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Author: Lars Andreas Larsen	Lars Andreas Larsen ………………………………………… (signature of author)

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Abstract

There are 7.6 billion people on this planet today, and it is predicted that the world's population will exceed 9 billion people by 2050, which will lead to a significant increase in the worldwide demand for food. With this immense growth in population, it is estimated that the world must increase the production of meat and animal products by 40% over the next 15 years. When oceans cover more than two thirds of the world's surface, and only 2% of the food energy for human consumption comes from the sea, the increasing food demand will cause the fish farming industry to play a major part in feeding future generations.

In addition to the fact that the fish farming industry need to produce more fish in the future, the industry is required to do so using less resources and with a minimal environmental footprint. This increasing demand will threaten the sustainability of fish farming and cause the industry to be even more exposed to the already major challenges associated with salmon lice and environmental pollutions.

To achieve growth and maintain sustainability, the industry need to invest in technology development to improve today's solutions in line with evolving challenges and the expected increase of production demand. To comprehend with these emerging biological, economic and social challenges, the fish farming industry in the future is assumed to be moved more out to the sea, to maintain an ethically sound, productive and environmental friendly production of salmon. When fish farming will be placed offshore and on remote locations, the fish farms will also increase in size and complexity, as well as being more exposed to harsher environment. It is therefore important for the industry to adapt to the emerging technology trends and aspires to more innovative and sophisticated technology that will improve farming management and create farming solutions that provide sufficient knowledge and information to monitor and control the biological process.

The innovative opportunities for a future sustainable fish farming industry are mainly derived from emerging technology trends such as renewable energy and energy storage, sensorization, connectivity (IoT) and autonomization. This thesis investigates how these technology trends can impact fish farming, and identifies various innovative opportunities derived from these trends. The innovative opportunities and solutions identified are evaluated in terms of how they can improve current solutions and improve fish farming in relation to monitoring and control of biological processes, net pen and surrounding environment, feeding processes, lice infestations, as well as their potential for realization of more automated, unmanned and remotely operated farming systems and operations.

After reviewing the possibilities for energy storage and offshore power generation, it has been found that there is a high readiness level for off-grid energy solutions for fish farming. The recent development in offshore wind power, solar power and wave power in combination with Li-Ion battery storage enables the possibility for self-sufficient energy systems that can power a full-size farm site, while eliminating CO2 emissions and the excessive costs from diesel generator systems.

The development in sensorization, connectivity and digitalization has increased the level of computational capacity which enables algorithms to collect and interpret data recorded by sensors and transform this into useful information. With advanced algorithms, robotic technology and artificial intelligence this information can without human intervention be interpreted and acted upon automatically. This technology is well established in other industries, and if implemented in fish farming, it can contribute to move commercial fish farming from a current state of manual monitoring and operations and experience-based decision-making towards a more automatic/autonomic and knowledge-based farming regime. The *Precision Fish Farming (PFF)* concept breaks down the operational phases in fish farming and types of sensors that can be implemented, showing how the utilization of sensorization and connectivity is the key technology trend in realization of more automated, unmanned and remotely operated farming solutions and processes.

Opportunities in autonomization are investigated, with an evaluation of several ongoing and already implemented projects that utilizes robotics technology for improved lice control and lice removal, as well as specific possibilities for autonomous operations as net cleaning systems, feeding systems and daily operations as cage inspection, maintenance and repair. The already implemented *Stingray*-system uses laser technology and advanced software and camera vision, to identify and shoot sea lice that are attached to salmon, without causing any harm to the fish. The Stingray technology has also the possibility for automatic and optical sea lice counting and biomass measurement. Other patent pending project research on enabling unmanned fish farms and land-based control centres, by utilizing an unmanned surface vehicle (USV) to carry a ROV and drone between sea cages to perform daily operations and inspections.

Together, all these innovative opportunities that emerge from the technological trends will in the near future contribute to move fish farming more out to sea, as well as contributing to cope with the various challenges that will evolve in line with the growing industry.

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1 Introduction

As the rapidly growing world population will lead to a significantly increase in the global demand for meat and animal products in the future, the fish farming industry will become a major priority area industrially and face great pressure to increase production in the years to come. Norway, which is the second largest exporter of farmed fish in the world, has over the last decades seen rapid growth in production volume and economic yield, and will continue to be key provider of seafood and be forced to expand and produce increasing amounts of fresher and high-quality salmon to the global market in the future.

However, the Norwegian fish farming industry will face great challenges regarding technical and operational aspects of fish farming. As Norwegian fish farms always have been located in fjords and in shallow waters along the cost, the industry have continuously coped with issues such as space limitations, sea lice, spreading of sickness and environmental pollution. As the scale of production will increase rapidly, the industry will face even greater emerging biological, social and economic challenges that will threaten Norwegian fish farming and its ability to maintain an ethically sound, productive and environmentally friendly production of salmon.

To achieve growth and maintain sustainability, it is therefore important that the industry invest in technology development and improves today's solutions to monitor and control the potential upscaling challenges when upscaling production. To comprehend with the emerging challenges, modern technology trends such as mainly sensorization, in addition digitalization and connectivity, are key elements in opportunities to implement innovative and improved solutions regarding monitoring and control of the fish, net pens, environment, feeding and lice infestations. Application of these trends has the potential to solve specific challenges as biomass monitoring, control of feed delivery, lice counting and parasite monitoring and general farming management and documentation of biological processes.

Due to the expected increase in demand and production of salmon, it is predicted that fish farming will be moved further out to the sea, in more exposed locations. Offshore based farming will create a better environment for fishes, due to the large change-out of water, and the large area and high currents will transport waste materials away reducing the environmental impacts. The deeper waters can also eliminate the challenges related to sea lice. When fish farms are moves farther at sea and in more remote locations, existing solutions and operations that consist of manual labor and staffing at site can be insufficient in relation to the more challenging and harsher environment and its environmental loads as waves, currents and winds. To address these challenges, a lot of research is being performed on developing unmanned and remotely operated fish farms that utilizes autonomous and automated systems that can be controlled and monitored from land-based control centers. To enable these solutions, the fish farming industry must apply principles from technology trends in autonomization, such as artificial intelligence, robotics technology and advanced algorithms in combination with sensor systems, big data gathering and connectivity between systems and devices.

Existing solutions in today's salmon farming depend on manual labour and crew/operators on the cage rings. The trend will be that fish farms will move farther at sea, where existing technology and methods are insufficient in relation to the challenges of harsher environment and where staffing at site is difficult. In addition, the methods of which salmon lice and environmental issues are handled are also not sufficient. To address these challenges, there are several players already well in the process of utilizing autonomization to develop innovative systems and methods for remote and sustainable fish farming. All the upcoming examples of innovative solutions for improved monitoring and control in fish farming are based on PFF principles, as well as the mentioned technology trends.

As fish farms will be located more out to sea and offshore, they will consume more energy and connection to the onshore electricity grid can be challenging. The fish farming industry must therefore develop opportunities for off-grid and self-sufficient energy systems. The emerging trends in energy and recent development in offshore power generation, solar power and battery storage can also be key technology trends in realization of offshore fish farming, as well as an opportunity to make the entire fish farming industry more climate friendly by eliminating the need for diesel systems.

1.1 Objectives

The objective of this thesis is to identify and investigate various innovative opportunities arising from trends in modern technology that can contribute to future growth and a sustainable fish farming industry with minimal environmental footprints and human safety at risk. The identified opportunities need to be evaluated in terms of how they can affect and improve current solutions and farming management, as well as their ability to enable for more offshore based and future-oriented fish farming. To achieve innovating in the fish farming industry, these innovative opportunities must also be evaluated in relation their possibility to eliminate or reduce the impact of the existing challenges the industry are and will face.

To perform this evaluation, an overview of the Norwegian fish farming and all its segments must be carried out, with a breakdown of all products, systems, processes and operations involved in the salmon production cycle. All existing challenges must be identified, as well as their extent, possible consequences and current methods of handling. Before evaluating possible innovative opportunities, the most relevant technology trends must be identified, as well as determine what these trends consist of and their possible significance for current and future fish farming.

After a thorough review of all ongoing and recent research, development and projects in fish farming emerged from trends in technology, the identified opportunities will be evaluated against each other and in relation to their ability to innovate in the fish farming industry. The thesis shall then conduct an assessment of the most promising opportunities for a sustainable future.

1.2 Outline of the thesis

Chapter 1 is an introduction to the fish farming industry, with problem description and background, as well as the objectives of the thesis.

Chapter 2 provides an overview of the Norwegian fish farming industry, with a breakdown of its most relevant segments and the production cycle. The most common challenges are identified, and their origin, consequences and methods of handling are described.

Chapter 3 shows which delimitations that are set in the relation to the production cycle of fish farming. The chapter breaks down and reviews all the main components and technology used in a traditional Norwegian fish farm.

Chapter 4 describes the relevant emerging technology trends, what they consist of, how they materialize and how they can impact and generate opportunities for the fish farming industry. This chapter presents all identified opportunities, with a description of their composition, functionality, feasibility and improvement potential.

Chapter 5 evaluates the identified and presented opportunities and presents the following results on the most promising innovative opportunities that will contribute to growth and a sustainable fish farming industry today and in the future.

Chapter 6 provides the conclusive remarks of the work performed in the thesis and describes the main findings. The chapter discusses the evaluated opportunities for innovation in fish farming.

2 Fish Farming

Fish farming is a form of aquaculture that involves raising varied species of fish commercially in tanks or enclosures, usually for food. Fish farming was known in China already 2500 BC., with farming of Carp in freshwater. Today, more than 50% of seafood is produced by aquaculture, and China provides more than 62% of the world's farmed fish (NOAA Fisheries, 2017). The most common species of fish that is farmed is carp, salmon, tilapia and catfish.

Farming and harvesting of salmonids are the most important fish group in Norwegian aquaculture and are performed in marine environments. The ideal temperatures for farming of salmonids in the ocean is in the range between 8 – 10°C, with moderate current conditions. One of the key reasons for the rapid development and that Norway has become a leading producer of Atlantic salmon is because of the available infrastructure along the coast, with ocean temperatures mostly inside the ideal range, and a coastline that consists of many fjords with sheltered areas and stable currents.

2.1 The Norwegian Fish Farming Industry

In Norway, the aquaculture industry started around the 1970s, and since then, Norway has been the leading producer of farmed salmonids. In 2010, Norway produced over 65% of the world's production of Atlantic salmon (Dyrevernalliansen, 2016). Salmon is by far the number one farmed animal in Norway, and the production yearly exceeds 1.2 million tonnes of salmon, of which 95% is exported (Dyrevernalliansen, 2016). Norway is the second largest exporter of seafood, and from Table 1 it shows that Norway exported salmon and seafood for NOK 94.5 billion in 2017, of which 67.7 billion were from aquaculture, an increase of 3% from 2016 (Norwegian Seafood Council, 2018). Table 2 illustrates the amount of exported seafood measured in million tonnes, which in 2017 was 2.63 million. This corresponds to 36 million meals each day throughout the entire year (Norwegian Seafood Council, 2018).

