Bachelor's thesis

Michael Cantillon
Mads Ulrich Mjanger

Preliminary Design and Modeling of a System for Collecting Dead Fish in Offshore Aquaculture

May 2023

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Norwegian University of Science and Technology
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Kunnskap for en bedre verden

Preliminary Design and Modeling of a System for Collecting Dead Fish in Offshore Aquaculture

Grunnleggende Design og Utforming av et System for Oppsamling av Døde Fisker i Offshore Fiskeoppdrett

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Preface

We would like to express our sincere gratitude to our advisor at NTNU, Lene Østby, for her guidance and insight throughout the development of this bachelor thesis. We thank the staff of the Department of Materials Science and Engineering, IMA, NTNU, Gerhard H. Olsen for his help with technical design questions, and Kristian Etienne Einarsrud for his help with flow and pump calculations. This thesis was made possible by our client and we would like to thank our external advisors, Farshad Mohammadi, Øystein Refsland Andreassen and Haavard Stavaas, for their cooperation from start to finish with objective development and expertise within fish farming.

We hereby declare that this work has been carried out independently and according to the examination regulations of The Norwegian University of Science and Technology (NTNU).

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Abstract

This bachelor thesis aims to address the issue of dead fish collection and ensilage by developing a preliminary design solely intended for offshore fish farming. This is done by defining the operating conditions at best effort from the available literature. Followed by choosing and designing process equipment to best cope with the conditions.

The operating conditions are split into two scenarios, the normal operating scenario requires removal and treatment for 42 dead fish per hour. The other scenario is defined as a mass death scenario where 4.6 fish per second need to be removed without processing.

The system components chosen are a mort cone; an eductor; a centrifugal pump; a strainer; a fish grinder; three intermediate bulk containers; two screw pumps of different capacities and a storage tank. To reinforce the system design, calculations are made to determine the flow and pressure characteristics of the system, and a fluid dynamic simulation is done to determine the flow and pressure characteristics inside the eductor.

The system design is still in a preliminary phase. Further development and experimental work are needed before implementation.

Sammendrag

Denne bacheloroppgaven tar sikte på å håndtere problemet med innsamling og ensilering av dødfisk ved å utvikle et grunnleggende design for offshore fiskeoppdrett. Dette gjøres ved å best mulig definere driftsforholdene fra tilgjengelig litteratur. Deretter velges og designes prosessutstyr som kan best takle forholdene.

Driftsforholdene er delt inn i to scenarier, det normale driftsscenarioet krever fjerning og behandling av 42 dødfisk per time. Det andre scenarioet er definert som et massedødscenario der 4,6 fisk per sekund må fjernes uten prosessering.

De valgte systemkomponentene er en dødfiskkjegle, en eduktor, en sentrifugalpumpe, en sil, en fiskekvern, tre IBC-kontainere, to skruepumper med forskjellig kapasitet og en lagringstank. For å støtte systemdesignet er det gjort beregninger for å bestemme strøm- og trykkegenskapene til systemet, og en væskedynamisk simulering er gjort for å bestemme strøm- og trykkforholdene inne i eduktoren.

Systemdesignet er fortsatt i en grunnleggende fase. Videre utvikling og eksperimentelt arbeid er nødvendig før implementering.

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1 Introduction

1.1 Background

Fish farming is one of the most area effective food production forms in the world. Within one acre, up to 59 tonnes of salmon can be farmed every year. Because of this, two of the main goals for the Norwegian aquaculture industry are to reach an annual export of 200 billion kroner worth of farmed salmon by 2030, and a fivefold increase in exported services and products by 2050. To achieve these goals the fish farming industry must eliminate problems with salmon lice and escaped fish. This is where offshore fish farming could play a big role [1].

The production of Atlantic salmon has stagnated since 2012, despite an increase in demand. This is mostly due to stricter rules and regulations combined with biological and environmental issues. The biggest challenges are algae flourishing, salmon lice and other fish diseases. For the fish farming business to meet the demand and tackle the different obstacles, it must have a sustainable development that ensures the fish's health and minimizes the environmental impact [2].

To decrease pressure on today's fish farming locations, different companies are looking at production in other more exposed locations. New technology needs to be developed to build these fish farms offshore. These constructions have more in common with the existing oil platforms than the close-to-shore farms. The goal for these production facilities is to increase the capacity of each farm and utilize the larger available areas. This could ensure a more sustainable increase in food production in a cost-effective way.

Land-based fish farming is also a suggested solution. These fish farms are closed off, meaning the contaminated water can be processed and the leftovers could be used for fertilizer. These farms have environmental benefits and avoid the problems from salmon lice and algae. The largest problem today is that the economic cost is considerably larger. Onshore farms also face the challenge of available area and often have to remove bedrock or otherwise affect the landscape.

1.2 Objective

The main objective of this thesis is to create a preliminary design for the collection and ensilage of dead fish. According to rules and requirements, dead fish must immediately be ground and ensiled to a pH below 4 [3]. Safe removal is necessary to prevent the spreading of pathogens and a good hygiene system keeps the risk of infection low. The dead fish must be undamaged when they arrive at the surface. This makes it easier to both find the cause of death and transport the fish through the system. As well as normal operation, the system must also be able to deal with a mass death scenario.

This preliminary design should contain a description of every system component. And a more detailed description of the main component which is the pumping system that needs to pump dead fish from a depth of 80 metres below sea level. To evaluate the effectiveness of the system, detailed calculations and flow simulations are required.

2 Theory

2.1 Conventional and offshore fish farms

Conventional Norwegian fish farms normally operate close to fjords along the coastline. The salmon are normally located inside open pens that are separated from the open sea with a net where water flows through the gaps. A farm usually consists of many smaller pens that are operated by the same company, shown in Figure 1 [4].

Figure 1: Conventional fish farm[4].

Offshore fish farms are operated similarly to conventional farms, but with larger dimensions. The system designed in this thesis is developed for offshore use and is based on the structure of a similar farm already in use. Figure 2 shows the existing pilot project Ocean Farm 1 created by SalMar. This facility has been operated since 2017, has a volume of 250 000 m^3, and a diameter of 110 meters. Ocean Farm 1 is designed as a semi-submersible structure located in Frohavet outside Frøya [5]. The system designed in this paper operates under similar circumstances as Ocean Farm 1. However, the total biomass will be larger, thus the construction will have to be bigger. Nonetheless, a similar dead fish collection is used. There are also many other offshore fish farming projects under construction or development. These vary from totally submerged fish pens to smaller farm sections within larger constructions, shown in Figure 3 [6].

Figure 2: Ocean Farm 1[7].

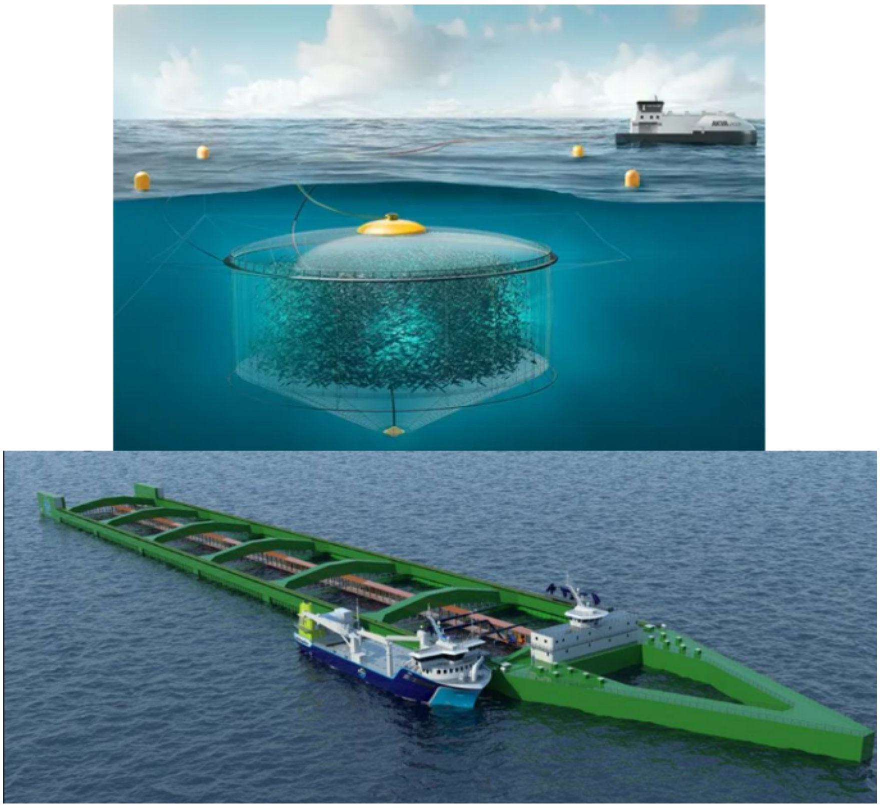

Figure 3: Example of other offshore farm projects [8][9].

2.2 Wild and farmed Atlantic salmon

Atlantic salmon is a salmon species native to Norwegian waters. The salmon start their life cycle in freshwater rivers where they are hatched from fertilized eggs. The hatched alevin spends 1-3 months to transform into fry. Whenever they begin to swim freely, they are called parr. The parr spend at least 1 year in the river before they wander out into the sea. The parr then goes through a physiological change to live in seawater and transform into smolt. The smolt can spend from 1 to 6 years in the sea growing into adult salmon. When the salmon are ready to reproduce they wander back into the rivers, to their spawning ground [10]. The salmon life cycle is shown in Figure 4.

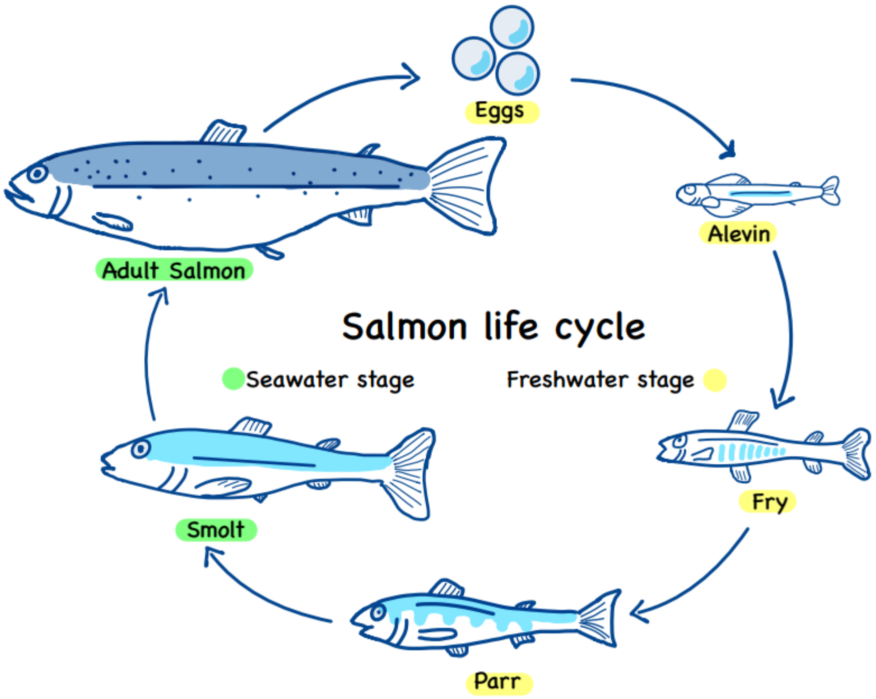

Figure 4: Salmon life cycle.

