to a greater extent.

5.2.2 Environmental Forces

As mentioned in the last section, the water currents are only modeled in the x-direction in the horizontal plane and stays constant with time, but varies with depth. It is unlikely that this would be the situation at a Norwegian fish farm, and thus, the feed waste produced with the current model might deviate from reality. Including local water current data would be necessary to model a realistic current profile for a desired location.

The fish cage has a constant volume throughout the simulations, but according to full-scale tests, will an increase in current velocities between 0.13-0.35 m/s cause a decrease in the cage volume between 20-40% [85]. Since the model is testing the feed waste for current velocities up to 0.25 m/s, a shrinkage in cage volume can be expected. This is not considered in the model and indicate that the achieved results might be wrong. A decreased cage volume lead to a higher fish density, which triggers stress, and an increase in feed waste can be assumed [53].

Waves and whirls are large contributors to the distribution of pellets, and are included in the random component of the pellet movement in the model [10]. However, the influence waves have on the pellet distribution is not modeled explicitly. This also applies to wind forces. Only calm weather conditions are considered. Extreme weather conditions can therefore not be tested with the current model. Many fish farms in the north of Norway are exposed to harsher weather and could benefit from knowing how the feed is dispersed during these situations [53].

Extreme weather can also cause the feed spreaders to move, which affects the feed distribution. High waves and strong currents reduce the surface feeder efficiency because the feed will be spread in an uneven manner. Fish also tend to swim lower when high waves are present [53]. It is likely that the subsea feeder will be influenced by extreme water currents and waves as well. The subsea structure is large and has a larger surface area than the surface spreader. If the subsea feeder is exposed to high environmental forces, the structure might rotate about the x-axis or y-axis. Consequently, a skewed feed distribution, which does not deploy the feed at the wanted location, is reasonable to assume.

5.2.3 Behavioural model

The fish behaviour is not explicitly modeled as this is a complex and comprehensive task. The behaviour of salmon is difficult to predict because there are multiple factors that affect them always. Most of them are mentioned in Chapter 2.

The model assumes that all fish are distributed equal to the feed dispersal, and that they always know where the feed is. From a realistic perspective, it is clear that not all fish can know where the feed is deployed at any time. Additionally, environmental factors, such as water currents, oxygen levels, light intensities etc., might influence their position in the cage and guide the population far away from the pellet distribution area. It will, therefore, take them a little while to react at the beginning of each feeding process. This delay which in reality occurs at the start of every meal is not included in the model.

There are no areas in the modeled cage that are preferred by the population. In previous studies, it has been documented that fish actually do have favored locations in the cage that varies with their health and environmental situation [73]. It is possible, however, to define areas in the model that are favored by the fish. If the model were to include this behavioural cue, the feeding technologies might produce completely different results.

An arbitrary number of fish groups is determined to represent a normal distribution of fish in the cage. The level of detail in the fish population representation can be improved by increasing the number of super-individual groups. However, by doing this, computation time will increase.

The appetite of the fish in the model includes some uncertainty as explained in section 3.5. Finding the maximum stomach volume of Atlantic salmon would improve the feed ingestion rate equation. If the right stomach capacity is implemented in the model, it might alter the feed waste results.

Under perfect farming conditions, salmon can add up to 2% of its body weight in one day [53]. The model does not take weight gain into account because the time scope for the simulations is too small. It might be desirable to simulate a feeding scenario, which extends over a longer period. In that case, the model should be altered to include a weight gain function to see the interaction between growth and feed intake.

5.2.4 Remarks on Monitoring

The most common monitoring method today is to use underwater cameras. Feed operators constantly look for cues that can indicate if the fish are losing or gaining their appetite. Uneaten pellets that sink by the camera is the clearest indication the operator has to tell if the feeding should be reduced or stopped. The efficiency of this method is determined by how the operator chooses to interpret the observations made from the underwater pictures and act accordingly. This can mean that every fish farm is fed in a different manner. Some operators prefer a high local concentration of feed in the cage because it is easier to detect pellets that drift by the cameras. On the other hand, a large feed dispersal area is wanted to feed as many fish as possible. Thus, deciding upon a feeding area is a trade-off between monitoring preferences and feeding efficiency.