Table 1: Norwegian exports of seafood distributed by aquaculture and fisheries measured in billions NOK (Norwegian Seafood Council, 2018)

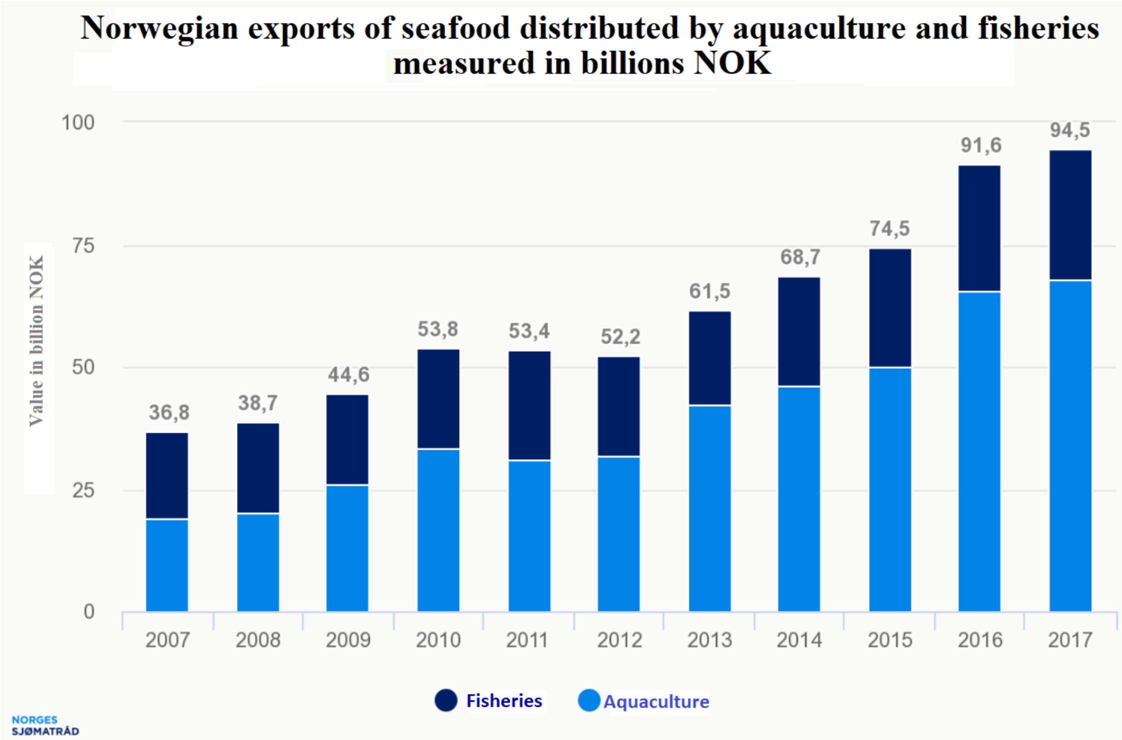
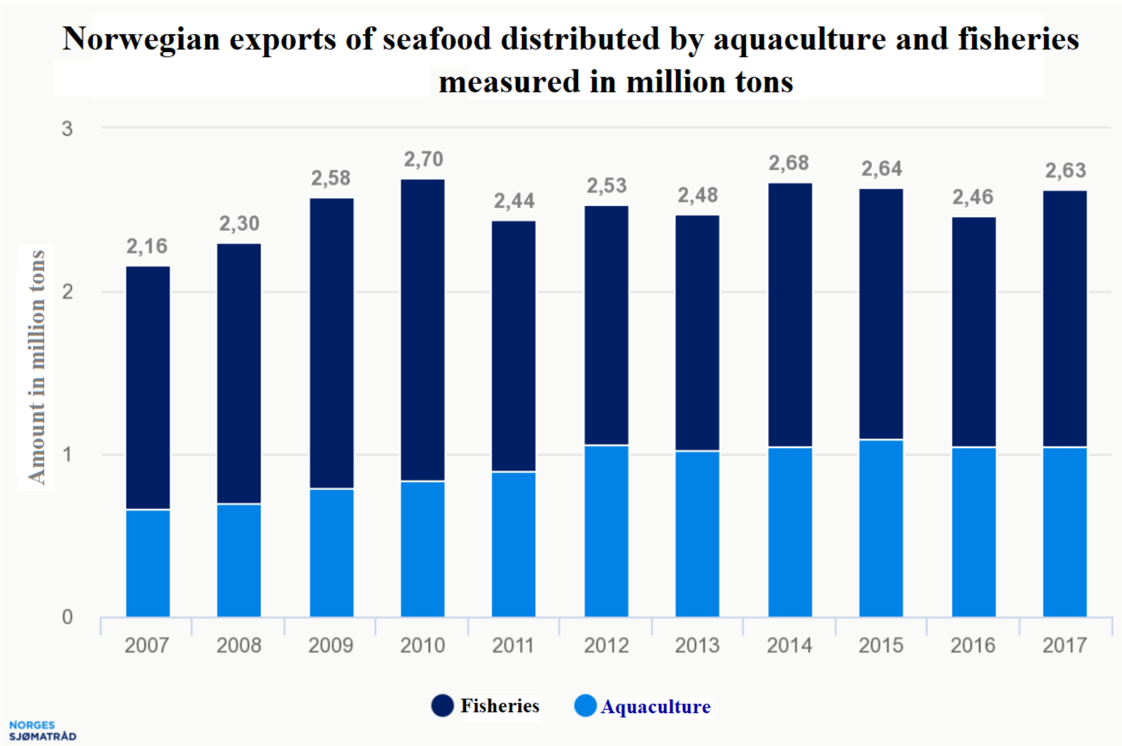


Table 2: Norwegian exports of seafood distributed by aquaculture and fisheries measured in million tons (Norwegian Seafood Council, 2018)



The aquaculture industry is Norway's second most important export industry after the oil and gas sector, where aquaculture in 2015 employed over 24 000 people and contributed to 50 billion NOK to Norway's Gross Domestic Product (GDP) (Norwegian Seafood Council, 2018).

The Norwegian fish farming industry can be divided into four main segments as shown in Figure 1.. The industry consists of companies that acts as manufacturers and suppliers of equipment, technology and service necessary to produce salmon. The key players in the technology & service segment are partners for salmon producers and specialize in developing technology and solutions for the industry, but do not practise farming themselves. Many of the companies that are engaged in salmon production, often covers the entire production chain and salmon life cycle, all the way from hatcheries to sales and distribution. In addition, many of these companies are starting to perform own research and development on new technology and solutions, both to improve quality and become more independent of other actors. Finally, there are wellboat companies that specialize in transporting live fish in the most efficient and safest way, as well as they perform delousing operations. In addition to the mentioned segments, there are also companies that specialize in net cleaning services and suppliers of cleaner fish.

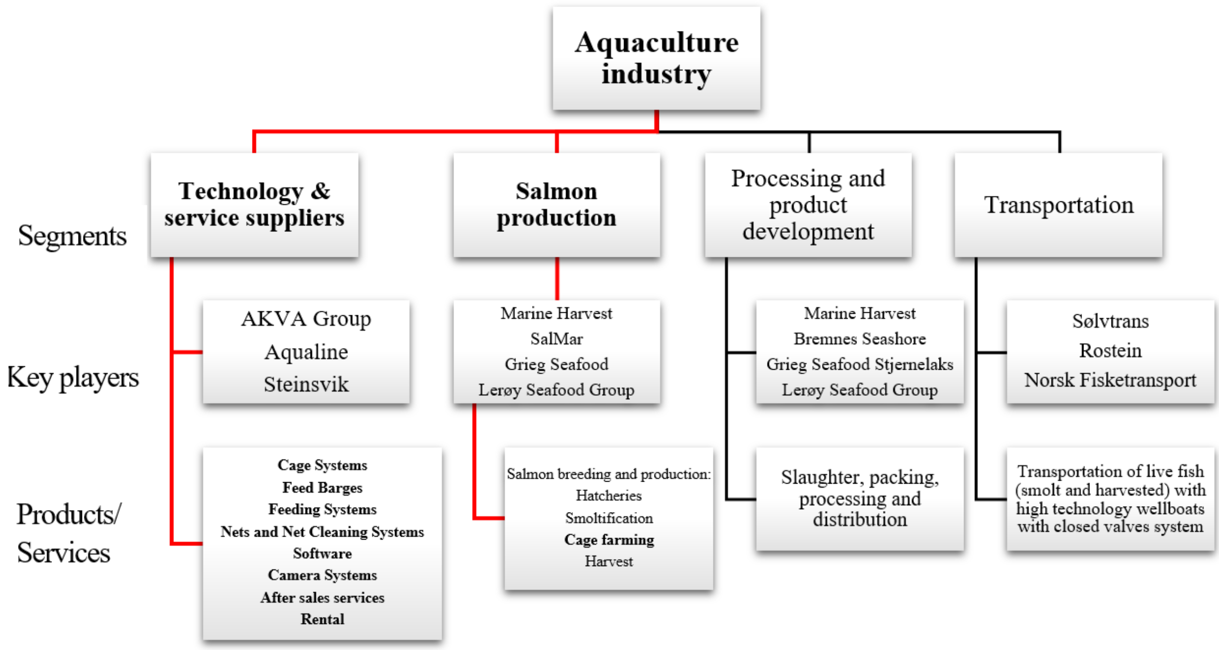


Figure 1: Overview of the Norwegian Aquaculture industry

In the figure above, the two segments, "salmon production" and "technology & service suppliers" are highlighted as it is within these two segments this thesis will focus on. As the thesis will focus on the phase from where the salmon are placed in the ocean and until it is harvest ready, "cage farming" are also highlighted along with all relevant products and services relevant to this area. To get a better understanding and overview of the two segments, Table 3 and Table 4 breaks down the segment into the way they create value, their role in the market, and their challenges.