Farmed Atlantic salmon follow mostly the same life cycle as wild salmon, but it is subject to human interference. It takes about 8 to 18 months in freshwater for the salmon to go from egg to 100 gram smolt. Afterwards, the smolt spend 12 to 18 months in the fish farm before they reach slaughter weight. The slaughter weight varies from 3 to 6 kg. How much and how fast the salmon grow is dependent on the oxygen content of the water, water temperature, feeding, salt content in the sea and light level. Fish farms prefer that the salmon reach slaughter weight before they become fertile [11].

2.3 Fish welfare and diseases

Fish welfare and how to optimize it is a central theme within commercial fish farming. Welfare is important for the farm's total production and sustaining the existing fish population within the enclosure. Fish welfare is as important to the consumer as to the fish farmers. This causes heavily regulated welfare conditions and product quality. ”VI” or welfare indicators are used to determine if the welfare needs are fulfilled. The welfare indicators are either direct indicators that describe characteristics and behavior, or indirect indicators that describe the salmons' access to adequate resources and environment. The goal with ”VI's” is to be easily accessible and useful information in different production systems before, during, and after handling [12].

Important welfare indicators [12]:

- Food access
- Respiration
- Osmotic balance
- Water quality
- Hygiene

Salmon lice are a large welfare problem for the fish farming industry. Salmon lice are parasites that live off the salmon's skin and blood. This creates wounds in the fish skin that can eventually kill the salmon, but also causes the salmon growth to decline. The infection pressure increases if many fish are bunched up together [13]. This makes it much more common for farmed salmon than wild salmon. The salmon lice enjoy warmer water conditions. Regular delousing and chemical treatment are necessary to keep the fish population healthy, but the treatment can cause higher mortality. [12].

Water temperatures are another welfare factor that can cause higher mortality in the enclosure. The temperature affects many aspects of the salmons' performance and behavior like enzymatic reactions, respiration and osmoregulation. The sea temperature also affects the total amount of oxygen dissolved in the water. Higher temperatures result in less accessible oxygen for the fish [12].

Water currents are also important to the water quality inside the enclosure. Low currents will result in less water exchange. The current inside the farm is affected by the size of the farm, total biomass and growth on the fish net. A negative effect of high current is decreased volume, due to the net getting deformed and pressed together. Strong currents will also affect the salmons' ability to move freely inside the net. If the current through the pen is too large, the fish could get pushed around and exhausted by swimming against the flow [12].

Light level and artificial light are used to control the fish's growth and change swimming patterns. To reach the smolt stage in the life cycle, the salmon are kept under constant light to simulate longer days. Before the parr change to smolt, the light level is reduced to shorter days, to simulate winter. Then the light level is increased to simulate spring and with the right timing, the smolt are ready to be set into the sea. When the smolt are put into the enclosure, their swimming patterns follow natural light. During the daytime they swim lower in the net, and during the night closer to the surface. To reduce pressure from salmon lice, artificial lights in the water can be used to direct fish to deeper locations in the net. Artificial light is sometimes used to prevent sexual maturation, but can also speed up the process if done incorrectly [12].

2.4 Mass death scenarios

Salmon lice are already described previously as one of the major welfare problems in fish farming. A high number of lice per fish can cause problems for the fish and result in death, but a high mortality rate can also occur if the treatment is done incorrectly. In 2016 126,225 salmon died within 26 minutes in a fish farm owned by SalMar. This was due to a large exposure of hydrogen peroxide during delousing [14].

A flourishing of toxic algae can cause substantial amounts of dead fish. The algae can produce a poison that harms the cells in the gills, leading to the fish being unable to take up oxygen. The result is that the fish suffocates. Algae also consume oxygen and more algae growth results in less oxygen available for the fish [12]. A mass death scenario was caused by toxic algae in 2019 when fish farms in northern Norway experienced a large flourish of algae that caused 8 million fish to die. Algae blooms can occur both offshore and close to shore [14].

Constant exchange of seawater is positive for oxygen levels and water freshness, but can also bring more pathogen viruses and bacteria. The pathogens alone would usually cause little fish death, but combined salmon lice or toxic algae blooms it could cause a bigger problem [15]. Currents can also bring jellyfish into the farm. Salmon can usually avoid jellyfish, but a large swarm can overwhelm the fish farm. The jellyfish can damage the gills and cause mass death [12].

Other mass death scenarios can be caused by more extreme situations such as weather disasters and large equipment malfunctions. Large waves could tear holes in the net and make the fish escape, or push shoals of fish into the net. Because the farm is located in the North Sea, other companies in the petroleum industry operate nearby. A large oil spill from an oil rig nearby could have a massive effect on the fish farm and result in mass mortality [16].

2.5 Applicable rules and regulations

All existing fish farms must follow many rules and regulations to operate within the government's parameters. The main standard for aquaculture systems in Norway is NS9415. The standard is focused on preventing escaped fish, project demands, execution and use of the aquaculture facility [17]. NYTEK is a regulation that a company needs to fulfill in order to adhere to the law. The regulation contains the requirements for fish farming installations and building a new installation will have to follow these requirements [18].

Rules and regulations for offshore fish farming are not yet fully developed, but will likely have to follow many of the same rules as conventional fish farms. Regulations regarding locations are controlled by the "Produksjonsforskriften", but how to manage an increase in biomass is still not answered in detail [19]. One of the strictest rules set in place for close-to-shore farms is the "Traffic light" system [20]. The system operates along the Norwegian coast and ensures predictable and sustainable growth in the aquaculture industry. A picture of the sections is shown in Figure 5. This system controls how many farms and how many fish can be farmed in specific sections. Biomass production must decrease by 6% in red zones, remain stable in yellow zones, and can increase by 6% in green zones [21]. This rule is currently applicable in regions 1 to 8 nautical miles from the Norwegian shore [19].

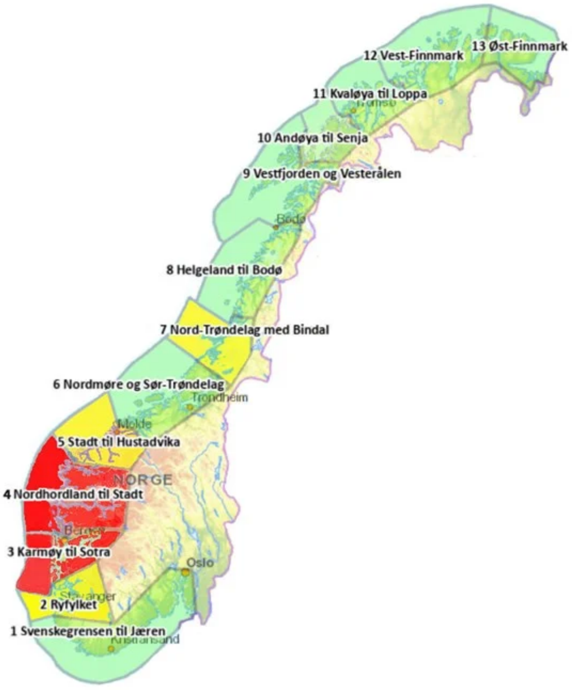

Figure 5: "Traffic light" zones[20].

Regulations on salmon lice control state that the maximum average of salmon lice per fish is allowed to be 0.2 female lice in periods when young wild salmon swim out of Norwegian rivers into the Atlantic [22].

Regarding the collection of dead fish in the farm, ”Akvakulturdriftsforskriften” states that dead fish need to be collected immediately from the enclosure, then be converted to ensilage with a pH below 4 [3]. This is to prevent pathogens from spreading to healthy fish and keep the farm hygienic.

In case of a mass death scenario, the fish farm must have a precise plan for effective and safe removal. Nearby vessels must be able to quickly react and bring the dead fish to shore [16].

2.6 Statistics for fish size

The sizing of the fish is critical to the design of the system. Fish size varies depending on the environmental conditions, such as temperature, light and water composition [23]. The fish size can be estimated using statistics. Variables like fish size can be considered to be normally distributed.

The normal distribution is probably the most common statistical distribution[24]. A variable can be said to follow normal distribution if the probability density can be described using Equation 1 .

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{(x-\mu)^2}{2\sigma^2}} \tag{1}$$

With (μ) being the expected value and (σ) being the standard deviation. The function produces a curve shaped somewhat like a bell, hence the colloquial term ”bell curve”. The width of the ”bell” is decided by the size of the standard deviation. And the placement of the peak on the x-axis is decided by the expected value, Figure 6 provides an example of a bell curve.

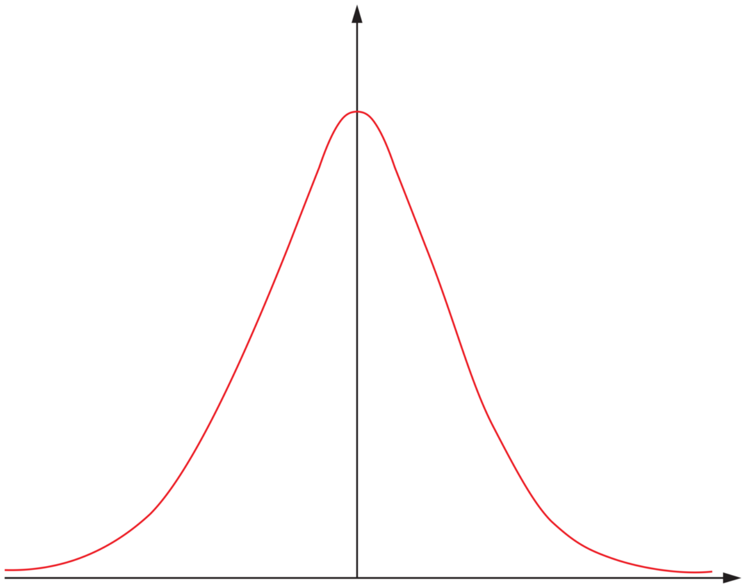

Figure 6: Typical bell curve with the y-axis representing the frequency and the x-axis representing the value [25].

The normal distribution has the property that no matter the values of (μ) and (σ) the area under the curve up until μ+zσ will be identical. This means that the probability of a variable x being less than μ+zσ is a function of only the z value.

The standard normal distribution is a distribution with $\mu = 0$ and $\sigma = 1$ any normally distributed variable can be transformed, to fit the standard normal distribution using the variable Z, described in Equation 2.

$$Z = \frac{X - \mu}{\sigma} \tag{2}$$

The probability of the variable Z falling below a value z can be calculated by the Equation 3.

$$G(z) = P(Z < z) = \frac{1}{\sqrt{2\pi}} \int_{z}^{-\infty} e^{\frac{-t^2}{2}dt} \tag{3}$$

This integral is only possible to solve numerically. [24]

2.7 Bernoulli's principle and equation

Bernoulli's principle is a statement about the relation of the speed of a fluid and the pressure of the fluid. It states that ”within a horizontal flow of fluid, points of higher fluid speed will have less pressure than points of slower fluid speed.” This means that within a horizontal pipe that changes in diameter, the areas with fast-moving water are under less pressure than areas with slow-moving water [26]. The principle can be shown in general with a mathematical formula, Equation 4.

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 \tag{4}$$

$P_{1,2}$, $v_{1,2}$, and $h_{1,2}$ refer to the pressure, velocity, and height at their respective points. Figure 7 shows points 1 and 2 in a general fluid pipe.