Chapter 6

Conclusion

The aquaculture industry is rapidly growing due to the world-wide increase in demand for seafood products. It is estimated that the industry in Norway alone will grow by a factor of five within 2050. New inventions and better use of resources are needed to reach this demand. Feeding fish is a vital process for achieving this goal, with feeding technology being a core component. Moreover, guarding the environment is another factor that needs to be addressed.

This thesis summarizes how complex the process of feeding fish actually is and why the industry is dependent on this being done correctly. However, feeding fish the optimal amount at the right time under the best conditions possible is something the aquaculture industry is constantly striving for. Achieving the best possible feeding outcome is a challenging task, and fish farmers lack sufficient information about their feed use to know if their operation is sustainable to a certain extent. There are various feeding solutions on the market, but to the author's knowledge little information regarding their environmental impact exist. Thus, this thesis also conducts a comparison of two different feeding technologies to see which technology produces the least feed waste under certain circumstances. The technologies in question comprise of a standard surface rotor spreader and a subsea feeder.

To perform this comparison a mathematical model of the feeding process has been used and further developed. The model developed in this paper is based on an initial model made by SINTEF Ocean, which was originally created for the surface rotor spreader. This model has been altered to include the distribution pattern from a subsea feeder. Since the surface rotor spreader is the dominant feeding technology today, it is desirable to test the subsea spreaders design against it, and perform simulations for both spreaders under different water current conditions. The design parameters that this thesis looks into are the feeding depth and the bottom ring radius of a subsea feeder. An additional parameter, the local fish density threshold (FD_{thresh}), is examined to show how sensitive the model is to changes in the fish behaviour part of the model.

Before any parameters are changed, a realistic feeding regime is established in conjunction with operators from Nordlaks Oppdrett AS. This is done to see how the feed waste outcome varies when changes are made to the subsea feeder design parameters. The chosen design parameters are simulated three times for each current profile: uniform current, linear decreasing moderate current and linear decreasing strong current. The results indicate that the surface feeder is the most sustainable option overall. However, an improvement is observed in the feed waste outcome for the subsea feeder when the feed distribution area increases. Deploying feed further down the water column seemed to be the least sustainable option. However, examining other parameters that the model entails, and looking into other combinations of these might benefit the subsea feeder, which is why further analysis on this topic is recommended.

For this model to produce realistic and more accurate results, it will be necessary for each fish farmer to implement local data from their fish farms. It is intended to provide more information about fish farmers feed utilization, and make it possible to optimize feeding strategies. The feed waste data can also serve as an essential part of a decision support system during the daily feeding operations. This way emissions from the aquaculture industry can be reduced and save fish farmers production costs in the process. Without an eco-friendly production that safeguard the animal welfare and the environment, there will most likely be no sustainable expansion for the industry in the future.

6.1 Recommendations and Further Work

This thesis has through a parameter study analyzed which feeding technology provides the least feed waste under different water current conditions. Based on the outcome of this analysis, the following recommendations for further use of the model can be made:

- To know if the subsea distribution pattern in the model is valid, full-scale tests should be conducted to see if the exit velocity and angle at the outlets make out a big difference.
- Improve the subsea distribution model to make sure the feed concentration in the assigned cell is correct when more outlets are added.
- Test more parameters to gain more knowledge about their interactions and to build a better base for the comparison of both feeding technologies. Testing higher resolutions can also be of interest.
- Alter the model to consider harsher weather conditions and deformations of the fish cage volume.
- Implement an extended range of behavioural preferences regarding location and appetite in the cage, including factors such as light preferences and dynamic water currents, and a more realistic fish density threshold.
- Simulate other feeding regimes and add cyclic feeding as an option.