Table 3: Breakdown of the fish farming and salmon production segment

Industry segment		**Fish farming: Salmon production**
Value creation flow	**Process flow** What are the steps being taken to produce the product?	- Fertilized eggs are kept in fresh water tanks until they hatch into tiny fish (Alevins) and once they are large enough to feed themselves the fish are moved to larger fish tanks. - After around 1 year and when the fish is 60 – 80 grams, the fish is called smolt and moved over to net pens (cage farming) in the sea to mature into adult salmon. - Just over a year with pellet feeding in sea water and when the fish reaches marked weight (4,5kg – 5,5kg), the fish is transported with wellboat to process plant and sold to the public.
	Features/properties What are the key features and properties required in the value creation process?	- Investors and product- and service partners - Knowledge, competence and experience with salmon breeding, fish health and aquaculture in general - Production licenses
	Cost/cost structure What are the main cost drivers of the process flow?	- Fish feed (pellets) - Area fees - Equipment, spare parts and maintenance - Operational costs, energy, diesel - Delousing costs (cleaner fish, bath treatment) - Disease and fish deaths - Rent and service costs (farming equipment and systems, net cleaning services)
Market	**Needs covered** What need does it cover?	- The global food and fish need

	Main customer groups What are the main customer groups?	- Retailers - Food service providers - Global public
Key	**Key challenges** What are the key challenges?	- Disease and parasites (sea lice) - Fish escapes - Environmental (pollution and contaminants) - Stress during handling - Competitors and high market activity

Table 4: Breakdown of the technology and service suppliers

Industry segment		**Technology and service suppliers for the aquaculture industry**
Value creation flow	**Process flow** What are the steps being taken to produce a product or service?	- Research and development on aquaculture technology (products, equipment, systems, operations) - Clarify business and customer needs, as well as improvement needs and issues - Design, manufacturing, project planning - Partnerships and business agreements (fish farming customers) - Installation and implementation - After sales services (service, support, maintenance, spare parts, upgrades) - Rental agreements
	Features	- R&D department - Technical/mechanical expertise and competence in aquaculture technology and solutions (feed barges, feed systems (pumps, valves),

	What are the key features required in the value creation process?	workboats, camera and sensor technology, automation, IT and software etc.) - Engineering, machining and fabrication (machine- and production halls, equipment, machinery) - Product portfolio - Customers and partnerships
	Cost/cost structure What are the main cost drivers of the process flow?	- Premises and equipment costs - Operational costs - Commodities/raw material and intermediate goods
Market	**Needs covered** What need does it cover?	- Equipment, systems, solutions and operations needed to produce salmon and other fish species (cage farming) - Equipment failure and service need - Support need
	Main customer groups What are the main customer groups?	- Fish farming and aquaculture companies (salmon producers)
Key	**Key challenges** What are the key challenges?	- Competitors and high market activity - Developing innovative technology and solutions that will resolve the ongoing challenges associated with sea lice infestations, escapes and environmental pollution

2.2 Salmon life cycle

The life cycle of farmed Atlantic salmon is illustrated in Figure 2. The first part of the salmon life cycle takes place in hatcheries. Fertilized eggs provided from the parent/adult fish, called *broodstock*, are placed in incubators with fresh water source flow kept at eight degrees. The fertilized eggs are stored indoor in trays with approximately 5 000 eggs per litre, and hatches after around 60 days.

After hatchery, the tiny fish are called *alevin*, and at this stage the fish is attached to a yolk sac, which provides it with the sustenance it needs during its first few weeks of life, until the fish are large enough to feed themselves (SalMar, 2018).

After the fish have fully absorbed their yolk sac, and can feed on regular kibble, the fish is called *fry*. For initial feeding, the fry is moved from the incubator into a fish tank, which is exposed to dim lighting 24 hours a day, and fresh water at 10 – 14 degrees Celsius. The feeding period lasts for six weeks, and as they grow, the fry is sorted and moved to larger tanks. Before transportation to sea water and fish farm's net pens, the fish are vaccinated against common salmon diseases. (SalMar, 2018)

When the fry is around one year old, and about 100 grams, it is called *smolt.* In the smoltification process, their gills change, and the fish develop a silver sheen to their bellies, while their backs turn a blue-green colour. It is then ready to live in saltwater, and the smolt is carefully transported by truck and boat to ocean pens at the farm sites. (SalMar, 2018)

The farming of smolt and adult salmon fish takes place in large net-pens suspended in the sea by flotation devices. The fish grows to the harvest size (5-6 kg) under the care of fish farmers. The fish is fed with pellets, which is made of marine and vegetable oils and proteins, and contains vitamins, minerals and antioxidants. In addition to feeding, the growth of the fish is also affected by light and water quality.

Around a year after transfer to net-pens, and a total age of around 2.5 years, the fish are ready for harvesting. Once the fish reach harvesting size, the salmon are kept live in holding pens by wellboats and transported to the processing plants.

Prior to slaughter, the fish gets stunned with CO2, electricity or blow to the head, before it is killed and bled out in a tank. After the fish is gutted and filleted, it is put on ice and distributed to markets around the world. The fish can be sold either as fresh or frozen, whole gutted, fillets, in individual portions or a wide range of other products (SalMar, 2018).

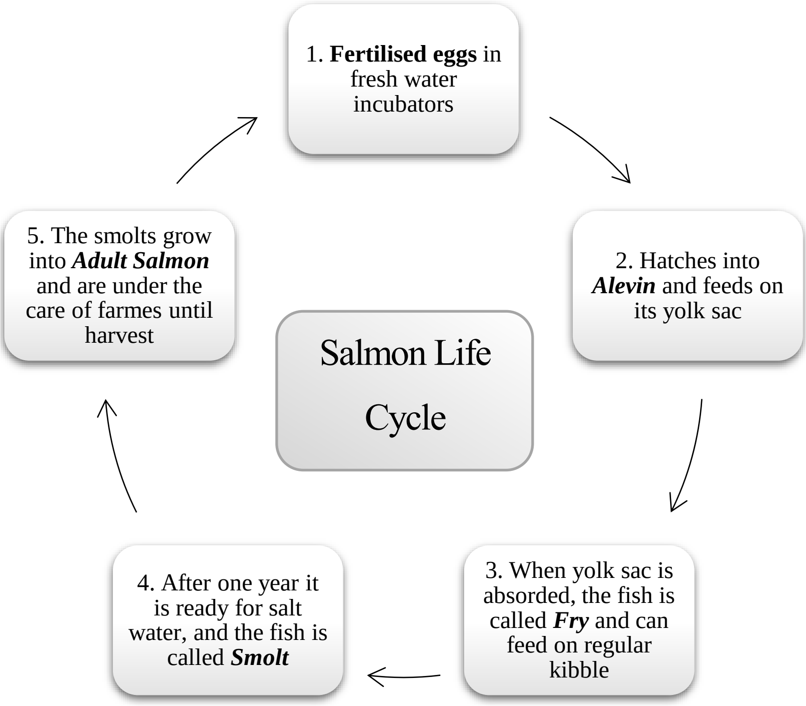


Figure 2: The life cycle of farmed salmon

2.3 Sea farm systems

A typical Norwegian salmon farm are in a remote area consisting of 4 to 16 separate open sea cages, usually made of mesh, framed with steel or plastic. The salmon farms are placed in sheltered bays and fjords, with the cages placed side by side, forming a system called *sea farm* or *sea site* (Watershed Watch Salmon Society, 2004). The net pens are usually accessed by a floating wharf or feed barge, and the pens have walkways along the net boundaries. Figure 3 illustrates a typical Norwegian salmon farm, with a feed barge pumping feed pellets via piping to all five sea cages. As we can see, each sea cage has piles around the cage sticking up in the air. These piles hold an additional protection net (bird net), intended to prevent birds from catching the fish in the cage. Birds is a threat when the fish is in the salmon stage or juvenile salmon.

Figure 3: Illustration of a typical Norwegian salmon farm (Bremnes Seashore, 2018).

The net pens can be circular or squared, and each cage can hold up to 200 000 salmon in a net that is 20-50 meters deep and 50 meters in diameter. The maximum stocking density for Atlantic salmon is 25kg/m3 (kilogram fish per open space of water), which corresponds to approximately one bathtub of water for each full-grown salmon. (Dyrevernalliansen, 2016)

The feeding itself is controlled by the personnel aboard the feed barge, and the feeding can either be carried out automatically at intervals or demand, or manually by the crew. Pumps aboard the barge ensures that the fish feed is blown from the feed silos and dispersed into the cages.

The fish cages are equipped with submarine camera systems, as well as underwater lighting and environmental sensors. With use of different software on the barge, the crew can control and monitor the fish, feeding process, dead fish etc., to ensure optimum operations and healthy environments.

Marine fouling is a critical factor in fish farming, causing algae growth on the cage/net, which can lead to reduced oxygen levels in the pens, disease and breakdown of the cage construction. All fish farms are therefore required to wash the nets. This is performed up to several times per month , and is either performed by the breeders themselves, or hired as a service by another company.

2.4 Salmon farming issues

The fish farming industry has developed into one of Norway's most important export industries, but there are still major challenges towards salmon farming that need to be addressed and solved, as well as methods and processes that need to be improved. Companies in the aquaculture industry are constantly working on innovative solutions regarding issues as sea lice, fish that escapes, diseases, pollution and contaminants, and other environmental problems. These issues can cause major loss of resources for the breeder, as well as harm to the environment and wild fish life. Breeders that do not comply with the requirements of the government and the Environment Directorate, may also risk punishment and closure of the sea farm.

2.4.1 Environmental issues

Open net-cage salmon farming negatively affects other wild fish and has an impact on the surrounding marine environment. The flow through the nets and cages allows fish waste and excess feed to freely spread out into marine water. The salmon farm will gradually degrade the surrounding habitat, as these wastes frequently will accumulate around the farm. According to (Blindheim, 2013), was Norwegian farmed fish in 2012 responsible for sewage and releases along the Norwegian coast equivalent to the entire Tokyo population of 12 million people.

Substantial portions of the salmon feed will end up at the seabed, and the feed has added medicine and contains foreign substances. This causes the feed to end up in shellfish and crustaceans, as well as sediments around the fish farms. In addition, feed accounts for most of the costs in production of Atlantic salmon, so feed waste can have major impacts on the farmers profitability. There are also used many different compounds and chemicals to keep the fish healthy. Chemical slice and drugs such as antibiotics and therapeutants are used to treat the salmon for diseases and sea lice infestations. These chemicals also get released into the environment and may affect non-target wild fish and crustaceans.

2.4.2 Sea lice, lice counting and delousing

Sea lice are small parasitic crustaceans that lives and feeds on fish. They attach to the outside of the fish, either on the skin, fins or gills. They eat the mucous, blood and skin of salmon. The lice can usually not kill an adult salmon, but just a couple of lice on a juvenile salmon can be fatal. However, sea lice can cause serious fin damage, skin erosion, constant bleeding, and open wounds. This increases the fishes' stress levels and weakens their immune system, making them more prone to infections and parasites. The open wounds also allow bacteria and viruses to enter the fishes' body. (Watershed Watch Salmon Society, 2004)

Figure 4: Juvenile salmon infected with sea lice (Raincoast, 2010).

The sea lice will attach themselves to the salmon and grow until it becomes adult and can reproduce. In the sea cages, where there is thousands of salmon gathered, there is a risk of large development of sea lice. In addition, salmon farming leads too increased amounts of fish in the ocean, which again will lead to a spread of sea lice on other wild fish. The breeders are required to carefully monitor the amount of sea lice in the cages, and if the concentration of sea lice is too high and exceeds a certain level, the breeder is required to take action. To comply with the regulations and maintain the industry's goal of low lice levels, the fish is monitored throughout the year with sea lice counting at least every 14 days. At temperatures above 10°C, it is counted every week. Every Norwegian fish farm are obliged to report the lice numbers weekly to the Norwegian Food Safety Authority (Lusedata, 2015).