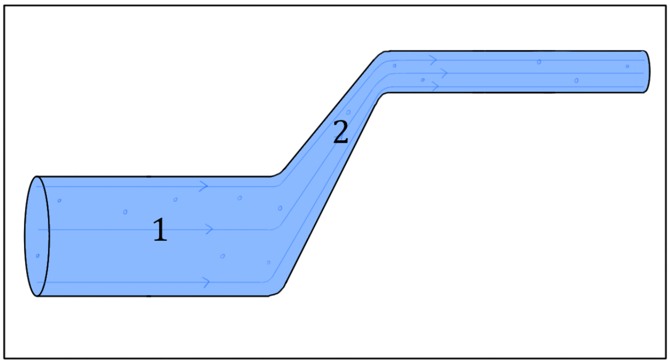

Figure 7: Fluid pipe with points 1 and 2 [26].

2.8 System component descriptions

2.8.1 Screw pumps

Screw pumps in their simplest form are some of the oldest displacement pumps known. In screw pumps inter-meshing rotors and a closely fitted housing creates moving seals between the inlet and outlet of the pump. These moving seals create enclosed cavities that continually move. The created cavities trap fluids and carry them along providing a smooth flow as shown in Figure 8. Because screw pumps are displacement pumps, they deliver in a predictable manner a fixed quantity with each revolution of the rotors. Their theoretical volumetric flow can therefore be described as a function of displacement volume V_d and rotational speed N, as shown in Equation 5.

$$Q_t = NV_d \tag{5}$$

In an ideal scenario with no internal clearance between the rotors and the housing the theoretical flow rate would be equal to the delivered flow rate. However, in practice, the pressure differential between the inlet and outlet will force some of the fluid through the clearance from the outlet to the inlet. This leakage is often called slip and noted as S, the actual flow rate can thus be described as follows in Equation 6.

$$Q = Q_t - S \tag{6}$$

To minimize slip the pump can be machined with a low tolerance for clearance, or the differential pressure can be lowered. High-viscosity fluids suffer less from slip than low-viscosity ones. [27]

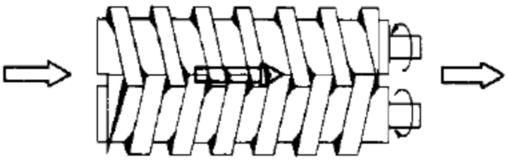

Figure 8: Rotors and cavities of a typical screw pump.

Some advantages of a screw pump include its continuous pulsation-free flow, its high tolerance for contamination and its ability to handle very viscous fluids or pulps. Screw pumps also have some disadvantages in that they are relatively expensive because of their close tolerances when machined. They also struggle to deliver at high pressure without being unreasonably large.[27]

2.8.2 Centrifugal pumps

Centrifugal pumps utilize a rotating impeller to generate flow and pressure dynamically. They differ from displacement pumps in that the inlet is not walled off from the outlet. A centrifugal pump delivers energy to the fluid through velocity changes that occur as the fluid flows through the impeller and fixed passageways of the pump this is shown in Figure 9.

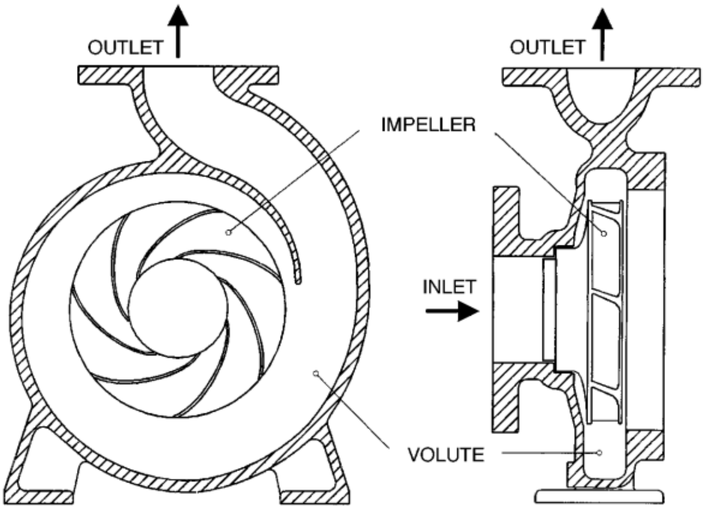

Figure 9: Cross sections of a centrifugal pump example [28].

The fluid is injected through the impellers which rotate at high speed (anti-clockwise in the Figure). The impellers accelerate the fluid, and the space between the impellers and pump housing gradually increases so that the energy is converted from kinetic to static.

Centrifugal pumps are relatively small and versatile compared to the pressure they can deliver. They deliver at a steady rate and offer a great deal of control regarding the delivered pressure as the impellers can be sped up and slowed down at need. Centrifugal pumps also have disadvantages in that they need to be primed i.e., filled with fluid before starting. They are also susceptible to cavitation which will impede the function if not taken into consideration [27].

2.8.3 Mort cone

Mort is the name of dead fish that has died of natural causes or diseases. In smaller pens, the mort is sometimes gathered by hand nets permanently mounted on the bottom of the net, with divers collecting in baskets. The mort cone is a useful collection device that is located at the bottom of the net, shown in Figure 10. The dead fish fall down to the outside rim and are fed into the suction point. A similar cone design is also used for sludge removal in conventional farms. The fish gather on the outside rim, a larger rim makes it possible for more fish to gather close to the suction point. A larger suction point permits more fish to be sucked in at once, but this will require more suction created by the pump. This mort cone is usually used in air-lift systems, where a compressor delivers air into the collector, and the fish is sucked up with the generated air stream [29].

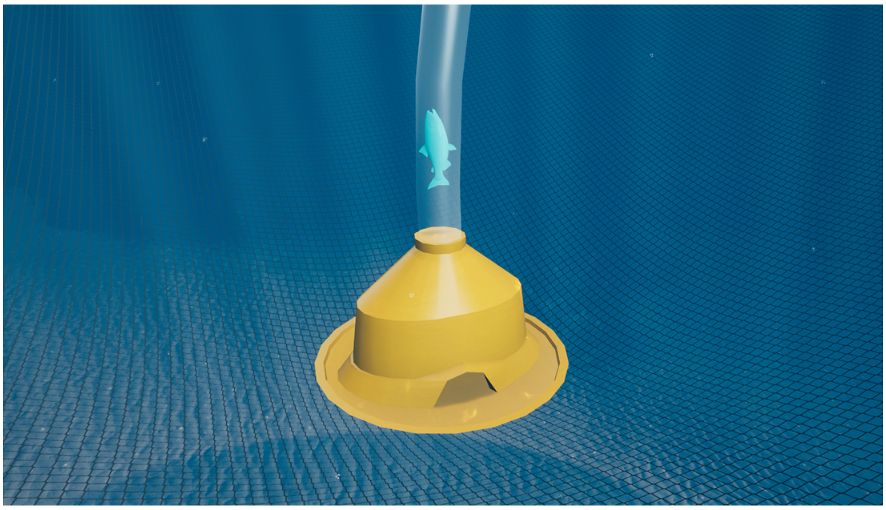

Figure 10: Example of a mort cone connected to a pump [29].

2.8.4 Grinder

A grinder is used to process whole dead fish into ensilage. The dead fish are fed into the grinder from the top and gets shredded by rotating blades into small pieces. The grinder automatically adds the correct dosage of acid to the fish mass before the ensilage is transferred to a storage tank [30].

2.8.5 Jet pump

A jet pump is a relatively simple device in that it does not have any mechanical moving parts, instead relying on a motive fluid to operate. This removes a lot of the difficult maintenance and allows the pump to be placed at inaccessible places while the pump driving the motive fluid can be placed easily available for maintenance. For simplicity, from this point on the pump driving the motive fluid will be referenced as the centrifugal pump and the jet pump will be referenced as the eductor. The eductor consists of four parts; nozzle, inlet, mixing chamber and diffuser. The different sections and nomenclature are shown in Figure 11.

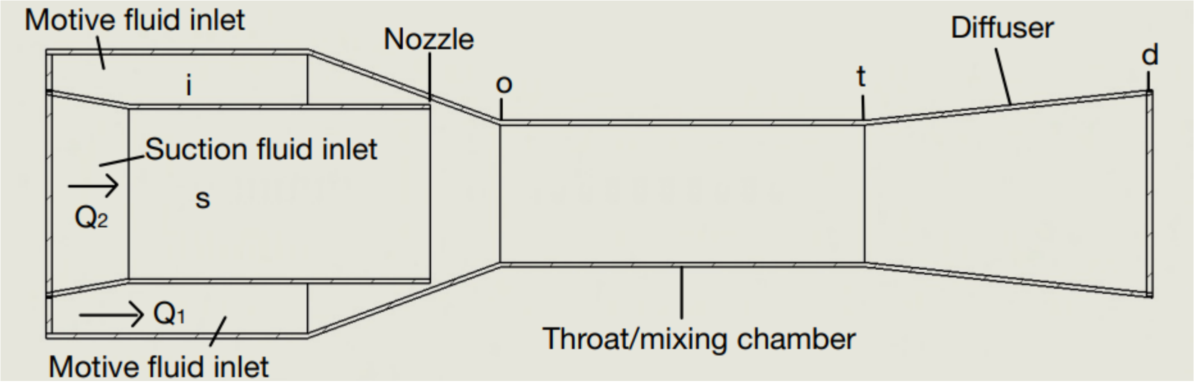

Figure 11: Eductor nomenclature.

The highly pressurized motive fluid enters through the nozzle and converts most of its energy from static to kinetic. This results in a pressure drop sucking in the fluid. The motive fluid and the suction fluid get mixed in the mixing chamber and the energy gets transferred between them. In the diffuser the combined fluid's kinetic energy gets converted to static, this head lifts the liquid toward the surface.

Nomenclature

M = Liquid/liquid flow ratio, Q_2/Q_1
N = Pressure ratio
η = Efficiency
b = Jet pump area ratio A_n/A_t
K_x= Friction loss coefficient at location x
Z = Jet dynamic pressure
c =Area ratio$(A_t - A_n)/A_n = (1-b)/b$
P_x=Pressure at position x

The equations governing the performance of a jet pump are quite complicated, but are somewhat simplified if the motive fluid and suction fluid share the same density and viscosity. The Equations governing the different sections of the eductor using the same liquid for both motive and suction are described in Table 1.

Table 1: Equations governing the sections of a jet pump

Nozzle	$P_i - P_o = Z(1 + K_n)$
Throat entry	$P_s - P_o = Z(1 + K_{en})\frac{M^2}{c^2}$
Mixing chamber	$P_t - P_o = Z[\frac{2b+2M^2b^2}{b^2(2+K_{th})(1+M)(1+M)}]$
Diffuser	$P_d - P_t = Z^2(1 + M)(1 + M)(1 - K_{di} - a^2)$

The pump efficiency η is defined as a ratio between the useful work rate on the suction fluid and the energy extracted from the motive liquid, shown in Equation 7 .

$$\eta = \frac{Q_2(P_d - P_s)}{Q_1(P_i - P_d)} = MN \tag{7}$$

Combining the equations in Table 1 and Equation 7, the theoretical pressure characteristic N for the pump is derived and presented in Equation 8.

$$N = \frac{2b + \frac{2SM^2b^2}{1-b} - b^2(1 + K_{td} + a^2)(1 + M)(1 + SM) - (\frac{SM^2}{c^2})(1 + K_e n)}{1 + K_n - numenator} \tag{8}$$

The equation above allows for a numerical way to decide the pressure and flow relations in the pump. One way to do this is to determine and fix the friction coefficient for each section and set a fixed value b while changing the M value in slight increments. Plotting both $N(M)$ and $\eta(M)$ allows for a way to find the point of best efficiency. [31],[27].