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Appendices

Appendix A

Static Simulation Plot with Uniform Current

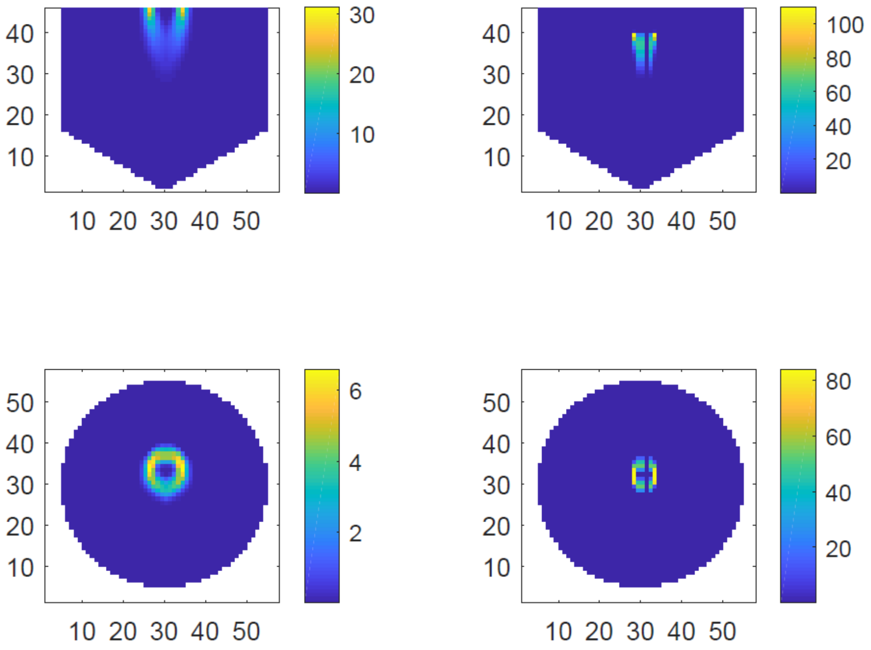


Figure A.1: Simulation plot of the realistic feeding scenario with low current velocity at t = 3600s, and where the color bar represents the concentration gram/cell

Appendix B

Uniform Current Profile

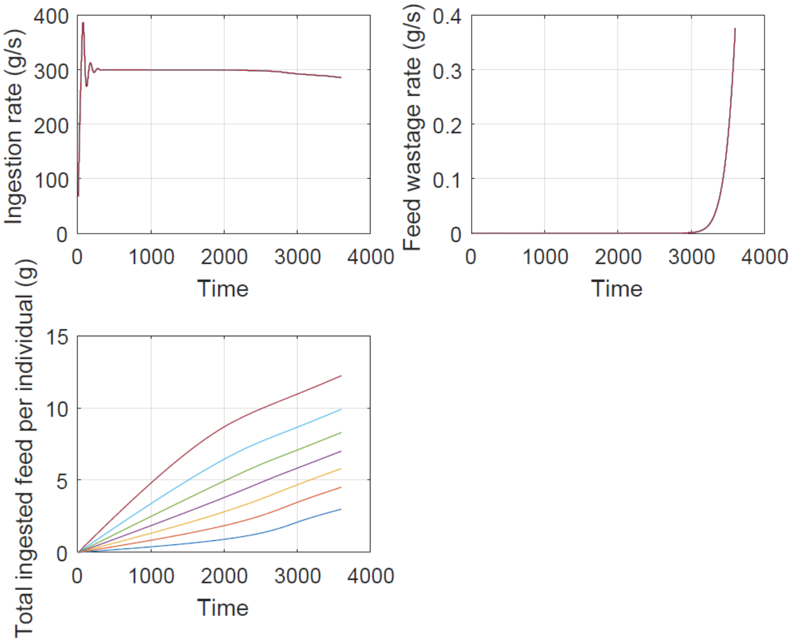


Figure B.1: Surface spreader simulation results for the realistic feeding scenario with uniform current