Lice counting are usually carried out manually, by physically removing 10 - 20 salmons from each pen for examination. The fish is placed in a tub containing sedative chemicals to make the salmon less prone to stress. The breeders examine the fish and identifies lice that is attached to the fish. In addition to measuring the number of sea lice, the breeders also categorize the lice into either adult female or others. This is because adult female lice often carry eggs and will reproduce.

Apart from this being time-consuming for the farmers, the physical handling can also be stressful and deadly for the fish. Another disadvantage with this method of lice counting in addition to increased stress levels on the fish and that it is labour intensive, is that lice counting on a small amount of fish will not give a completely accurate answer to how high the level of lice in the cage is. The fish that are captured from the pen, are also the fish that are near the surface. Sea lice is most present in the upper layer of the cage, as well as the fish that are near the surface are weak fish that are more affected by parasites and diseases.

If the registered lice number is above the limit, the breeders must delouse the farm. The most common methods of delousing are the use of wrasse in combination with chemical treatment (delousing drugs) approved by the Norwegian Food Safety Authority. Wrasse is a small type of cleaner fish that feeds on parasites on other fish, which is a more environmental friendly delousing approach. An e emerging challenge with cleaner fish is that is has started to develop diseases as well, which also can affect the salmon. The delousing method with use of drugs is known as bath treatment. The salmon is either isolated in the net pen covered with a skirt, or the salmon is immersed in a closed tank in a wellboat. Anti-louse chemicals are mixed in the water, and the salmon stays in the water for a couple of minutes. Problems with the use of chemicals is that it is getting released into the surrounding environment, as well as the salmon is subject to stress due to crowding. There are also other methods for combating sea lice as thermal or mechanical removal of lice, protective covers and special feeds.

One of the biggest problems with sea lice, is that the lice have started to develop resistance towards the medical treatments. Sea lice resistance towards medicals has been known in Norway since the 1990s but started to become a serious issue around 2007 (Helgesen, et al., 2018). The reason for this is that there has been continuous and intensive use of medical treatment the last decades, which have led the sea lice to develop resistance genes towards the different drugs.

There is extensive and continuous research and development of measures to control sea lice. In this work, the fish farming industry in Norway uses over NOK 50 million annually. In addition to new and improved measures such as mechanical removal, protective covers and specialty feed, the industry is working on breeding salmon with increased resistance to lice. The possibilities for developing a vaccine against salmon lice are also given a great attention. (Sjømat Norge, 2016)

2.4.3 Disease

Fish diseases cause major problems in farming and can lead to big financial losses for the companies. Disease outbreaks can be critical for wild fish life, as it usually represents infection release and hence an increased risk of infection of other wild fish in the area. Infect can also be spread with escaped infected fish and wild fish who seek out sea salmon farms. (Institute of Marine Research, 2014)

There are probably more than 250 organisms that can infect salmon. Most are harmless and will to little extent trigger infection (Miljødirektoratet, 2018). However, a considerable number of pathogens have been shown, which can lead to high mortality rates.

The industry’s biggest threats of viruses and bacterial diseases are (Sandvik, 2016):

- Pancreas disease (PD)
- Amoebic gill disease (AGD)
- Infectious salmon anemia (ISAv)
- Infectious pancreatic necrosis (IPN)
- Heart and skeletal muscle inflammation (HSMI)
- Cardiomyopathy syndrome (CMS)

With many individuals at each sea farm, and many farms located close together, these diseases are easily spread along sea farms along the Norwegian coast. Although breeders vaccinate the fish, and this have helped, certain diseases such as PD, CMS and HSMI are prevalent (Dyrevernalliansen, 2016).

2.4.4 Escapes

Another common issue that has often led to major financial losses for breeders is escaped salmon. The occurrence of escaped salmon may be due to equipment failure, storms or human error, and all can result in damage to the nets, and release thousands of salmon into the surrounding water (Watershed Watch Salmon Society, 2018). In addition to the economic consequences, escaped salmon can also have a major impact on the surrounding environment. The downside to the environment with escaped salmon that it spreads diseases and parasites to other fish, as well as it disturbs the genetic width of the salmonid family. Some of the escaped salmon will not manage out in the nature, but some will survive and swim up the rivers and breed with wild salmon. Due to systematic breeding and selection over time, farmed salmon has different genetics than wild salmon. Escaped farmed salmon can thus cause weakness to the wild salmon breed.

2.4.5 Stress, handling and transportation

If the fish are exposed to high stress levels, this will cause the fish to get a reduced tolerance for pathogens and more susceptible for further stress. Stress can also lead to increased infection release and have fatal consequences for weak or diseased fish, as well as it weakens the flesh quality and inhibits normal physiological processes (Institute of Marine Research, 2014).

Stress occurs when the fish is exposed to high density of fish, lack of space, sickness or poor environmental conditions. All handling of the fish such as transportation, sorting, vaccination and medical/chemical treatment can cause stress. Poor water quality such as too warm water (overheating) or too low oxygen level, which can occur during handling, can also cause increased stress levels. Recent studies have suggested that adding sedative to the water can reduce stress during handling and transportation (Dyrevernalliansen, 2016).

As mentioned above, every fish farm need to count the levels of sea lice at least every 14 days (every week in warm periods). Lice counting is carried out by the breeders by taking out a certain amount of salmon from every net pen on the farm and placing them in a tank for visual counting of sea lice. Although the water in the tank has sedative chemicals added, the fish is exposed to stress as it is in physical contact with humans and taken away from its normal habitat.

3 Cage farming

As mentioned earlier, in this thesis we will focus mainly on cage farming, and from the period when the fish is placed in salt water net pens until it is harvest ready and transported from wellboat to process plant. It is within this part of the farming process most problems occur and where there will be greatest potential for improvement and opportunities for innovation. It is also in this phase that there is already extensive research and utilization of advanced technology for monitoring, control and automation of farming processes, and this is where the industry must adapt and introduce modern technology trends to develop and evolve into a more environmental friendly and sustainable fish farming industry.

The chapter breaks down and reviews all the main components and technology used in a traditional Norwegian fish farm.

3.1 Cages

The main component and the most distinct and noticeable with a fish farm, is the cages or net pens that lay together in the sea containing hundreds and thousand of fish. These cages are either plastic or steel cages.

3.1.1 Plastic cages

Along the Norwegian coast, the most common type of sea cages used for salmon farming is plastic cages. These are circular cages made of PE (polyethylene) raw materials especially suited for the dynamic loads of the sea. The Norwegian company, AKVA Group ASA, is the world's leading supplier of both plastic and steel cages. With the most recognized brand in the industry, Polarcirkel, they have supplied more than 45 000 cages worldwide since 1974 (AKVA Group, 2017). Figure 5 shows AKVA Group's "flagship", Polarcirkel 630. A traditional plastic cage design with walkway sections, 63 cm circumference on the floating pipe and up to 240 meters across the cage. The cage has no metal parts to avoid corrosion problems. Both the hand rails and the brackets the nets are connected to are made of PE. In addition to PE being resistant to corrosion, PE will not be affected by high UV radiation and icing, unlike metal. With the rough weather along the Norwegian coastline, with high salinity, choppy seas, and both warm and arctic conditions, plastic cages are the best solution regarding lifespan, safety, maintenance and fish escapes.

Figure 5: Polarcirkel 630 (AKVA Group, 2017)

Most plastic cages are moored in a grid system and include sinker tube, centersupport stand (keeps the bird nets high off the water), feed system/barge, cameras and sensors. The nets are also corrosion free, with all-rope solution nets usually made of nylon (fiber) or PET (polyethylene terephthalate). (AKVA Group, 2017)

3.1.2 Steel cages

There are also some fish farms along the Norwegian coast that use steel cages, and these can have some advantages. Steel cages have wide and stable non-slip walkways with high free-board around all sides of the cages, allowing the operator full flexibility of operation with easy access from cage to cage (AKVA Group, 2017). **Feil! Fant ikke referansekilden.** illustrates a steel cage with a total of 4 net-pens in the s ame structure. In some cases, the feed barge and control room can also be in the same structure as the steel cages, making the operations and maintenance even more easy.

Steel cages can reflect a more safe and stable workplace for the operators compared to plastic cages, often with railings on both sides of the walkway, and a walkway so wide that in some cases it can accommodate a regular forklift. All metal components in steel cages are galvanized and UV stabilized, as well as hinge systems are rubber moulded to increase the life-span of the structure. (AKVA Group, 2017)

Figure 6: Illustration of a traditional steel cage consisting of four separate net pens (AKVA Group, 2017).

3.2 Feed barges

Feed barges are platforms at the sea farm with the main function to store and transport feed to the fish. In addition to feed systems, feed barges usually contain living quarters, control rooms, generator(s), safety equipment, and camera- and sensor systems for the silos.

Two of the leading suppliers of feed barges are the Norwegian companies AKVA Group and Steinsvik. Both companies have delivered robust and reliable platforms for cage farming worldwide, with the main purpose of providing efficient and reliable feeding systems, as well as safe and seaworthy barges that can withstand the forces of nature and contribute to comfortable and efficient working conditions for the keepers.

On Figure 7 we can see an example of Steinsvik's newly developed Nova 600 feed barge. The barge is designed around the central feeding system and are especially suited for beautiful coastlines and for customers which also appreciates a pleasant workspace. The Nova barges can be delivered with 4, 6 or 8 silos, with up to 1000 m3 silo capacity (Steinsvik, 2018).

Figure 7: Steinsvik's Nova 600 feed barge with 8 silos and 928 m3 silo capacity (Steinsvik, 2018)

3.3 Feed systems

The central feed system was invented by AKVA in the 1990s and is the most popular feed system for pellets and cage farming worldwide. Both AKVA Group and Steinsvik have produced and installed over thousands of central feeding systems, which is today fully integrated with camera control, pellet- and environmental sensors and production control software (AKVA Group, 2017).

Akvasmart CCS is AKVA Group's central feeding system, which is suitable for all species feeding on pellets, designed to handle more than 40 feed lines running in parallel and more than 1000 cage/tanks units, centralized- or hopper feeders, all operated from one PC, iPad or smartphone (AKVA Group, 2017). Figure 8 illustrates the function and units of AVA Group's CCS feed system, and the process from control room to the feed is distributed in the pens. This system is common for all cage farming, and feeding systems usually has a software which gives the operator full control over the feeding process, with automatically and manual feed functions such as meal planning, group feeding, and adaptive feeding. A feed blower generates transport air and blows the feed through the feed pipes. Before the air reaches the silos, the air goes through an air cooler and an air control system, to regulate the air to the right temperature and air speed. It is important that the pellets are gently handled to reduce the risk of blockage and feed breakage. When the air is at the right conditions, feed dosers ensures that the pellets are fed to the system with correct dosage. After feed doser, the feed goes through a feed selector valve, which distributes feed via feed pipes to the correct cage. In each cage there are installed rotor spreaders in the centre of the cage, which rotates during feeding and spreads the feed evenly into the pen.