2.9 Other possible pump designs

2.9.1 Vacuum pump

A common choice for conventional fish farms is to utilize a vacuum pump to suck the fish to the surface. This design utilizes a pump at the surface with a hose or pipe leading down to the fish cage, the pump and hose are filled with water and while the pump is running it lowers the pressure upstream. This reduction in pressure sucks the fish out of the water and to the surface. The benefits of this design are the simplicity of installation and maintenance and the fact that it is a common system easily available as a package. The main drawback of this design is the limited available head. A vacuum pump can only ever theoretically reach 1 atmosphere of suction at sea level and practically less than this due to leaks and friction.

2.9.2 Airlift pump

An airlift pump is also a common system used in smaller fish farms to suck up the dead fish at the bottom of the net. A compressor generates air pressure that gets pushed down into the mort cone. The fish are then pumped to the surface using the air stream through the pipe [29].

2.10 Cavitation

A common problem with pumps of all sorts is cavitation. The equations for the Eductor are derived with the critical assumption that no cavitation occurs. Cavitation is the term used to describe the formation of vapor bubbles in liquid flow when the local pressure falls below the vapor pressure. These bubbles heavily affect the flow rate in a pump. The bubbles also self implode creating surface damage on the pump casing [32]. To ensure this does not happen in the eductor the cavitation limited flow ratio M_L has to be calculated. This can be calculated from the operating conditions as follows in Equation 9.

$$M_L = c * \sqrt{\frac{P_s - P_v}{\sigma Z}} \tag{9}$$

where σ is a cavitation coefficient and the rest of the symbols are described in the nomenclature. The cavitation coefficient for water is determined experimentally to be between 0.8-1.4. For general use, Karassik et.al [27] suggests a coefficient of 1.35.

2.11 Mechanical Energy balance

A useful tool when dealing with flowing liquids is the mechanical energy balance. This is a way to balance everything in a system that either is or can be converted into work. For a flowing liquid, this includes mechanical work (energy from a pump or piston, etc.), kinetic energy, potential energy, and flow work (from pressure). Energy converted to heat can not be easily converted to work and is therefore considered lost energy, this is in most cases mostly due to friction. The mechanical energy balance equation is presented in Equation 10. Where (W) is the mechanical work, (v) the velocity, (P) the pressure, (ρ) the density, and (z) the position relative to a reference plane.

$$W + \Sigma F + \frac{v_2^2 - v_1^2}{2} + \frac{P_2 - P_1}{\rho} + g(z_2 - z_1) = 0 \tag{10}$$

2.12 Pressure loss due to friction

Whenever a fluid moves through a conduit there is some change in energy due to friction. When water travels through a pipe the friction between the pipe walls and the water converts some of the water's pressure into thermal energy. Usually, the change in temperature is not relevant to the flow, but the loss of pressure has to be accounted for in calculations [33].

The pressure loss due to friction in a pipe is a function of the; length of the pipe (ΔL), the diameter of the pipe (D), the friction factor (f) and the density of the fluid (ρ), as shown in Equation 11.

$$\Delta P_f = 4 f \rho \frac{\Delta L}{D} \frac{v^2}{2} \tag{11}$$

Or in terms of the energy balance, shown in Equation 12.

$$\Sigma F = 4 f \frac{\Delta L}{D} \frac{v^2}{2} \tag{12}$$

The friction factor has been determined experimentally for a wide range of Reynolds numbers and roughness. These experimental results are plotted in a log-log graph shown in Figure 12.

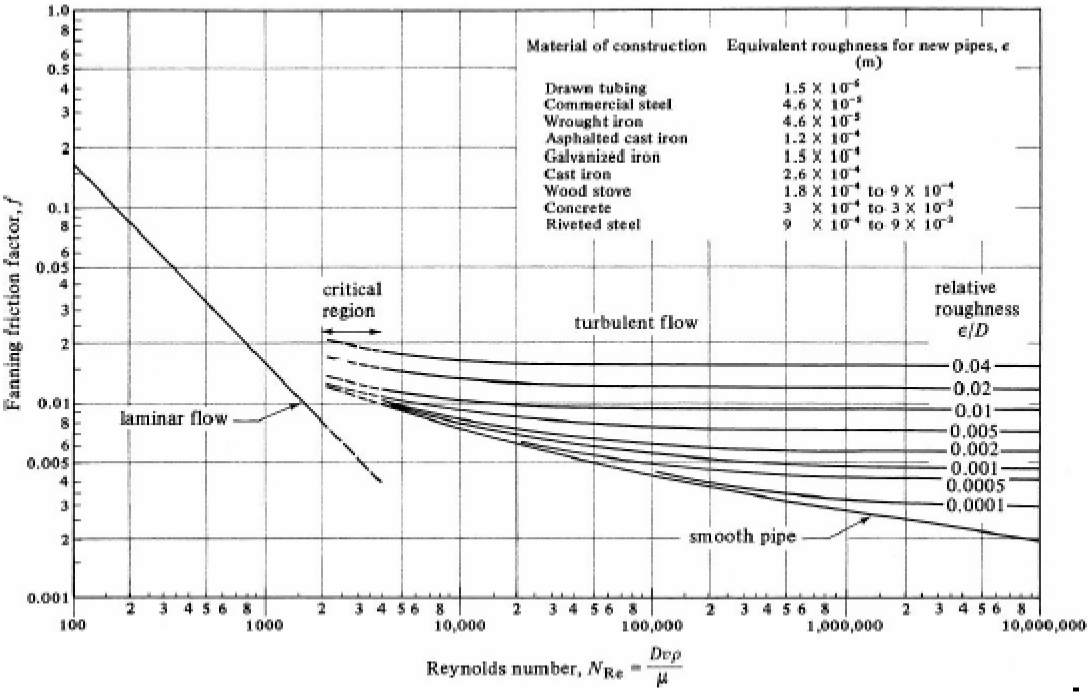

Figure 12: Graph showing the relation between the Reynolds number, relative roughness and the friction factor [33].

To utilize Figure 12 the Reynolds number has to be calculated and the relative roughness of the pipe has to be estimated. The Reynolds number is a function of the; diameter of the pipe (D), the velocity of the flow (v), the density of the fluid(ρ) and the viscosity of the fluid (μ), as shown in Equation 13.

$$N_{RE} = \frac{D v \rho}{\mu} \tag{13}$$

The relative roughness of the pipe is defined by Equation 14.

$$\frac{\epsilon}{D} \tag{14}$$

where (ϵ) is the equivalent roughness and (D) is the diameter of the pipe.

A typical ϵ-value for commercial steel has been experimentally determined to be $4.6 \cdot 10^{-5}$[33]

2.13 Pressure loss due to hydrostatics

Pressure can be thought of as the surface force exerted by a fluid against the walls of it's container. Fluid under the acceleration of gravity exerts force according to Newton's second law which states that force is equal to mass times acceleration, as shown in Equation 15.

$$F = ma \tag{15}$$

The acceleration on a static fluid is equal to the gravitational constant (g), and the mass of the fluid is equal to its density(ρ) times its volume(V). The volume can again be described as height(h) times area(A). Inserting this into newtons second law gives Equation 16.

$$F = \rho g h A \tag{16}$$

Pressure is defined as force per area. Meaning the pressure of a static fluid can be described by Equation 17.

$$P = \rho g h \tag{17}$$

This equation can be utilized to calculate the increase or decrease in pressure of a fluid while moving from one certain height to another. [33]

2.14 General formulas

Calculating mass percent shown in Equation 18.

$$Mass\ percent = \frac{mass\ of\ chemical}{mass\ of\ compound} \cdot 100 \tag{18}$$

Van der Waals equations for non-ideal gasses are shown in Equation 19 and 20.

$$P = \frac{RT}{V-b} - \frac{a}{V^2} \tag{19}$$

$$PV^3 - (Pb + RT) \cdot V^2 + aV - ab = 0 \tag{20}$$

3 Method & Results

To begin designing the system a few base parameters have to be set. The scenarios the system operates within also have to be defined.

3.1 Design basis

Table 2 describes some of the parameters essential to the design, the values marked with a source are sourced externally, and the values without sources are assumptions or estimates described in the discussion.

Table 2: General parameters

Water Temperature$[C^o]$	5
Water density $[\frac{kg}{m^3}]$	1028[34]
Fish density$[\frac{kg}{m^3}]$	1125[17]
Fish water mixture density$[\frac{kg}{m^3}]$	1036
Average full grown fish weight[kg]	5
Total full grown fish biomass[kg]	$1 \cdot 10^7$
System processing capacity[$\frac{Fish}{s}$]	4.6
Height from processing and loading area to the bottom of the fish cage[m]	88
Pipe diameter from mort cone to surface[m]	0.434
Pipe diameter from centrifugal pump to eductor[m]	0.3
Pipe roughness	$4.6 \cdot 10^5$[33]
Supply boat intervals [days]	20
Ensilage loading rate[$\frac{m^3}{h}$]	15
Acid used	Formic acid[35]
Acid density[$\frac{kg}{m^3}$]	1210[36]
Acidity of ensilage [pH]	4[3]

3.1.1 Process description and system overview

The fish farm must be able to contain a maximum biomass of 10000 tons. The fish parameter is an Atlantic salmon with a full-grown weight of 5 kg. The farm is a cylinder shape that stretches 80 meters into the sea. This system is designed to collect dead fish that sink to the bottom of the farm. The dead fish are then gathered on the bottom and fed into a pumping system that brings the dead fish to the surface. Seawater and fish are separated on the surface and the dead fish are fed into a collection tank.

This collection tank needs to be accessible for an operator to access fish samples and examine the cause of death. From the collection tank, the fish are fed directly into an ensilage system to be ground and ensiled to a pH below 4. Finally, the ensilage is transferred to a storage tank where it is accessible to transport vessels.