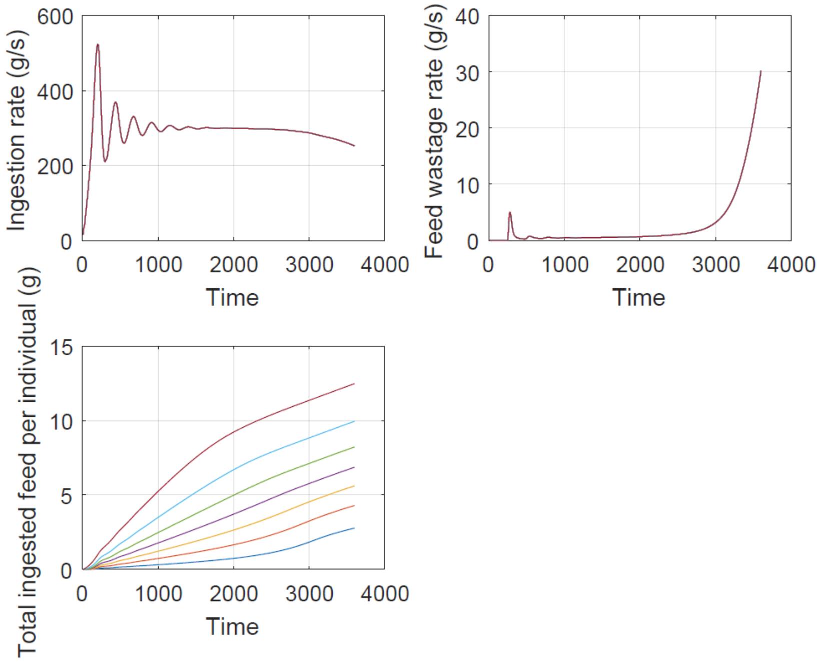


Figure B.2: Subsea spreader simulation results for the realistic feeding scenario with uniform current

Appendix C

Linear Decreasing Moderate Current Profile

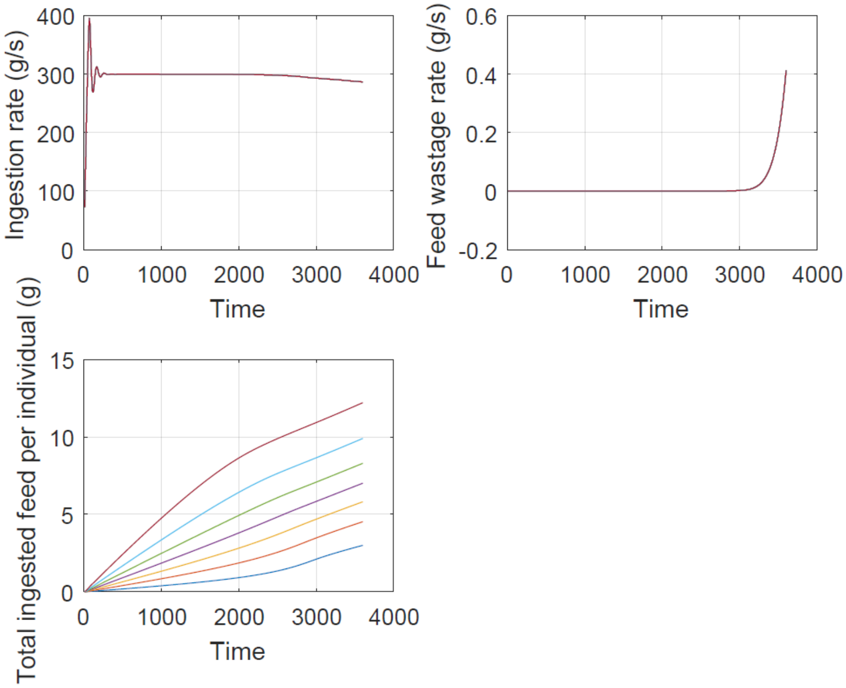


Figure C.1: Surface spreader simulation results for the realistic feeding scenario with moderate decreasing current

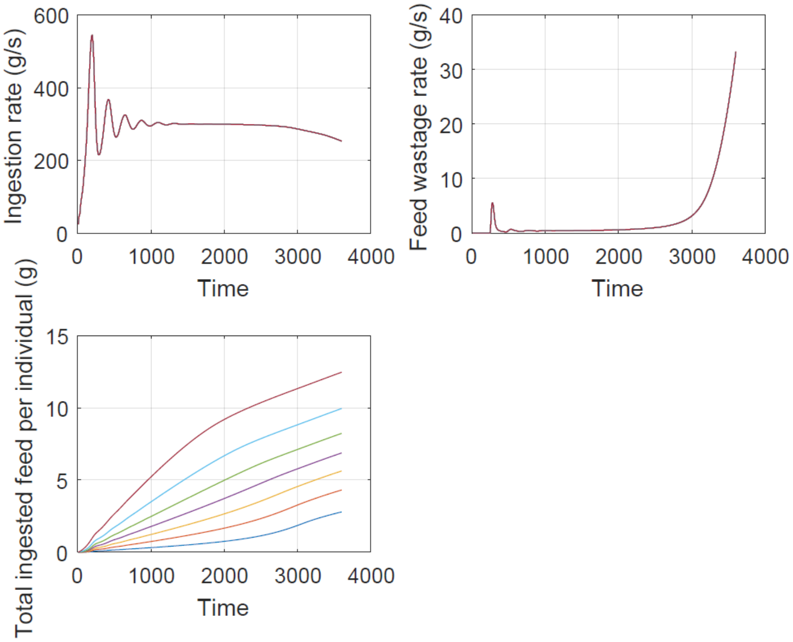


Figure C.2: Subsea spreader simulation results for the realistic feeding scenario with moderate decreasing current