Environmental sensors and camera systems are installed in each cage, and with a wireless transmitter, real-time video and sensor data are transferred to the control room.

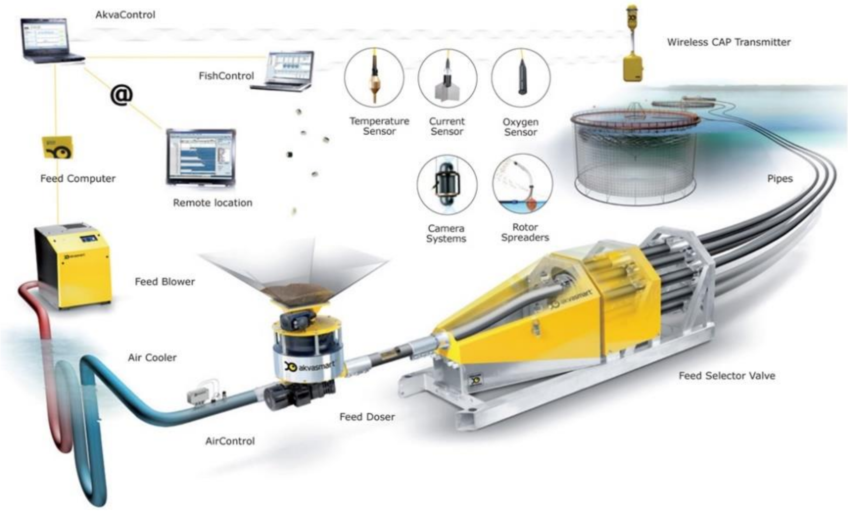


Figure 8: Akvasmart CCS Feed System (AKVA Group, 2017)

Although AkvaGroup has developed a partly automated feeding system, many fish farm manually perform feeding and determine the amount of feed based on human interpretation of fish activity shown on the images from the underwater feeding cameras. It is estimated that approximately seven percent of all feed that goes into Norwegian fish farms is never consumed by the fish. As a result, very large amounts of feed are released to the environment from the fish farms. This has a major impact on the company's profitability, as well as that it affects the surrounding environment (Mikkelsen, 2017).

3.4 Software

Today, most fish farms along the Norwegian coast are integrated with intelligent and high-end software solutions that cover all needs of process control, production control and planning, intended to ensure optimum efficiency, excellent fish quality and high profitability.

Examples on software Norwegian aquaculture and cage farming companies utilizes for production and process control are the software developed by AKVA Group. These software solutions are namely "AKVAconnect" and "Fishtalk", which together gives a complete of the value chain.

3.4.1 AKVAconnect

AKVAconnect is a process control platform which controls a wide range of equipment, technical processes, and activities at the fish farm. The system is open ended and compatible with all types of equipment, sensors and technical installations (AKVA Group, 2017). Figure 9 shows which equipment and technical processes AKVAconnect has access to.

Figure 9: AKVAconnect process control platform (AKVA Group, 2017)

3.4.2 Fishtalk

Fishtalk is a software designed to cover the aspects of biological production and planning. The software gathers and store data from broodstock to harvest, providing detailed reports and analysis of the process. "Fishtalk Control" is a tool with financial and planning modules, which provides the producers complete control over economy, production cost, finance, budgeting, and biology plan. (AKVA Group, 2017)

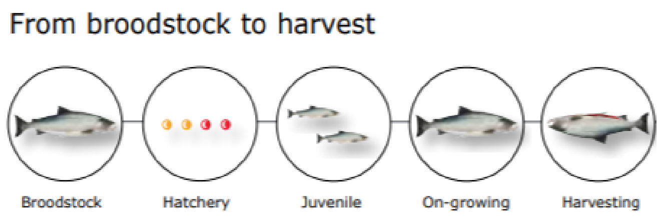


Figure 10: Fishtalk Control: From broodstock to harvest (AKVA Group, 2017)

"Fishtalk Equipment" is another software which organizes all the farming equipment with documentation and maintenance, giving the producers full traceability on component level (AKVA Group, 2017).

Figure 11: Fishtalk equipment: Full equipment control (AKVA Group, 2017)

3.5 Camera systems

The camera systems are a key component in the operation of fish farms, as they provide breeders with a full overview of what is happening both in and on site, and both below and above water surface. The camera technology can be used for purposes such as monitoring the feeding process, checking the amount of dead fish and left-over feed at the bottom of the cage, monitoring of fish behaviour and fish parasites (sea lice), monitor the cage and net conditions (algae growth), as well as monitoring of the net cleaning process.

Steinsvik have been making camera systems for the fish farming industry since 1985 and is now one of the world's leading companies in camera and control software (Steinsvik, 2018). The camera and sensor systems are based on ethernet, fibre or on wireless transmission between cameras/sensors and control room. They offer camera solutions for both underwater, surface and surveillance, as well as portable camera and boat solutions.

With Steinsvik's Orbit underwater camera series, the operator can get HD images all over the cage as the cameras can be moved both horizontally and vertically with a winch system, in addition to that the cameras can rotate 360 degrees in all directions (Steinsvik, 2018). These cameras have different sensors integrated, with the possibilities of temperature, depth, compass, oxygen and gyroscope. Not only will the operator get a full underwater view of the cage, but he will also get environmental readings, as temperature and oxygen levels, and where the camera is positioned.

Steinsvik also produces surface cameras that comprehends with the highly corrosive environments. These cameras are mounted on the cage railing, and with a powerful zoom lens and in combination with the underwater cameras, this will provide a good picture of the activity both below and above the surface.

3.6 Net cleaning systems

In cage farming it is as mentioned crucial to maintain good waterflow through the nets. This is especially important in high water temperatures, as algae growth increases exponentially with temperatures. As illustrated in Figure 12, increased marine fouling leads to reduced waterflow, which will lead to oxygen rich water flowing around the cage (AKVA Group, 2017).

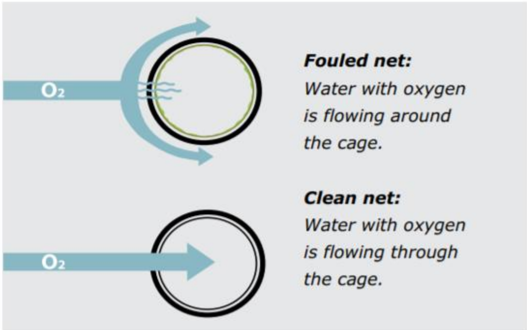


Figure 12: Difference between fouled and clean net (AKVA Group, 2017)

To maintain clean nets, every fish farm utilizes net cleaning equipment to remove marine fouling. The most used cleaning system are rotating cleaning discs mounted on a support frame, driven by high pressure pumps and filtered sea water. The cleaning rigs can contain one to seven cleaning discs, depending on desired washing area width. The cleaning procedure starts with submerging the frame on the inside of the net, with the rotating discs removes the marine fouling by blowing high pressure salt water from the inside of the net and out to the surroundings.

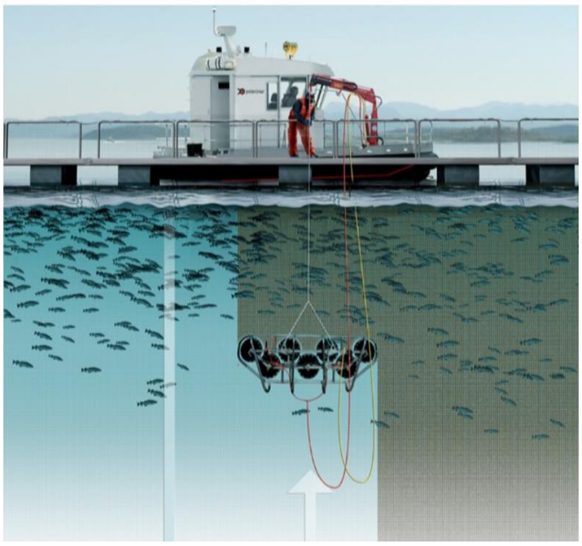


Figure 13: Net cleaning operation with seven-disc cleaning rig (AKVA Group, 2017)

Figure 13 illustrates the operation of a large net cleaning rig containing seven rotating cleaning discs. This net cleaning process is operated in automatic mode by two persons using a crane, winch, and cap stand. Net cleaners can in some case be operated as an ROV (remotely operated vehicle) and have integrated cameras for enhanced monitoring of the cleaning process.

3.7 Workboats

Fish farms often have a variety of workboats for different applications on and around the facility. These may be smaller boats with the main purpose of transporting personnel from land to farm and other facilities, as well as easy access to the sea cages. Fish farms also has larger workboats which contains a larger deck area, net cleaning equipment and small or larger cranes. These boats are used for larger operations on the facilities or the sea cages, as well as they are used to transport equipment and goods to and from the fish farms.

3.8 Service and rental agreements

Suppliers for the aquaculture industry, such as AKVA Group and Steinsvik, not only produce and sell products and technology for the industry, but also offers their partners/customers after sales services or rental agreements. The equipment involved in cage farming can be highly advanced and exposed to a lot of wear and tear, which leads to the need for professional service, support and preventive maintenance. Included with the product/system/solution, the suppliers offer a service agreement for the customer. This ensures that the fish farmers can focus completely on the fish, and the suppliers can profit by providing services and support for their customers that will prevent downtime and ensure predictable and uninterrupted production. The after sales services offered usually includes regular and preventive maintenance and service on products, software updates, 24-hour telephone support, on-site support, training programs on equipment/system/software, spare parts services, camera inspections etc. For some systems, such as feeding, camera and remote-control systems, the service agreement offers a fixed price. This means that the suppliers take an annual fixed price for the system, and in return the supplier provides a run-time warranty for the customer which includes that the supplier will take full responsibility of the system performance. The supplier is responsible for maintenance, updates, component and spare part replacements, and provide 24-support for the system. The service agreement and partnership between supplier and fish farming companies is highly beneficial for both parties as it ensures a cost-effective production for the breeders and ensures steady cash-flow for the suppliers.

Suppliers can also offer rental agreements on their products. The purpose with the rental concept is to ensure the customers total priority on the fish, while the supplier ensures optimum functionality and operation of the systems. Many customers today prefer rental agreements instead of traditional purchase, as they can choose rental period and get worry-free operations for a fixed monthly cost (AKVA Group, 2017). Rental agreements include the same services and support mentioned in after sales services, but rental agreements also include transport, installation, start-up, training, repairs, and no frond-end fee etc.