3.1.2 Scenario 1 (Normal Operation)

Scenario 1 is defined as the normal operation. A biomass of 10000 tons of Atlantic salmon with 5 kg weight, means a total of 2 million fish. It is estimated that 1,5 % of the fish die every month during normal operation, shown in Figure 13 [12]. Assuming a constant mortality rate, this equates to 42 fish per hour as shown in the calculations below.

$$\frac{(10000 \cdot 1000)kg \cdot 0.015}{30\ days \cdot 24\ h} = 208.33\frac{kg}{h}$$

$$\frac{208.33\frac{kg}{h}}{5\ kg} = 41.67\frac{fish}{h} = 0.0116\ \frac{fish}{s}$$

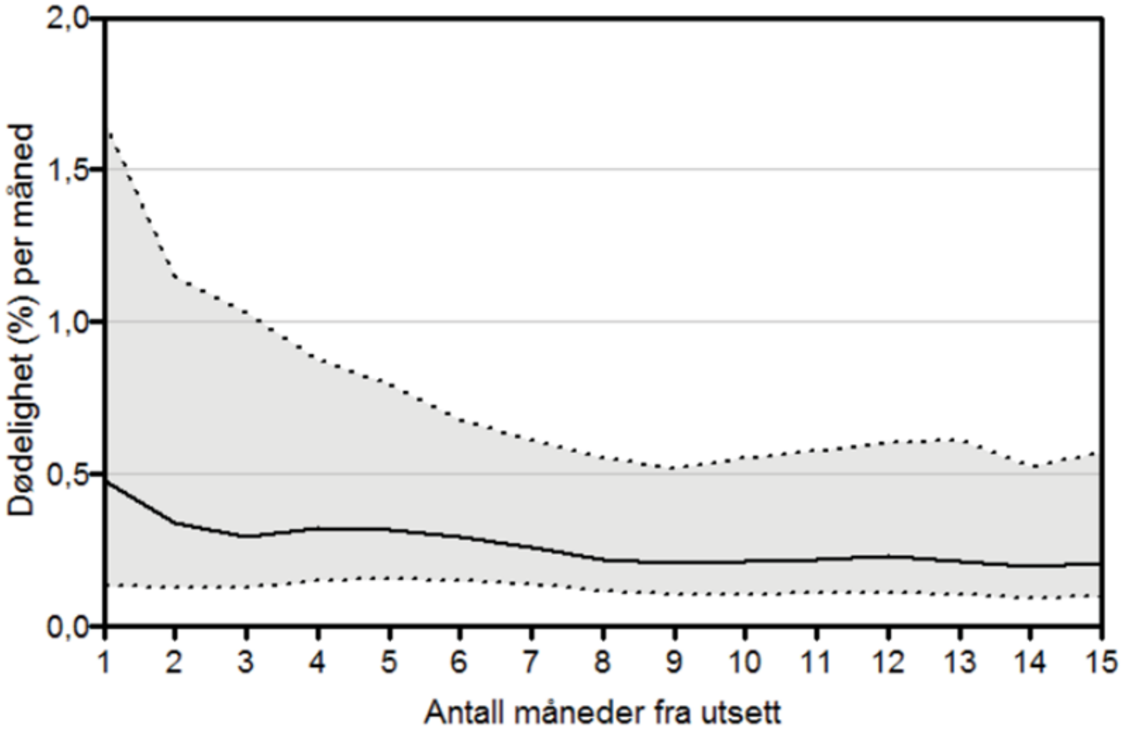

Figure 13: Mortality % per month relative to months in the farm [12].

3.1.3 Scenario 2 (Mass death scenarios)

A mass death scenario can be defined in different ways depending on the time frame and the number of dead fish. In this thesis, a mass death scenario is defined such that 60 % of all the salmon inside the farm die within a 3 day period. This means the system must remove 1.2 million fish within 3 days, or 400 000 fish every day. The weight of the fish depends on their life stage, this could be anywhere from a few kg at their youngest stage up to 23 kg per second for fully grown salmon. To make sure the system can cope with the mortality, the fish are assumed to be fully grown and the mortality rate constant. The removal system has to operate 24 hours a day to be most effective. The calculations are shown below.

$$2\ 000\ 000\ fish \cdot 0.6 = 1\ 200\ 000\ \frac{fish}{3\ days} = 400\ 000\ \frac{fish}{day}$$

$$\frac{400\ 000\ fish}{(24 \cdot 3600)s} = 4.63\frac{fish}{s} \cdot 5\ kg = 23.15\ \frac{kg}{s}$$

3.2 Design sketch

To simplify the design an early sketch of the system components was drawn up. This design sketch was then altered according to the results from calculations and scenario estimates. The resulting sketch containing the chosen system components is shown in Figure 14.'

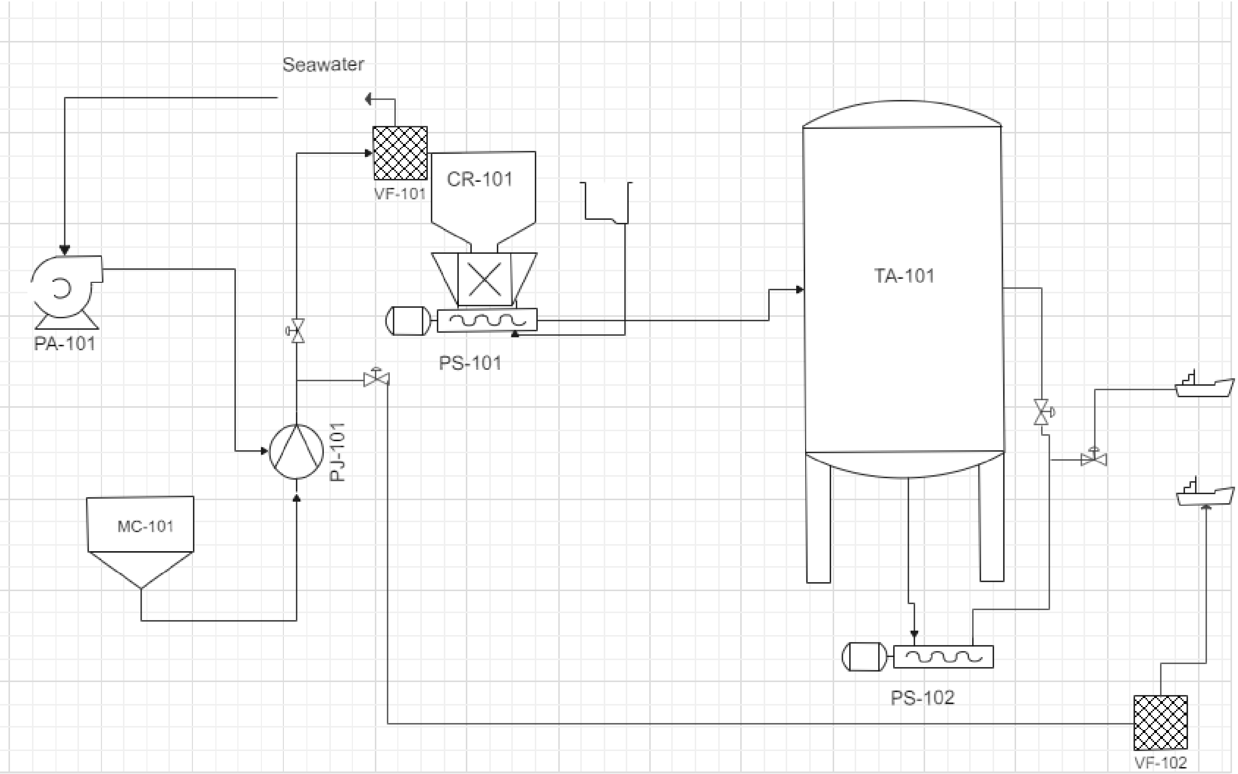

Figure 14: Design sketch.

3.2.1 Scenario 1 system operation (Normal operation)

During this scenario, the dead fish sink to the bottom of the cage and gather in the mort cone collector with tag MC-101. The pile of dead fish that gathers on the mort cone will be removed in intervals. Due to the eductor PJ-101 operating in intervals, a low pressure gets created in the collector. This low pressure sucks the fish the distance from the collector up to the eductor part of the jet pump. The eductor creates enough static pressure to lift the fish the required distance to the surface. All the aforementioned equipment would be submerged near the bottom of the cage.

At the surface the centrifugal pump PA-101 pressurizes seawater to serve as the motive fluid to drive the eductor PJ-101.

Continuing with the process flow the fish reach a strainer at the surface with tag VF-101 which is utilized to separate the dead fish from the seawater. The strainer is designed as a grating with a spacing size small enough to ensure no loss of fish. This ensures the seawater gets returned to the ocean and the fish get fed into the grinder with tag CR-101. At the grinder, the fish is ground to a pulp while acid is injected to create ensilage. After the ensilage is created it is transported through the use of a screw pump to the storage tank TA-101. At the storage tank, the ensilage is continually stirred using the loading pump PS-102 awaiting the next loading period. During the loading period, the circulation of the ensilage stops, and the loading pump is used to transport the ensilage to a ship.

3.2.2 Scenario 2 system operation (Mass death scenario)

During scenario 2 the pump system will operate continuously. After the dead fish are collected by the mort cone, it goes through the eductor as in scenario 1. Instead of going through the ensilage processing, the dead fish pass through a bypass that transports it directly to the strainer VF-102 before being loaded onto a response vessel.

3.3 Calculations for the system

3.3.1 Fish size

To ensure the piping and jet pump are adequately sized, the size of the fish needs to be determined statistically. Atlantic Salmon Fish who have grown up in the same environment, and with the same nutrients available display a normally distributed morphology. As would be expected with a sample size large enough. The quality of most interest, in this case, is the body height central on the fish as this is where the fish display the greatest width. This width is displayed in Figure 15 marked H_d.

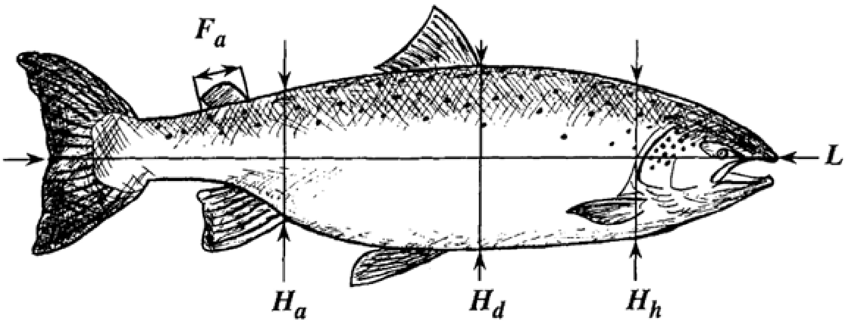

Figure 15: The dimensions of an Atlantic salmon with the central body height marked H_d[37].

A study from the University of Bergen measured 150 fully grown Norwegian Atlantic salmon and divided them into three groups by size[37]. The largest group of fish was measured to display a normal distribution with an expected body width (H_d) of 25.3 cm and a standard deviation of 0.9 cm.

Using Equation 3 the likelihood of a fish being bigger than a certain size can be determined. The piping and pump diameter needs to be big enough so that there is no reasonable chance of fish getting stuck. To start with the calculation of the biggest fish in the cage was made or put in other words an estimated size reached by one out of every 2 million fish.

$$P(z > \frac{(k-25.3)}{0.9}) = 5 \cdot 10^{-7}$$

Using pythons statistics package k was determined to be 29.703 cm. Using this size would run the risk of a fish getting stuck if the fish were fully grown during the fish removal. However, just a tiny increase in diameter up to 30 cm gives a likelihood of just $8.8*10^{-6}$ of a fish being that size. Or put in other words 1 out of every 11.36 million fish. [24]

3.3.2 Pump design

Using the derived 30 cm from the statistical estimation above, the jet pump can be determined to have the smallest diameter of 30 cm. The tightest passage in a jet pump is the mixing chamber. Setting the diameter of the mixing chamber to 30 cm allows the upscaling of the pump using the optimized ratios of smaller designs. The design chosen to upscale is a mixture between the one in Long et. al [38] and its basis which is pump nr. 6 in Shimizu et.al [39]. The nozzle-to-throat area ratio b is an important factor to consider when designing a jet pump. Karassik et al. [27]describes an optimal b ratio ranging from 0.2-0.3 meaning the annular nozzle for this pump needs to have an area of 0.014-0.021 m^2[[27]p. 749].

To find the flow and pressure ratio the method described in the theory was used. Python was used to plot the equations with M increasing in increments of 0.04. And the following constant parameters.
$k_n = 0.05, k_{td} = 0.2, k_{en} = 0, b = 0.2$
These parameters are estimates based on Karassik et al. [27]

The resulting plot is pictured in Figure 16.