Appendix D

Linear Decreasing Strong Current Profile

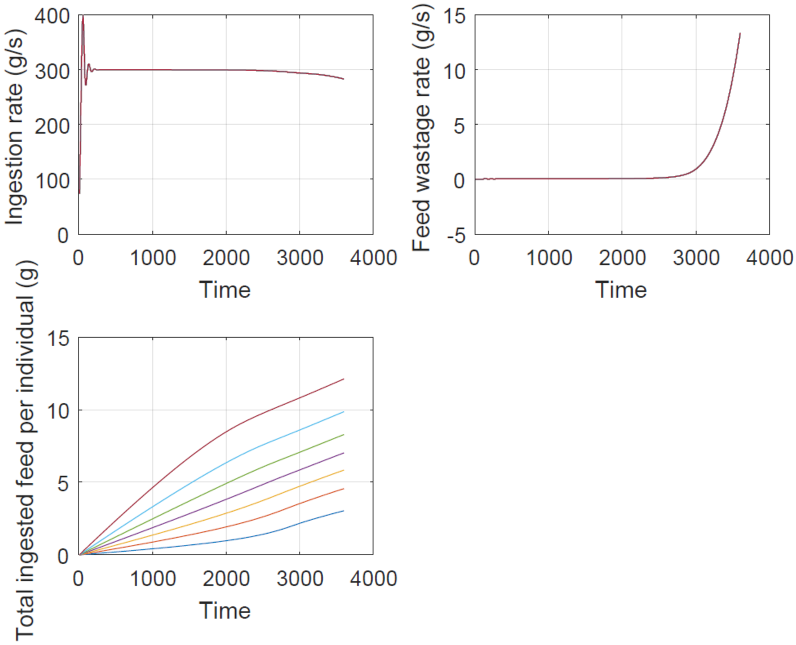


Figure D.1: Surface spreader simulation results for the realistic feeding scenario with strong decreasing current

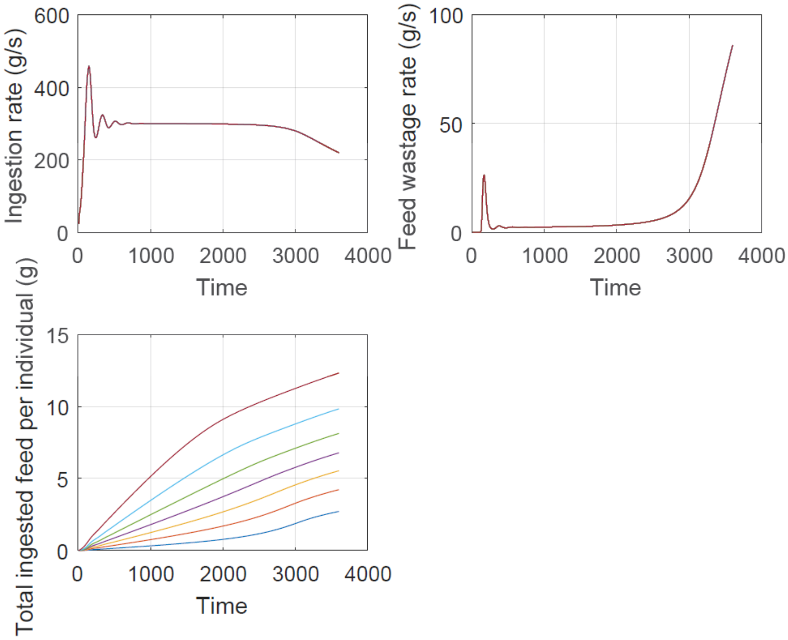


Figure D.2: Subsea spreader simulation results for the realistic feeding scenario with strong decreasing current