4 Innovation opportunities emerging from technology trends

The objective of this thesis is to identify and investigate innovative opportunities in the aquaculture industry, specifically cage farming, that are arising from technology trends. Hitherto, an overview of the Norwegian fish farming industry and its segments has been carried out, in addition to an break-down of the actual processes, components/products, and solutions that are included in cage farming and the production and farming of Atlantic salmon. The most common and critical issues of fish farming have also been identified, and an investigation has been made on how these issues are combated today.

When evaluating opportunities for innovation in fish farming, the broken-down parts of the products and processes in fish farming, as well as the present challenges need to be checked against technology trends and how these trends can affect or improve some of the technology and solutions in the industry, or possibly solve or reduce the impact on any of the common issues that are mentioned. To perform this evaluation, the most relevant technology trends must be identified, as well as determine what these trends consist of and how they are materialized. The innovative opportunities that emerge from these technology trends must then be identified as well, and evaluated in terms of composition, functionality and improvement potential.

4.1 Technology trends

The production of Atlantic salmon in Norway has had a rapid growth since its inception in the 1970s, and this can be closely linked to the advances in science and technology. Due to the constant and increasing demand for food and fish, the Norwegian fish farming industry has continuously been forced to develop and deliver increasing amounts of fresher and high-quality salmon. The previously mentioned issues the fish farming industry has struggled with all years has made it necessary for the industry to continuously adapt and benefit from the ever-evolving development in technology. This involves that the Norwegian aquaculture industry has performed continuous research and innovation to implement improved solutions regarding monitoring and control of the fish, net pens, feeding, parasite infestations, as well as more automated, controlled and fish-friendly operations.

It is predicted that the world's population will exceed 9 billion people by 2050 (today; 7.6 billion), which will lead to a significant increase in the worldwide demand for meat and fish in the future (Laks.no, 2018). According to Berckmans (2014), the future food demand for meat and animal products is expected to increase by at least 40% in the next 15 years. This increasing demand will threaten the sustainability of fish farming in the future, and the industry will continue to face major challenges related to salmon lice and environmental pollutions in the years to come. To achieve growth and maintain sustainability, the industry need to invest in technology development to improve today's solutions in line with the expected increase of demand and production of salmon. To comprehend with the emerging biological, economic, and social challenges in fish farming, application of technology trends will in the future contribute to a sustainable industry that maintains an ethically sound, economical, productive and environmentally friendly production of Atlantic salmon.

It is also assumed that fish farming in the future will be moved more out to the sea, which means that farming processes and operations must be more unmanned and automated. When farming cannot be carried out by manual operations and by crew on the site and cages, the industry must adapt to and rely on advanced technology that can enable remotely operated fish farms.

The changes in materials/hardware and energy are the key driver responsible for modern technology trends. The development in the field of energy, data and computational storage, as well as significant reduction in energy and hardware prices have enabled new trends in aquaculture such as sensorization, connectivity and autonomization to impact the industry, and they will continue to do so in the future. Some of the key features from these technology trends that has and will affect the fish farming industry are:

- Reduction in energy price, renewable energy, energy storage and grid independence (solar panels, wind/wave power, large battery storage etc.)
- Material development and reduction in equipment and hardware cost, enabling to produce smaller sensors and the possibility to install sensors to more equipment and products
- Exponential growth in computational and data storage capacity together with development in availability, bandwidth and low-cost internet enabling increased level of connectivity between equipment, devices, systems, and units (IoT technologies). IoT (internet of things) is the network of physical devices embedded with electronics, software, sensors, actuators, and network

connectivity which enables these devices to connect and exchange data. This improves the farmer's ability to monitor, control and document biological processes in fish farms.

- Jointly, sensorization, connectivity and digitalization will contribute to emerging opportunities regarding more automated systems and operations in the industry. Autonomization is the key element regarding opportunities for autonomous and remotely operated systems and operations.

4.2 Energy

Approximately half of the Norwegian fish farms along the coast use diesel generators to produce electricity, the other half are connected to the electricity grid via a sea cable. A medium sized fish farm with diesel generators emits the same amount of CO2 annually as 70 private cars combined (University of Stavanger, 2017). The future of fish farming is pointing more towards offshore farming, with cage farms far out in the sea, making them consume more energy and even more challenging for connection to the onshore electricity grid. In addition, the industry will face increasingly stricter CO2 emission standards. Thus, it will be important that the industry adapts to the new energy trends and implement more climate friendly fish farms with self-sufficient and off-grid energy systems from renewable energy sources.

There are essentially two emerging technology trends in energy, that are and will continue to affect the fish farming industry in the future:

- Energy storage capacity and grid independence
- Renewable energy and reduction in energy prices

Recent development in energy storage have made it possible for electrification of automobiles and other machines, such as electric cars, vacuum cleaners, drones, AUV's etc. The ability to store substantial amounts of electric energy in batteries also enables the possibility for grid independent houses, cabins and other buildings that are remotely located. Off-grid and self-sufficient energy systems harvest energy from renewable energy solutions such as wind turbines, solar power, and wave power. The recent development in solar technology and offshore wind turbines have also significantly decreased the energy prices. The fish farming industry have potential to benefit from this technology trend, by enabling the possibility for offshore farm sites and reducing both reducing CO2 emissions and the high costs from diesel generator systems.

4.2.1 Research on hybrid energy system

There is extensive research and work towards greener energy solutions within fish farming today. Syse (2016) investigated the possibility for off-grid energy solutions for salmon farming. Syse measured the energy consumption for a traditional Norwegian fish farm located along the coast which uses a diesel generator system and evaluated potential renewable energy sources and storage options for the farm. Three different systems were evaluated and measured against operational costs and environmental emissions; a pure diesel generator system, a hybrid energy system, and a 100% renewable energy system. The evaluation was performed with the software tool, HOMER energy, and it showed that for a fjord-based fish farm, the hybrid energy system provided the lowest cost of the three over a 20-year period. The hybrid system combined solar, wind, and battery power with a diesel generator for backup. The wind and weather conditions are varying and can lead to overcapacity of wind turbines and PV panels, hence the diesel generator for backup. The fish farm evaluated had a daily energy requirement of 341.92 kWh. To meet this demand the hybrid configuration consisted of a 14kW installed wind turbine capacity, 35 kW of PV, 146 kWh's of Li-Ion batteries and two diesel generators of 130 kW and 10 kW. With this hybrid energy system, Syse found that the fish farm had a potential to provide 34% of the electricity from renewable sources, which reduce 47% of CO2 emissions and 16% lower net present cost compared with the original energy system (Syse, 2016).

4.2.2 Salmo solar

Another exciting research on fish farming and self-sufficient energy systems is Unitech's patent pending Salmo Solar project. Unitech Salmo Solar has in 2017 been granted permission to develop a floating, offshore fish farm with a self-sufficient energy system that harvest power from both sun, wind and waves (Berthelsen, 2017). The Salmo Solar is a concept based on top Norwegian aquaculture and offshore technology, that is made for the harsh environment outside the Norwegian coast, that can comprehend with significant wave heights up to 8 meters and can harvest all energy needed for large scale seafood production (Unitech Salmo Solar, 2018).

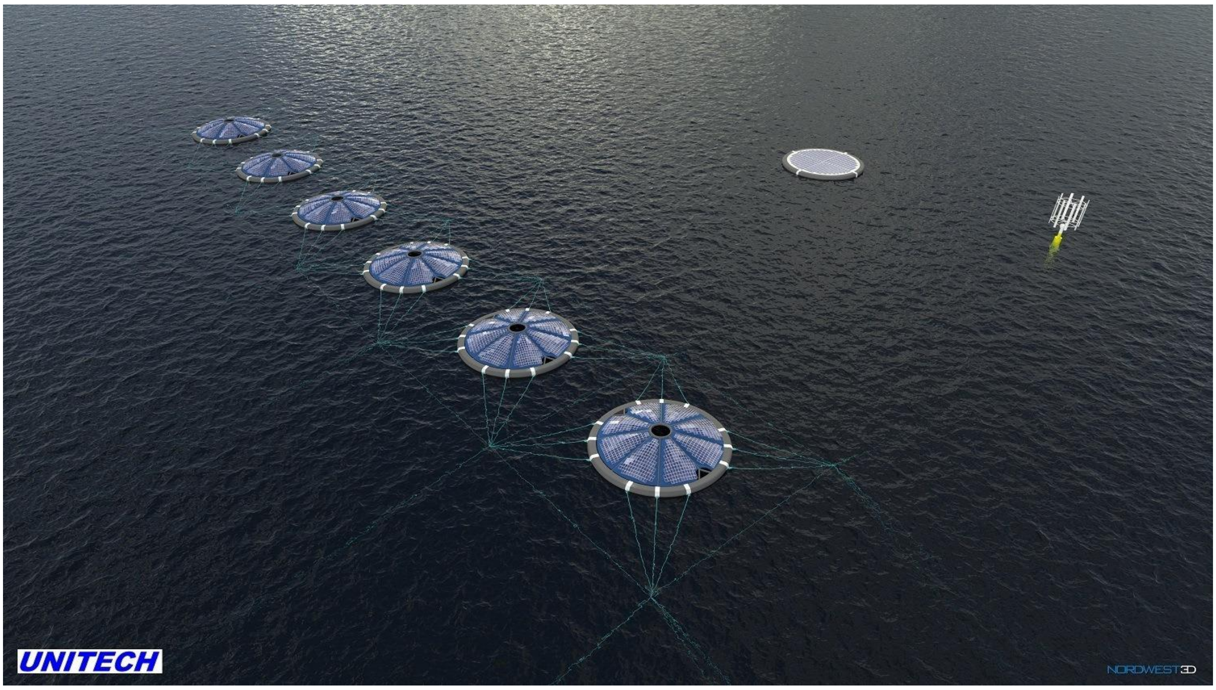


Figure 14: Illustration of UNITECH's Salmo Solar project (Unitech Salmo Solar, 2018).

The Salmo solar contains all infrastructure needed for efficient fish farming, including sea cages, feed systems, silos and control rooms. The construction will be similar to a very large sea cage, where each cage contains everything that is needed by technology. In addition to each cage is holding 200 000 salmon, each cage will consist of living rooms and control rooms, as well as feed silos and all other necessary features for a functioning farming facility. The sea cages will have a solar cell membrane as roof, which also will protect the fish against the upper water masses. In addition to solar panels on the sea cage roof, the facility will contain a floating vertical wind turbine to harvest wind power, and a subsea wave lens that diverges waves away from the sea cages and towards a wave energy plant. In the future there will be more electrical boats in the industry, and the Salmo Solar concept will also function as an energy station, where the farm collects energy surpluses, and can supply energy to electrical boats.

The project is currently still in the development phase, where the energy harvested from the sun are well-tested, while energy harvested from wind and waves are under implementation.