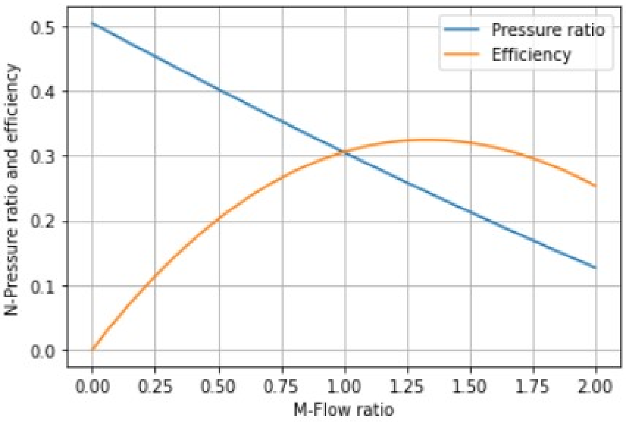

Figure 16: Plot of pressure ratio and efficiency as a function of flow ratio.

Using the plot in Figure 16 the optimal flow ratio M can be determined to be 1.3. To minimize the risk of cavitation it is normal to set the operating flow ratio of about 2/3 of the optimal ratio. This equates to an M- value of 0.8666, and a pressure ratio N of 0.33 with an expected efficiency of 28%.

To ensure the fish get transported to the surface the eductor needs to produce a discharge pressure of 8.98 bar. Using the pressure ratio and the nozzle equation in Table 1 means the centrifugal pump needs to deliver at a pressure of 11.55 bar. The flow rate from the centrifugal pump should be 0.14 m^3/s requiring 38.8 kW of hydraulic power. The suction flow resulting from this pressure is $0.12 m^3/s$, for a total flow of $0.26 m^3/s$ through the eductor. The flow and pressure through the eductor are enough to transport 4.6 fish per second to the surface.

The details of the up-scaling calculations are listed in Appendix A. The key dimensions of the eductor for this system are shown in Figure 17.

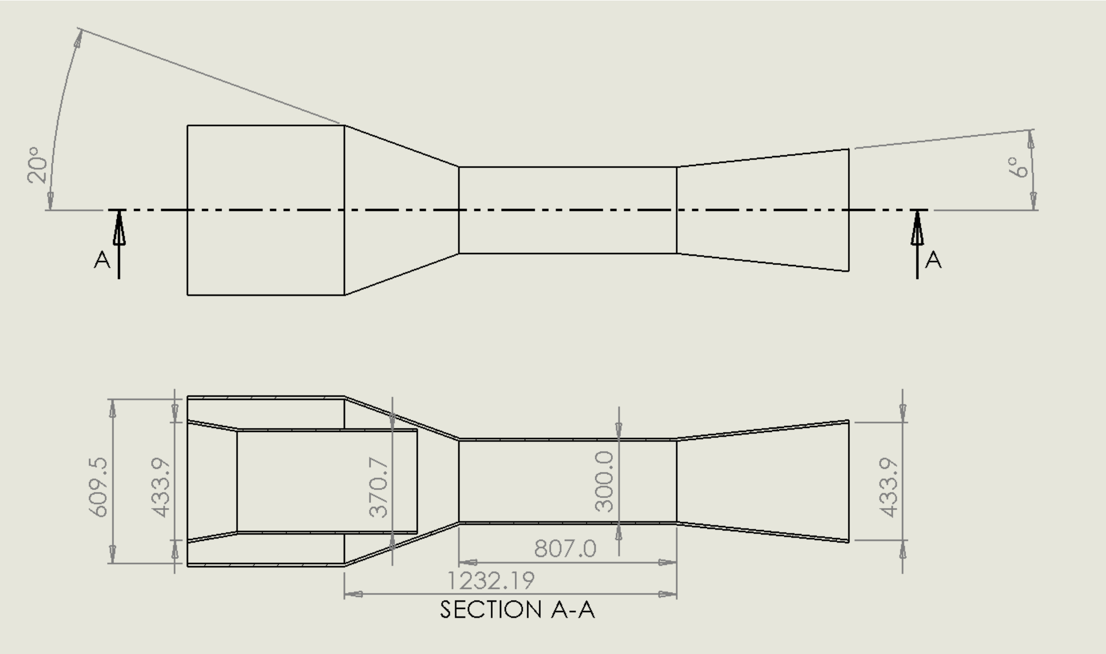

Figure 17: Eductor design with key dimensions [mm].

Determining discharge pressure
To determine the discharge pressure of the pump an energy balance was made from the outlet of the pump and to the outlet at the surface. The eductor was assumed to be placed close to the bottom of the fish cage and the outlet was set to be of the same diameter as the outlet of the pump and open to the atmosphere. These calculations show that a discharge pressure from the Eductor should be at least 8.98 bar_g.

Determining flow
The flow was determined by estimating that the transport of one fish requires one complete volume change through the throat of the eductor. The flow required to transport 4.6 fish per second was calculated to be 0.26 $\frac{m^3}{s}$, this is shown in Appendix A.

3.3.3 Acid injection

To reach a pH level below 4, the ensilage must contain a 3 wt% solution of 98% formic acid. Using Equation 18 it is found that 6.24 kg or about 5.16 L acid must be delivered every hour. To be able to operate for twenty days without refill, there must be at least 2453 L of acid available. Three intermediate bulk containers (IBC) will be adequate for the operation. The calculations are shown below.

$$\frac{x}{208kg} \cdot 100 = 3$$

Density formic acid = 1.21 g/cm^3

$$\frac{6240\ g}{1.21 \frac{g}{cm^3}} = 5157\ cm^3 = 5.16\ L$$

Acid container size:

$$5.16\ \frac{L}{h} \cdot 24\ h \cdot 20\ days = 2476.8\ L$$

3.4 Process equipment parameters

3.4.1 Mort cone (MC-101)

The mort cone suction point needs to have the same diameter as the suction fluid inlet, which is 43.4 cm. The mort cone must have a throughput of 4.6 $\frac{fish}{s}$.

3.4.2 Eductor (PJ-101)

The dimensions of the eductor need to be big enough for the largest likely fish size to pass through. The smallest diameter of the eductor needs to be a minimum of 30 cm. The eductor needs to deliver a flow of 0.26$\frac{m^3}{s}$, and with an outlet pressure of 8.98 Bar$_g$, to ensure adequate transport of fish to the surface.

3.4.3 Centrifugal pump (PA-101)

The centrifugal pump delivering the motive fluid needs to deliver seawater at a flow of 0.14$\frac{m^3}{s}$ at a pressure of 11.55 bar$_g$.

3.4.4 Strainer (VF-101/2)

Both strainers need to separate the water from the fish at a flow rate of 0.26$\frac{m^3}{s}$ where the fish biomass is 7.8% of the volume.

3.4.5 Fish grinder (CR-101)

The grinder needs to process 208 kg per hour. This includes both the grinding and acid injection. The acid injection system needs to inject 5.16 L of acid per hour.

3.4.6 Acid container

The acid container must be able to contain 2500 L of acid. Either as a single tank or with the use of several intermediate bulk containers of 1000 L.

3.4.7 Screw pump (PS-101/2)

The screw pump needs to have the same capacity as the grinder. 5 tons/day during normal operation. This equates to ca. 4.5 m^3/day. The loading pump needs to have a capacity of 15 $\frac{m^3}{h}$ to ensure fast loading.

3.4.8 Storage tank (TA-101)

To be self-sufficient for up to 20 days without a supply boat, the storage tank needs to be 100 m^3 large at the minimum.

3.5 Simulation

3.5.1 3D model

To get a better idea of the flow and pressure characteristics in the pump a 3D model was created in Solidworks, Figure 17 and the other drawings through the thesis are based on this 3D model.

Using the 3D model and Solidworks Flow simulation package. A study was conducted with the following boundary conditions. Shown in Table 3.

Table 3: Water parameters

$Liquid$	$Tempereture[C^o]$	$Q_i[\frac{m^3}{s}]$	$Q_s[\frac{m^3}{s}]$	$P_d[Bar_a]$
$Water$	5	0.14	0.12	9.99

3.5.2 Pressure gradient

In Figure 18 the pressure changes in the different regions of the eductor are displayed as a colour gradient.

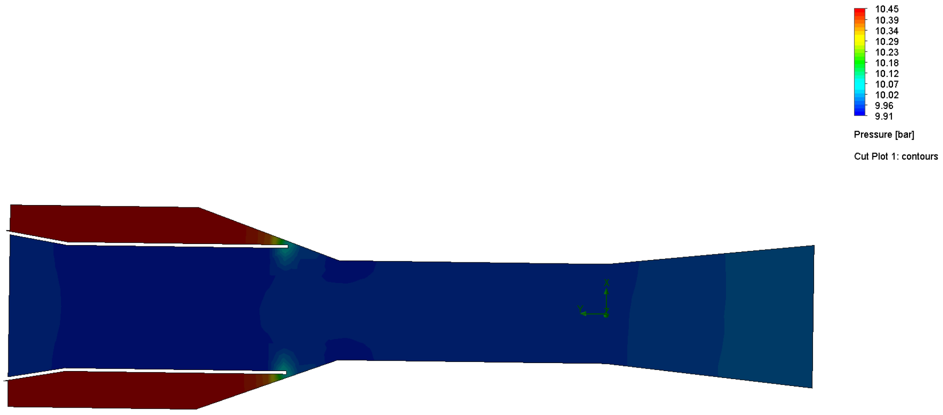

Figure 18: Pressure gradients through the eductor.

Flow trajectories and velocity
In Figure 19 water trajectories are displayed with arrows, with their color gradient showing their velocity changes.

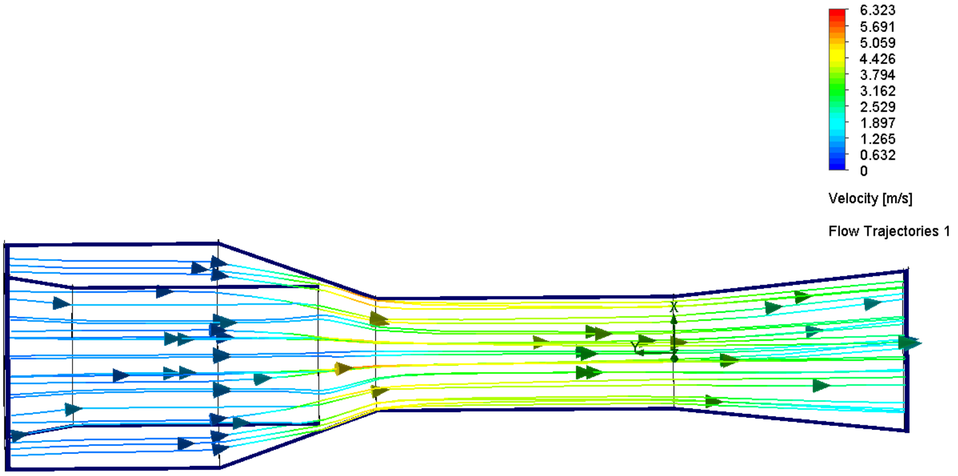

Figure 19: Flow trajectories and velocity of the fluid through the eductor.

4 Discussion

As this thesis is theoretical some of the parameters and scenarios are estimates or assumptions made at the best effort from the source material available.

4.1 Design basis

4.1.1 Parameters

The water temperature at depth in the north sea is relatively constant at 5 C^o, however, at the surface it fluctuates quite a bit with the seasons. The water density is only slightly dependent on temperature and a fluctuation of a few degrees will not create an appreciable effect on the density[34].

The fish density is taken from government recommendation[17]. Other sources describe salmon with a somewhat lower density[40]. An overestimate is beneficial as an underestimation could result in the pressure and flow being too scarce.

The water fish mixture density is based on the assumption that each fish requires a volume of water equal to the volume of water in the throat of the eductor. Whether or not this is a reasonable estimate needs to be determined experimentally.