Appendix E

Best Subsea Feeder Result

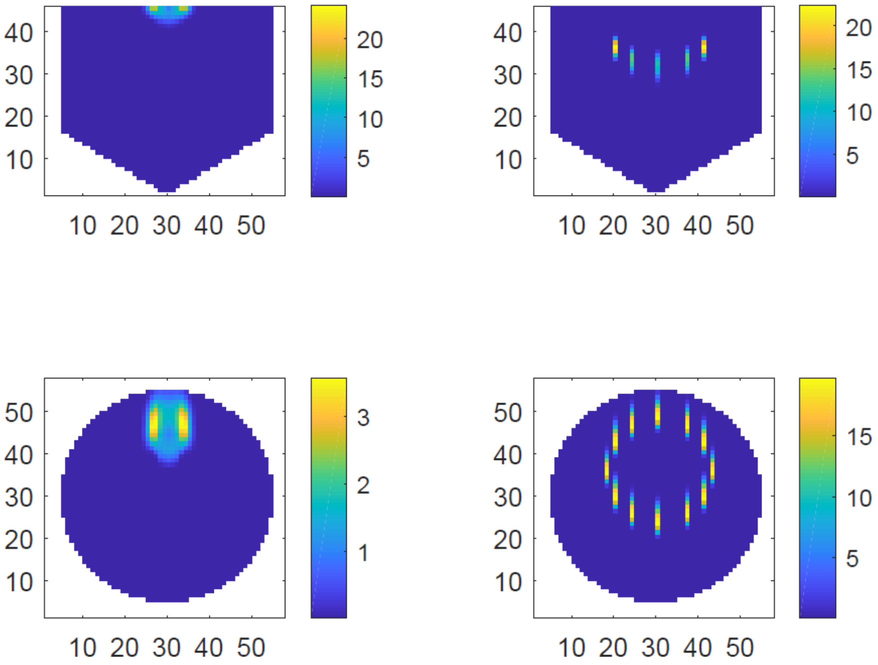
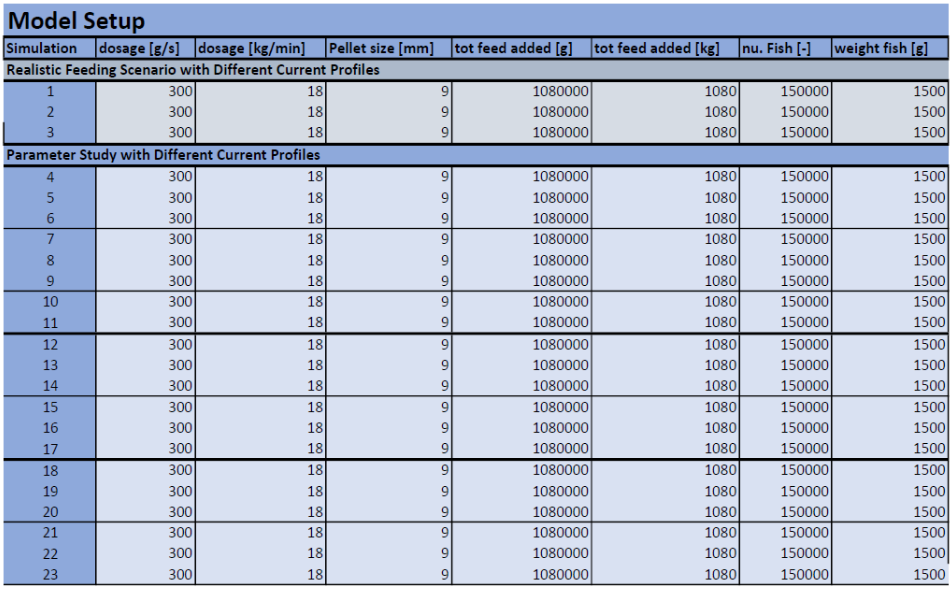


Figure E.1: The best feed waste result (top and bottom right) with the bottom ring radius equal to 12.5 m and high current velocity at t = 3600s