4.2.3 Electric workboats

In addition to grid-independent and self-sufficient fish farms, electric boats are starting to become a trend, making this an innovative opportunity for fish farmers to reduce CO2 emissions, as well as save fuel costs.

In 2017 introduced Siemens and Salmar the world's first electric workboat for fish farming industry, "ELFrida" (Fish farming expert, 2017).

Figure 15: ELFrida, the first electric workboat used in the Norwegian fish farming industry. Image: Enova (Fish farming expert, 2017).

ELFrida is a double-hulled boat, which is 14 meters long and 8 meters wide. With one hundred percent battery capacity this boat can perform farming operations and transport feed and equipment throughout a normal working day of eight hours.

4.3 Sensorization and connectivity

Technological development and progress in sensorization have advanced to such an extent that sensors can be applied to almost any device or application, and sense, record and analyse parameters anywhere. Sensors and embedded sensor networks are present in every day devices and are placed in the physical world to interact with the environment and monitor different parameters. Sensors are placed in devices and applications such as cell phones, watches, household appliances, vehicles, and other machines, with the intention to sense parameters as for example temperature, vision, velocity, location, moisture, motion, force/load, flow, pressure etc. The increase in computational capacity enables algorithms to collect and interpret the data recorded by these sensors and transform this into useful information. With the possibility of wireless transmission, internet of things, and the connectivity between sensors, devices, systems and software, the improvement of real-time monitoring and independent decision-making systems will continue to have a significant impact on the fish farming industry regarding production and process control. Sensorization and connectivity may also be the key technology trend in realization of more automated and remote/unmanned farming operations and processes.

Modern technology has reached a point where it's application to biological processes has become realistic. Sensors and wireless data transmission has become cheap, small and reliable enough for the harsh environment of fish farming. Sensors, software, wireless transmission and communication, internet connectivity and cloud storage are essential in farming decisions and feeding regimes. Sensorization and connectivity enables control over the environment, biological processes, feeding processes, growth and fish welfare. Today, sensors are used to measure farming parameters such as temperature, oxygen, salinity and pH for environmental control, and parameters as speed and swimming directions for feeding control. Cameras replace the farmer's eyes and are installed both above and under the surface for real-time monitoring of the fish for control of lice infestation, algae growth, dead fish and feeding processes. Although sensors are widely used in fish farming at this time, many farming operations are experience-based and performed manually, and sensors and cameras are more like an aid or a "third eye" in making farming decisions. Farmers are physically out on the sea to carry out daily tasks such as monitoring of fish welfare, farm/cage inspection, and control of feeding and lice counting.

Research suggests that future fish farms will be located more out to sea to comprehend with the emerging biological, economic and social challenges, to maintain an ethically sound, productive and environmentally friendly production of salmon (Føre, et al., 2017). To achieve this, the industry is dependent on more remotely operated fish farms and automated systems. When fish farming will be placed offshore and on remote locations, the fish farms will also increase in size and complexity and exposed to harsher environment. It is therefore important for the industry to adapt to modern technology trends and aspires to more innovative and sophisticated technology that will improve farming management and farming solutions that provide sufficient knowledge and information to monitor and control the biological process. Føre et al. (2017), developed a concept called Precision Fish Farming (PFF), where the aim is to apply innovative technology trends in sensorization, connectivity, and automation/autonomization to improve the farmer's ability to monitor, control and document biological processes in fish farms. As the PFF concept will by utilization of emerging technologies and automated systems contribute to move commercial fish farming from traditional experience-based to a more knowledge-based production regime (Føre, et al., 2017), it will also help fish farming in realization of a move towards offshore farming.

4.3.1 Precision fish farming (PFF)

PFF is a framework for how to improve production in fish farming with the utilization of modern sensor technologies to monitor animal variables for improved level of autonomy. The overarching aims of the concept is to (Føre, et al., 2017):

1. *Improve accuracy, precision and repeatability in farming operations*

2. *Facilitate more autonomous and continuous biomass/animal monitoring*
3. *Provide more reliable decision support*
4. *Reduce dependencies on manual labour and subjective assessments, and thus improve the staff safety*

Together, these means are intended to improve fish health and welfare while increasing the productivity, yield and environmental sustainability.

In defining how PFF will move fish farming from experience-based with manual monitoring and operations to a more knowledge-based regime, fish farming can be envisioned as four cyclical operational processes as shown in Figure 16. The cyclical representation of PFF consist of the four phases; observe, interpret, decide and act. Today, the phases are mostly conducted manually, starting with the observe phase by direct visual observation of the fish or observation with data acquisition tools as cameras. The information given is qualitative or quantitative, and to interpret this information the farmer uses primarily subjective experience to get a perception of the current state and condition of the fish. The farmer's interpretations are the foundation for the following decision regarding farming operations and management, which is furthermore put into manually induced actions on the cage or fish. The cycle illustrates how PFF can influence the four phases of the cycle and move fish farming from the inner cycle and current state with manual monitoring and operations, to the outer cycle with a more knowledge-based and automated farming industry. (Føre, et al., 2017)

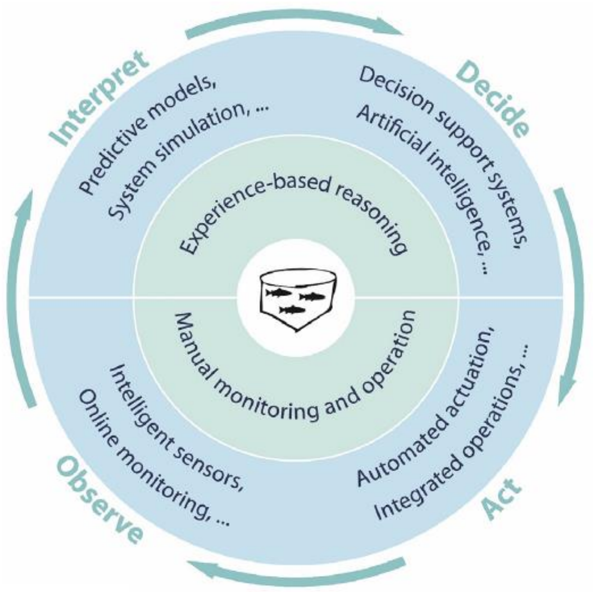


Figure 16: Cyclical representation of Precision Fish Farming. Figure credit: Andreas Myskja Lien, SINTEF Ocean (Føre, et al., 2017).

Observe

The most common use of sensor technology to observe animal variables today are submerged camera systems for manually monitoring and analysation of fish behaviour and lice infestation. However, computer vision techniques and use of algorithms are rapidly expanding, leading to an increased potential of application of intelligent sensors and innovative computer vision methods for automated monitoring of several different animal variables in a fish farm setting. Animal variables that are possible to measure with modern sensor technologies are skin status, clustering and movement, sea-lice infestation levels, fish size, behaviour and behavioural changes. In addition, modern sensor technologies also have the possibility to monitor important parameters of the physical environment such as surface activity, feed pellet quantities and waste, algae growth and net conditions. The technological tools that can measure these parameters in addition to cameras are sensor technology such as hydroacoustic devices and several types of sonars. Hydroacoustic and the use of echo sounders can obtain echograms that describes the vertical fish distribution and schooling density in the cage (Oppedal, et al., 2017). More advanced hydroacoustic devices and sonars such as split-beam and multibeam sonars are in use within other marine segments and have the potential to obtain additional data on animal variables in the sea cage. Split-beam sonars can estimate the fish' swimming speeds and directions, while multibeam sonars can produce 3D data on fish distribution and movement (Føre, et al., 2017). These parameters can be essential for more optimized feeding regimes, as feeding amounts is determined by fish behaviour, swimming speed and direction during feeding. As fish feed accounts for 60 – 90 % of the production cost in fish farming (AKVA Group, 2017), improved monitoring on fish behaviour during feeding process will optimize feeding decisions and reduce pellet waste and feed cost. Sonar based systems can also monitor individual fish sizes, both mass and length.

Another interesting opportunity for improved observation and online monitoring in the PFF concept is the use of acoustic fish telemetry. Acoustic fish telemetry is widely used on wild fish research and is a method for remote sensing where individual fish are equipped with electronic transmitters containing small, intelligent sensors. These sensors measure individual animal variables such as depth movements, 3D-positions, swimming activity levels, muscle activity levels and respiration rates/feed intake, as well as heart rate and blood composition (Føre, et al., 2017). The electronic transmitters transfer raw or post-processed data wirelessly to submerged stationary receiver units using acoustic signals or sound waves. The downside with deployment of acoustic fish telemetry is that every individual fish need to go through physical handling, which involves surgery. This can lead to increased stress levels and the deployment of the sensors can be labour intensive. However, as acoustic fish telemetry is at present the only viable technique for obtaining continuous data on individual fish in commercial cages, and sensor costs are low and have small size, this technology has potential to improve fish monitoring and enable more automated and independent decision-making systems.

The observe phase is the most important process in fish farming, as it is the observations made which are the foundation for the decisions taken in relation to delousing, feeding, net-cleaning, environmental issues and general maintenance on the farm and cages. To enable fish farming to be located more out to sea and become more autonomous and knowledge-based, as well as improve handling and control of salmon lice and environmental parameters, it is necessary for the fish farming industry to implement intelligent sensor technology to improve monitoring of fish and the surrounding environment. The sensor systems that are most commonly used to observe fish variables, and that have the potential to improve the observe phase in the industry are summarized in Table 5. The table also lists how these sensors are implemented and which variables they measure, as well as information level and sensor range.

Table 5: Sensor systems and monitoring methods for observation of fish variables in commercial sea-cages (Føre, et al., 2017).

Sensor type	Sensor implementation	Animal variables	Information level	Sensing range
Sonar	Single beam sonar	- Biomass depth distribution within beam	Group	1 – 200 m
	Split-beam sonar	- Biomass depth distribution - Movement dynamics (position, speed) within beam	Individual based group	1 – 200 m
	Multibeam sonar	- Biomass depth distribution - Movement dynamics (position, speed) within entire cage volume - Feed pellet detection	Group	1 – 200 m
Hydroacoustic telemetry	Individual fish tags	- Depth, position, acceleration, spatial orientation	Individual history	0 – 1000 m
Passive hydroacoustic sensing	Hydrophone	- Sound emitted from fish population, general soundscape	Group	0 – 50 m
Camera	Surface camera	- Surface activity (jumping/splashing)	Group	0.5 – 30 m
	Feeding camera (submerged)	- Sea-lice count - Skin characteristics (scratches, wounds) - Behavioural characteristics (systematic vs. chaotic swimming patterns, normal vs. unexpected behaviour) - Species identification	Individual based group	0.5 – 25 m
	Stereo camera (submerged)	- Sea-lice count - Skin characteristics (scratches, wounds) - Behavioural characteristics (systematic vs. chaotic swimming patterns, normal vs. unexpected behaviour) - Species identification - Swimming speed and direction - Size estimation	Individual based group	0.5 – 25 m
	Hyperspectral imager	- Skin spectral characteristics - Sea-lice detection and count	Individual based group	0.5 – 25 m
	Multispectral imager	- Detection of spectral signatures - Sea-lice count	Individual based group	0.5 – 25 m

These sensors can be deployed in a commercial sea-cage to observe the fish. The sensor types can be categorized in four different systems, with surface camera, stereo video (submerged), sonar and acoustic telemetry. Together these sensors will collect data and provide information for optimal monitoring, control and decision-making. Figure 17 illustrates how these sensors can be arranged in a sea-cage, covering all necessary fish variables.