The full grown fish weight is a parameter, that like the fish width, is normally distributed. For calculation purposes, the average weight is of most interest as several fish will be present in the pipes at the same time.

The full grown fish biomass is a parameter set by the client.

The system processing capacity was chosen based on the mass death scenario, and the flow requirements of the eductor. There is great difficulty in designing a system capable of handling vastly different loads. Setting a fixed load and instead utilizing the system in intervals helps solve this issue. The actual system capacity needs to be determined experimentally as a lot of assumptions are made in the design.

The distance of 88 meters from the bottom of the cage to the processing system was chosen to be able to handle the 80 meters of depth of the fish cage. As well as the height from sea level to the processing area. The processing area needs to be a few meters above sea level to accommodate for waves and the height of supply vessels.

The pipe diameter was chosen to match the inlet width of the eductor, this diameter results in quite a bit more water having to be moved as opposed to more conventional designs with the suction being provided at the surface. But is necessary to accommodate the eductor.

Pipe roughness has been determined experimentally for industrial steel and is probably a reasonable estimate. However, the friction factor is only meant as a placeholder as the actual material used in the piping may have a different friction factor. Industrial steel is very susceptible to corrosion and an unlikely choice for underwater operation.

The system was designed to operate for 20 days self sufficiently. This is longer than most conventional fish farms, but was chosen as it is a more strenuous journey to reach an offshore fish farm.

15 $\frac{m^3}{h}$ as an ensilage loading rate may be a bit low, but was chosen as there are commercial screw pumps for ensilage easily available. A higher loading rate may be beneficial to reduce the time the supply boat spends at the farm.

The acid used was one recommended in El-Hay et al. [35], and what a lot of conventional fish farms utilize today[41].

The acid density is a table value from SI Chemical data[36] and thus probably correct. The temperature could affect the density.

The ensilage pH is a requirement from the government[3] and has to be fulfilled.

4.1.2 Scenario 1

During normal operation, there is an expected chance of death of ca. 1.5 % per month for young fish. This number decreases relative to the salmons' total time spent in the farm, shown in Figure 13. Young fish do not weigh their full 5 kg yet, but a system capable of handling that amount will offer sufficient redundancy later in the life cycle.

4.1.3 Scenario 2

60% mortality within three days is selected for the mass death scenario. This number is estimated from other mass death scenarios in the past. Mainly considering the amount of dead fish in the delousing treatment accident and the algae flourishing mentioned in section 2.4.

It is also important to consider the time it takes for the fish to bloat and start floating. When the fish start to decay gases build up and lower their density, rendering the system useless. Luckily, the cold waters of the North Sea help keep this at bay for at least a few days. Giving time for the removal of dead fish quite a while after their demise.

Another challenge in this scenario is the weight of the dead fish accumulation. This could cause structural damage to the net, and cause a decrease in buoyancy for the farm.

4.2 Operation

4.2.1 Normal system operation (scenario 1)

The decision to run the system in intervals was made because most processing equipment is designed for large batches of dead fish and not continuous low loads. Having the system run at intervals also allows for only one pumping system. As two pumping systems would be needed for the large difference in load between the two scenarios in the case of continuous operation.

4.2.2 Mass death system operation (scenario 2)

During a mass death scenario, the main priority is getting the dead fish out of the water. Because of this, the ensilage system is bypassed. Since the fish get transported to the surface without grinding, sampling of the fish can be done at the strainer or directly from the response vessel.

4.3 Equipment choice

4.3.1 Collection device

For the collection of dead fish at the bottom of the net, there are not many options available. It is common to collect the mort by hand in smaller farms located in fjords, but this will be more problematic than useful in offshore farms.

The mort cone was the most applicable collection device that can continuously collect mort. Instead of lowering it down in short intervals, as in some conventional farms, the mort cone will be installed permanently to be most effective [42]. The suction at the inlet is created by the chosen pump equipment that delivers enough flow to suck in dead fish, but live fish can still swim away from the suction. To be most efficient and create space for more dead fish, the outside rim of the cone will be bigger than normal collectors. The suction point diameter was chosen to be 43.4 cm. This was the smallest diameter that would not affect the flow created by the pump because the smallest diameter of the eductor was set to 30 cm.

4.3.2 Pumps

Three different design options for dead fish pumping are described in section 2.8.5 and 2.9 of the theory.

One of the most commonly used pumps today is the vacuum pump. The vacuum pump works well in smaller farms where the dead fish are located around 20 meters under sea level. This is because it is cheap to install and most of the equipment is located at the surface for ease of operation and maintenance. It is possible that this design could operate in offshore farms, but the main drawback of this design is the limited available head. Because the vacuum pump can only reach 1 atmosphere of suction at sea level (practically less than this due to leaks and friction) it gives little control over flow and pressure.

Another commonly used pump design is the airlift system. Similar to the vacuum pump system, it pumps up fish from much shallower farms than offshore farms. If this system was to be scaled up to an offshore-sized farm, both the dimensions and the pressure would need to be increased massively. When the air is pushed through the pipe, the air bubbles expand closer to the surface due to decreased water pressure. This will cause a problem when the air inlet is located 80 meters below sea level. Most of the volume inside the pipe near the top will be air, this can cause damage to the fish. The calculation for air expansion is shown in Appendix A.

A third option and most discussed design is an eductor with a centrifugal pump that generates flow through the system. This is not a design in use at this scale today. But it offers a lot of advantages, it has the benefit of having all the moving parts at the surface (like the other systems) but it is not subject to the same pressure and flow limitations. And because water is in practice in-compressible the large volume changes found in the airlift system are not a problem. This system is not without its limitations either. Being a new system more practical experimentation is needed to accurately optimize the dimensions, flow and pressure ratios. There is also little production and maintenance infrastructure available today for eductors of this size further increasing costs.

For the ensilage transport the pump needed to be able to handle high viscosity and suspended impurities with a steady flow. A screw pump handles both of these issues and delivers flow at a steady rate. The main drawback of screw pumps is the low pressure delivered, this is not a problem in this scenario as the tank is not very tall. Screw pumps are also easily available in most capacities as they are common processing equipment.

The centrifugal pump was chosen because of its high flow and pressure delivery at a steady rate and the low viscosity of the motive fluid. Centrifugal pumps are not 100% efficient meaning that the 38.8 kW of required hydraulic power translates to somewhat higher power requirements for the pump engine.

The decision was made to utilize the same pump for both circulating the ensilage in the tank and for loading. This requires a pump able to operate at very different revolution speeds. Screw pumps are quite forgiving when it comes to changes in revolution speed, but it may be easier to utilize separate pumps instead.

4.3.3 Grinder

A lot of fish grinders, with large capacities, are commercially available today from conventional fish farming. The main difference between grinders except for their capacity is the option for integrated acid injection. Integrated acid injection removes the need for an external acid regulation system outside the grinder that would be needed in different circumstances.

4.3.4 Strainer

To separate the fish from the water, a strainer should be enough as the fish are a solid mass before the grinder, and the water will flow out due to gravity. The strainer will also have to take into account that not all the fish remain structurally intact when being transported to the surface.

4.3.5 Acid Container

A single tank would have the benefit of not being refilled as often, but this would require some infrastructure design to enable the refilling. 3 intermediate bulk containers could instead be used. These containers could easily be delivered by a supply vessel and switched between manually.

4.3.6 Storage tank

Storage tanks are commercially available in most sizes. A large redundancy would be highly recommended to accommodate unforeseen increases in load or supply boat periods.

4.4 Fish size

The fish size estimates were made with three assumptions.

1. Fish grown in conventional fish farms share the same size as fish grown offshore.
2. Fish size follows a normal distribution
3. The sample size is representative of the entire population

The first assumption is dependent on the offshore fish experiencing similar conditions as the close-to-shore fish. The light and feed conditions are mostly going to be the same, but the current and temperatures are going to be different. Also, the water composition may differ. This may effect the growth of the salmon as mentioned in the theory.

As for the second and third assumptions, Lange, T. [37] shows the fish displaying a normal distribution. However, the sample size is relatively small compared to the massive amount of fish in the offshore cage meaning the expected value and standard deviation can't be considered completely accurate. To adequately predict the size distribution an experiment with large amounts of fish grown in the same environment as offshore fish farms would have to be conducted.

4.5 Eductor design

The design of the eductor is based on a lot of previous experimentation with smaller eductors. There is no guarantee that the behavior of these smaller eductors accurately predicts the characteristics of a larger eductor. The larger space allows for more free movement of the fluid, and it is possible this affects the efficiency. The proposed design in section 3.3.2 is meant as a starting point for further development. To properly develop an eductor, experimentation is needed. According to the calculations, the proposed design is quite far from cavitation, which is normally the limiting factor. Meaning the eductor could probably operate at a higher capacity without being subject to performance limitations from cavitation. An efficiency of 28% is also quite low compared to other types of pumps. But stems from the fact that the pump can have no moving parts.

4.6 Flow and pressure simulations

The flow and pressure simulations had to be very simplified as flow simulation with semi-solid fish within the liquid would quickly get very complicated. The simulation program utilized also didn't allow for both pressure and flow conditions at the same place. Because of this the calculated flow conditions of the inlet and the pressure conditions of the outlet were utilized.

4.6.1 Flow simulation

The flow simulation shows a behavior similar to the one predicted. With the highest velocity at the exit of the annular nozzle and the fluids mixing their velocity through the throat. Before converting their kinetic energy to static in the diffuser. The velocity at the diffuser is very close to the predicted 1.75 $\frac{m}{s}$.

4.6.2 Pressure simulation

The pressure simulations shown in Figure 18, show a pressure somewhat deviating from the prediction, especially in the suction part of the pump. However, the general pressure characteristics are as expected. The pressure is lowest in the suction inlet part of the eductor. And increases towards the end of the diffuser. The largest pressure gradients are found around the annular nozzle. These pressure gradients might be a cause of trauma for the fish and should be considered during further development of the pump.

4.7 New rules and regulations

The offshore fish farming business is still in development and likewise are rules and regulations regarding control and fish welfare. Companies that want to build a facility will still need to consider the same fish welfare rules as the existing farms. This could cause problems due to the fish count being ten times larger. The current ”Traffic light” system is only applicable to farms along the Norwegian coastline, but will most likely apply to many regions in the North Sea when other farms start construction [20]. The amount of farmed fish in certain areas will have to be increased due to more accessible space and less impact on the close environment.

The regulation regarding the maximum number of salmon lice per fish would probably be changed in offshore farming locations. Offshore farms will be less impactful on the wild salmon population, because of the distance to river outlets. A larger distance between each farm will also decrease pressure from salmon lice. This will probably allow a higher number of lice per fish, which will overall decrease the amount of dead fish from delousing treatment.

5 Conclusion

To be able to handle the dead fish in an offshore fish farm both during normal operation and during a mass death scenario, a system consisting of the following equipment was proposed.

- A mort cone with a suction inlet of 43.4 cm
- An eductor capable of delivering 0.26 $\frac{m^3}{s}$ of a water fish mixture at 8.98 bar
- A centrifugal pump driving the eductor and delivering 0.14 $\frac{m^3}{s}$of water at 11.55 bar
- A strainer
- A fish grinder able to process 208 kg of dead fish per hour
- Three acid containers with 1 m^3 capacity
- A screw pump able to transport 208 kg of dead fish per hour
- A storage tank with a capacity of 100 m^3
- A screw pump for both circulating the ensilage in the storage tank and loading ensilage to ships at a rate of 15 m^3 per hour

This system is theoretically capable of handling 4.6 fish per second while operating continuously, but is designed to operate in intervals during normal operation. Computer simulations show the liquid through the eductor behaving close to what was predicted in the calculations.