Appendix F

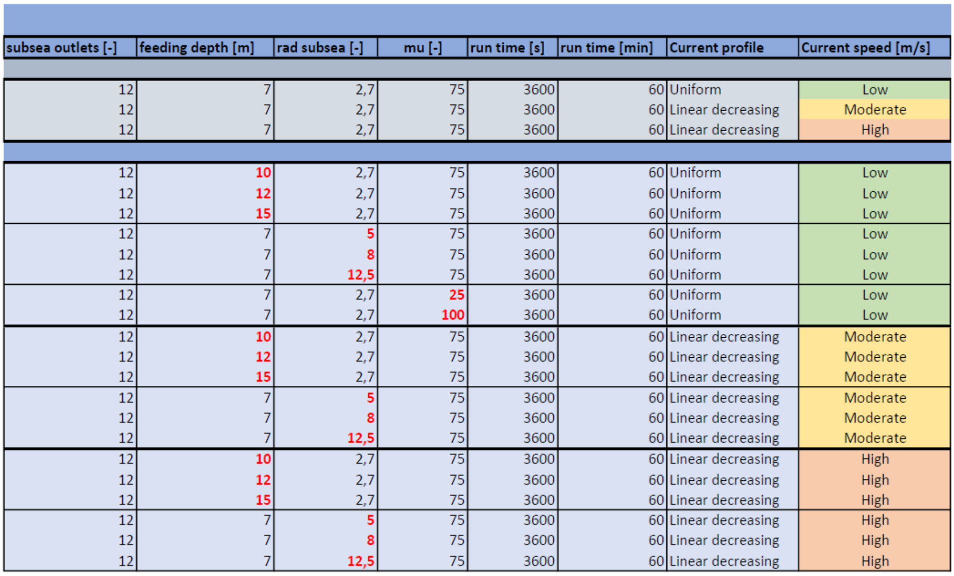
Parameter Simulation Table



Model Setup

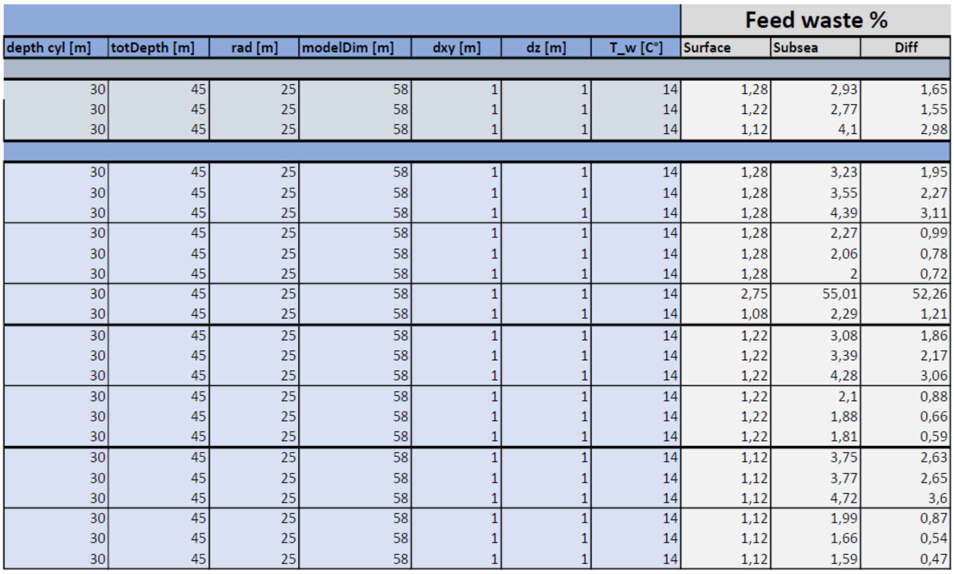
Simulation	dosage [g/s]	dosage [kg/min]	Pellet size [mm]	tot feed added [g]	tot feed added [kg]	nu. Fish [-]	weight fish [g]
Realistic Feeding Scenario with Different Current Profiles							
1	300	18	9	1080000	1080	150000	1500
2	300	18	9	1080000	1080	150000	1500
3	300	18	9	1080000	1080	150000	1500
Parameter Study with Different Current Profiles							
4	300	18	9	1080000	1080	150000	1500
5	300	18	9	1080000	1080	150000	1500
6	300	18	9	1080000	1080	150000	1500
7	300	18	9	1080000	1080	150000	1500
8	300	18	9	1080000	1080	150000	1500
9	300	18	9	1080000	1080	150000	1500
10	300	18	9	1080000	1080	150000	1500
11	300	18	9	1080000	1080	150000	1500
12	300	18	9	1080000	1080	150000	1500
13	300	18	9	1080000	1080	150000	1500
14	300	18	9	1080000	1080	150000	1500
15	300	18	9	1080000	1080	150000	1500
16	300	18	9	1080000	1080	150000	1500
17	300	18	9	1080000	1080	150000	1500
18	300	18	9	1080000	1080	150000	1500
19	300	18	9	1080000	1080	150000	1500
20	300	18	9	1080000	1080	150000	1500
21	300	18	9	1080000	1080	150000	1500
22	300	18	9	1080000	1080	150000	1500
23	300	18	9	1080000	1080	150000	1500