This system is meant as a preliminary design, further development and experimentation is needed before the system is ready for implementation. Further work may include further development of the eductor, testing the removal capacity and defining intervals, and checking some of the assumptions experimentally.

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Appendix A

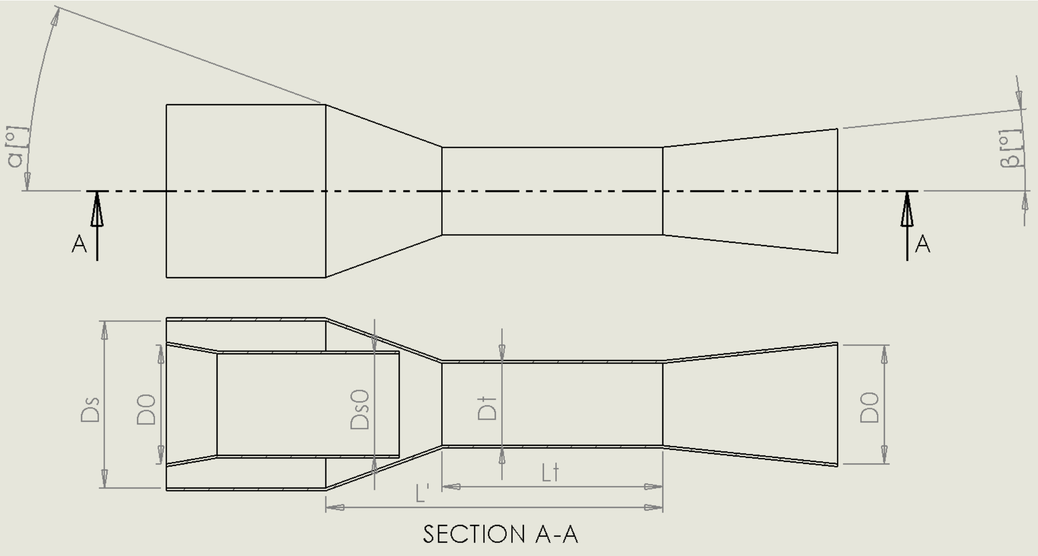
Up-scaling calculations

Eductor ratios:

$\alpha[°]$	$\beta[°]$	L_t/D_t	L_t/D_0	$D_t[mm]$	L'/D_0	$A(D_0)/A(D_{s0})$
20	6	1.86	2.69	300	2.84	0.73

$L_t = 2.69 \cdot 300 = 807mm$
$D_0 = 807 \cdot 1.86 = 433.87mm$
$L' = 2.84 \cdot 300 = 1232,19mm$
$L' - L_t = 425.19$
$D_s = 2 \cdot tan20° \cdot 425.19 + 300$
$b = 0.2 \cdot A_t = \pi \cdot (\frac{300}{2})^2 \cdot 0.2 = 0.014m^2$

Finding the length of extrusion that gives correct nozzle area:
$\pi \cdot r_1^2 - \pi \cdot (\frac{D_{s0}}{2})^2 = 0.014m^2$
Solved for r_1 gives:
$r_1 = 195.35mm$
Distance from throat can be found by:
$\frac{(206.44-150)}{tan(20^o)} = 155.07mm$
meaning the nozzle should be placed 155.07mm from the beginning of the throat.



Estimating motive fluid pressure

$\frac{P_d - P_s}{P_i - P_s} = \frac{N}{N+1} \; \frac{8.98. - 8.13}{P_i - 8.13} = \frac{0.33}{1.33}$

$P_i = 11.55$

Checking cavitation limit

$P_i - P_s = Z(1 + K_n)$
$Z = \frac{3.42}{1.05} = 3.26$

$M_L = \frac{1-0.2}{0.2} \cdot \sqrt{\frac{8.13-0.0087}{1.35 \cdot 3.26}} = 5.43$

$5.43 >> 0.866$ meaning the Flow ratio is lower than the ratio likely to create cavitation.

Dead fish removal rate calculations

Total biomass in the farm: 10000 tonnes
Average fish size: 5 kg
Fish density: 1125 kg/m^3
Occupied fish area:

$$\frac{5\ kg}{1125\ \frac{kg}{m^3}} = 4.44 \cdot 10^{-3}\ m^3 = 0.0044\ m^3$$

Volume of the eductor throat:
Throat diameter (DT) = 30 cm
Throat length = 80.7 cm Volume of water filled throat area

$$\Pi \cdot (\frac{30}{2})^2 \cdot 80.7\ cm = 5704.5\ cm^3 = 0.057\ m^3$$

To simplify the water-fish liquid is assumed to be behaving like a liquid with a density consisting of a combination of the two. Assuming there is one fish per change of throat volume the density can be calculated as below

$\rho = \frac{4.44 \cdot 10^{-}3}{0.057} \cdot 1125 \frac{kg}{m^3} + \frac{0.057 - 4.44 \cdot 10^{-}3}{0.057} \cdot 1028 \frac{kg}{m^3} = 1036 \frac{kg}{m^3}$

During a mass death scenario the eductor needs a throughput of about 4.6 fish per second. This means that the throat volume needs to be changed 4.6 times per second

or put in other words the total flow needs to be 4.6 times 0.057 m^3 per second
Calculating flow:
Flow rate ratio (M) = Q_s/Q_i = 0.866

$$Q_i + 0.866 \cdot Q_i = 4.6 \cdot 0.057 \frac{m^3}{s} = 0.26 \frac{m^3}{s}$$

$$Q_i = 0.14 \frac{m^3}{s}$$

$$Q_s = 0.12 \frac{m^3}{s}$$

Finding discharge pressure

To find the discharge pressure an energy balance was made from the outlet of the Eductor to the opening of the pipe over the grating. Energy balance:
$W + \Sigma F + \frac{v_2^2 - v_1^2}{2} + \frac{P_2 - P_1}{\rho} + g(z_2 - z_1) = 0$
There is no change of diameter from the outlet of the eductor to the surface meaning $v_2^2 - v_1^2 = 0$, there is also no mechanical work being done after the pump meaning $W = 0$.
ΣF can be calculated as shown below:
$D = D_0$

$\rho = 1036 \frac{kg}{m^3}$

$v = \frac{0.26 \frac{m^3}{s}}{\pi (\frac{D_0}{2})^2} = 1.75 \frac{m}{s}$

$N_{RE} = \frac{Dv\rho}{\mu} = \frac{0.434 \cdot 1.75 \cdot 1036}{1.61 \cdot 10^{-3}} = 4.9 \cdot 10^5$

This is turbulent flow.

$\epsilon = 4.6 \cdot 10^-5$

$\frac{\epsilon}{D_0} = 1 \cdot 10^{-4}$

from Figure 12:

f=0.0035 ΣF= $4f \frac{\Delta L}{D} \frac{v^2}{2} = 4 \cdot 0.0035 \cdot \frac{88}{0.434} \cdot \frac{1.75^2}{2} = 4.34 \frac{J}{kg}$

The flow out of the Eductor was assumed to be 0.26 $\frac{m^3}{s}$ and the pipe diameter was set to equal D_0. The height from the eductor to the surface was set to 88 m:
$g(z_2 - z_1) = 9.81(88 - 0) = 863 \frac{J}{kg}$

Solving the energy balance for P1 gives:
$P_1 = \rho(g(z_2 - z_1) + \Sigma F) + P_2$

$P_1 = 1036(863 + 4.34) + 101325 = 9.99\ bar_a$
However it is more useful to operate with bar$_g$. This means the pressure at the outlet should be 8.98 bar$_g$.

Power requirements for the centrifugal pump

$D = 0.3m\ W = \Delta P Q$
$\Delta P = P_i + \rho(g(z_1 - z_2) + \Sigma F)\ v = \frac{0.14\frac{m^3}{s}}{\pi 0.15^2} = 1.98\frac{m}{s}\ \Sigma F = 0.004 \cdot 4 \cdot \frac{88m \cdot 1.98\frac{m}{s}^2}{0.3m \cdot 2} = 9.19\frac{J}{kg}$
$\Delta P = 11.55 \cdot 10^5 pa + 1028\frac{kg}{m^3}(9.81\frac{m}{s^2} \cdot (-88m) + 9.19) = 2.76 \cdot 10^5 pa$
$Q = 0.14\frac{m^3}{s}$
$W = 38.8kW$

Without regarding the efficiency of the pump.

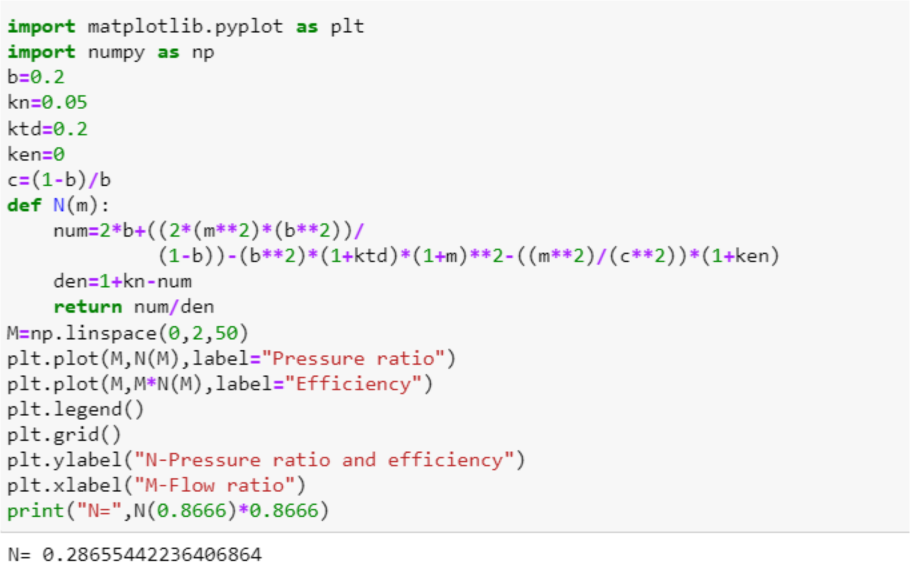
Air expansion calculations for air lift system

Using equation 20 the large change in air volume from the pressure change was found:
a = 1.4
b = 0.039
T = 5°C
P1 = $1 * 10^5$ Pa
P2 = $8 * 10^5$ Pa
Volume 8 bar = 2.87 L/mol
Volume 1 bar = 23.84 L/mol

Apendix B

Python code

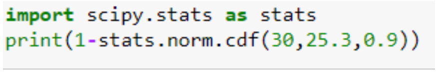
Eductor plot



```
import matplotlib.pyplot as plt
import numpy as np
b=0.2
kn=0.05
ktd=0.2
ken=0
c=(1-b)/b
def N(m):
    num=2*b+((2*(m**2)*(b**2))/
             (1-b))-(b**2)*(1+ktd)*(1+m)**2-((m**2)/(c**2))*(1+ken)
    den=1+kn-num
    return num/den
M=np.linspace(0,2,50)
plt.plot(M,N(M),label="Pressure ratio")
plt.plot(M,M*N(M),label="Efficiency")
plt.legend()
plt.grid()
plt.ylabel("N-Pressure ratio and efficiency")
plt.xlabel("M-Flow ratio")
print("N=",N(0.8666)*0.8666)
```

```
N= 0.28655442236406864
```

Fish size statistics



```
import scipy.stats as stats
print(1-stats.norm.cdf(30,25.3,0.9))
```