Figure F.1: Simulation Table 1/3



subsea outlets [-]	feeding depth [m]	rad subsea [-]	mu [-]	run time [s]	run time [min]	Current profile	Current speed [m/s]
12	7	2,7	75	3600	60	Uniform	Low
12	7	2,7	75	3600	60	Linear decreasing	Moderate
12	7	2,7	75	3600	60	Linear decreasing	High
12	10	2,7	75	3600	60	Uniform	Low
12	12	2,7	75	3600	60	Uniform	Low
12	15	2,7	75	3600	60	Uniform	Low
12	7	5	75	3600	60	Uniform	Low
12	7	8	75	3600	60	Uniform	Low
12	7	12,5	75	3600	60	Uniform	Low
12	7	2,7	25	3600	60	Uniform	Low
12	7	2,7	100	3600	60	Uniform	Low
12	10	2,7	75	3600	60	Linear decreasing	Moderate
12	12	2,7	75	3600	60	Linear decreasing	Moderate
12	15	2,7	75	3600	60	Linear decreasing	Moderate
12	7	5	75	3600	60	Linear decreasing	Moderate
12	7	8	75	3600	60	Linear decreasing	Moderate
12	7	12,5	75	3600	60	Linear decreasing	Moderate
12	10	2,7	75	3600	60	Linear decreasing	High
12	12	2,7	75	3600	60	Linear decreasing	High
12	15	2,7	75	3600	60	Linear decreasing	High
12	7	5	75	3600	60	Linear decreasing	High
12	7	8	75	3600	60	Linear decreasing	High
12	7	12,5	75	3600	60	Linear decreasing	High

Figure F.2: Simulation Table 2/3



							Feed waste %		
depth cyl [m]	totDepth [m]	rad [m]	modelDim [m]	dxy [m]	dz [m]	T_w [C°]	Surface	Subsea	Diff
30	45	25	58	1	1	14	1,28	2,93	1,65
30	45	25	58	1	1	14	1,22	2,77	1,55
30	45	25	58	1	1	14	1,12	4,1	2,98
30	45	25	58	1	1	14	1,28	3,23	1,95
30	45	25	58	1	1	14	1,28	3,55	2,27
30	45	25	58	1	1	14	1,28	4,39	3,11
30	45	25	58	1	1	14	1,28	2,27	0,99
30	45	25	58	1	1	14	1,28	2,06	0,78
30	45	25	58	1	1	14	1,28	2	0,72
30	45	25	58	1	1	14	2,75	55,01	52,26
30	45	25	58	1	1	14	1,08	2,29	1,21
30	45	25	58	1	1	14	1,22	3,08	1,86
30	45	25	58	1	1	14	1,22	3,39	2,17
30	45	25	58	1	1	14	1,22	4,28	3,06
30	45	25	58	1	1	14	1,22	2,1	0,88
30	45	25	58	1	1	14	1,22	1,88	0,66
30	45	25	58	1	1	14	1,22	1,81	0,59
30	45	25	58	1	1	14	1,12	3,75	2,63
30	45	25	58	1	1	14	1,12	3,77	2,65
30	45	25	58	1	1	14	1,12	4,72	3,6
30	45	25	58	1	1	14	1,12	1,99	0,87
30	45	25	58	1	1	14	1,12	1,66	0,54
30	45	25	58	1	1	14	1,12	1,59	0,47

Figure F.3: Simulation Table 3/3