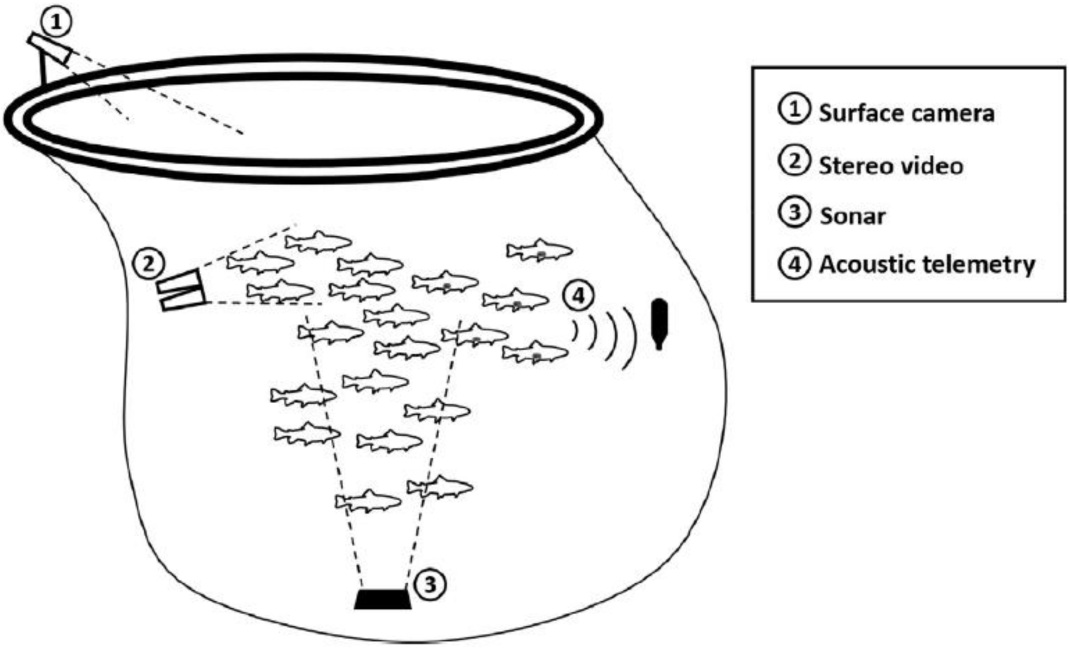


Figure 17: Illustration of how four sensor systems and monitoring methods can be deployed in a commercial sea-cage (Føre, et al., 2017).

Surface camera (1) covers the surface activity (splashing/jumping), stereo video (2) are submerged cameras covering fish behaviour, skin characteristics, feeding activity, swimming activity, sea-lice infestations and swimming speeds and directions etc. Sonar (3) produce data on biometric parameters such as biomass, depth and fish size distribution, movement dynamics and pellet detection. Acoustic telemetry (4) collects continuous data on the individual fish.

Interpret

In fish farming today, most interpretation of the fish observations are conducted by farmers based on personal knowledge and experience. Although there are ongoing research and innovations on making the interpret phase more automated, automated interpretation are much less established than automated monitoring. This means that the interpret phase has potential to develop new PFF methods in this area to maintain a sustainable fish farming industry both inshore and offshore.

Before the information provided by the sensors in the observation phase can be of use for the decision phase, the aggregated knowledge need to be synthesized and structured into a complete system representation. To achieve this, mathematical tools and algorithms derived from control engineering can be utilized for interpretation of the observation outputs and provide better estimations on current features. Mathematical models of dynamic systems can be given a set of inputs that can include distinct types of auxiliary data such as environmental measurements, feed delivery, feeding schedules, infestation levels, waste levels, fish size and other animal variables. The model will then predict and estimate properties of the fish and environment based on the outputs from the sensors. With sufficiently good input data and a combination of existing knowledge through mathematical models and real-time data measured by sensors, it will provide better estimations and interpretations than it is possible to obtain by sensors alone combined with personal experience. (Føre, et al., 2017)

Decide

Every important decision made in present fish farming are made by humans. These decisions are a result of the interpretation of the observations made on the fish and other cage processes based on personal experience, the use of protocols, legislation and recommendations on farm management (Føre, et al., 2017). Making decisions is a complex task and can at this time be difficult and risky to assign to a computer-based system. However, as earlier mentioned, fish farming will be moved out to more remote areas, making human access more limited. This will increase the need of automated farming operations and automated decision-making processes. There is at this time no operative systems for automated decision making in the fish farming industry, but emerging opportunities from autonomization can enable this need. This technology trend and its advances in artificial intelligence and information technology is the basis for the development of Decision Support Systems (DSS) (Føre, et al., 2017). DSS is a computer tool commonly used in oil & gas, finance and medicine, that suggests appropriate decisions based on input and output variables. The DSS takes a given situation and combines inputs from sensors and mathematical models with historical user experiences.

There are more opportunities emerging from autonomization, but these will be discussed in the next chapter.

Act

Most actions and tasks performed in fish farming are assigned to a human operator and are manually controlled and often include manual operations of mechanical equipment such as winches, cranes, crowding nets and ropes (Føre, et al., 2017). The only exception is the centralised feeding systems employed at most commercial fish farms. These systems are integrated with cameras, sensors and remote-control systems, and has an automatic integration to production control. Combined data from the environmental sensors and feeding activity allows the system to make independent decisions on optimal feeding rates, pellet amount and time schedules.

Other daily tasks in fish farming are mostly performed manually by the farmers. This include net cleaning, dead fish tasks, and general maintenance on the sea cages. First, observations on the fish and cage are carried out with the help of camera and control systems. The farmers make an interpretation of the current status related to parameters such as algae growth, amount of dead fish and other cage conditions. Afterwards, decisions are made on when it is time for net cleaning, removal of dead fish or other maintenance operations, and the following actions are conducted manually. As described in chapter 3.6, net cleaning is performed by operators manually, and in some cases the net cleaning can be performed with ROV technology. Dead fish removal and sea lice counting are also performed manually with farmers physically out on the sea cages.

As previously mentioned, sea lice counting, and dead fish control can be automated with implementation of modern sensor technology. For net cleaning and maintenance operation sub sea in the cages, existing ROV technology with human pilots has the potential to be extended to Autonomous Underwater Vehicles (AUV) technology. For offshore based fish farming, AUV technology is key for operations without human interference. AUV's are commonly used in several industries, performing tasks as hydrographic surveys, inspections and prospecting for oil & gas applications, ship hull inspections and military applications (Nicholson & Healey, 2008). With the use of acoustic positioning methods, computer vision-based systems and improved navigation of ROVs, AUVs can conduct remote operations as minor repairs and other underwater tasks autonomously, as well as remote net cleaning operations.

Opportunities for more autonomous actions and unmanned operations in fish farming will be further discussed in the next chapter.

Potential application of Precision Fish Farming

Much of the technology principles and sensor solutions mentioned in the PFF concept are already used industrially and commercially in other market segments, and several already within aquaculture. However, there exist some technical challenges in implementing this technology in a subsurface and aquatic environment. These challenges need to be overcome before a realisation of industrial PFF applications. The technology mentioned, and its existing challenges and potential solutions are listed in Table 6.

Table 6: Potential PFF technology principles and main challenges of implementation to the fish farming industry (Føre, et al., 2017).

Technology principle	Present industrial applications	Main challenges in transfer to industrial aquaculture	Suggested remedies
Sonar	Seismic surveys, stock assessment in fisheries	Difficult to capture behavioural details on high density populations	Use higher acoustic frequencies for higher spatial resolution
		Complex datasets that may be difficult to visualise in relevant manners	Develop visualisation concepts customised to applications (e.g. feeding)
Acoustic telemetry tags	Fish conservation and ecology studies in relation to hydroelectric dams	Complex and time-consuming tag deployment through surgery	Enable more efficient and simple tagging by e.g. miniaturising tag sizes or using other principles such as oral tagging
		Low bandwidth of acoustic communications channel	Improved communication protocols based on e.g. chirp/sweep signals and TDMA principles
		Difficult to ensure that tagged fish are representative for the population	Increase percentage monitored fish through more efficient tagging methods and higher bandwidth
Passive acoustics	Terrestrial livestock production	Limited knowledge on relation between sound and Animal variables of salmon	Long term monitoring in parallel with other systems to generate new knowledge
Computer vision	Medicine, robotics, manufacturing and mass- production	High turbidity caused by e.g. feed particles or net cleaning particles	Strategic camera placement during feeding/ cleaning operations
		Suboptimal lighting conditions during winter/at night-time	UV lights invisible to fish
Remote controlled or autonomous vehicles (ROV/ AUV)	Oil and gas, shipping, military	Risk of hitting structures/fish while navigating cage volume	Equip vehicle with acoustic/computer vision-based navigation means, giving input to adaptive mission planning systems
		Risk of fish responding to presence of vehicle	Incorporate control system features enabling the vehicle to adapt to fish responses
Decision Support Systems (DSS)	Oil and gas, finance, medicine	Insufficient reliability and quality in sensor data	Increase robustness of instruments and communication channels to prolonged submersion in sea water
		Difficulties obtaining detailed descriptions of user experiences	Introduce routines for systematic registration of metadata during farm operations

To summarize, the PFF framework developed by Føre, et al. (2017), is only a concept study based on innovation in technology trends as sensorization and autonomization. However, if thoroughly evaluated and tested, these PPF methods can contribute to improving fish welfare and health, reducing fish losses, improving production efficiency and product quality, and/or reducing environmental impacts. In addition to the future of fish farming is suggested to be more offshore and unmanned, the present trend within the industry is increased volume of production due to increasing demand of sea food, which also will lead to increased production per worker. These lead to a greater need to monitor and control the production, and the future methods of fish farming therefore need be more advanced and intelligent. Exploitation of new sensor, connectivity and automation technology will be central in addressing these challenges, and the Precision Fish Farming concept seeks to harness this potential in representing a framework for the development of technologically founded methods for fish farming (Føre, et al., 2017)

4.4 Autonomization

As previously mentioned, sensorization, connectivity and digitalization are the foundation for the technology trend, autonomization. This technology trend, as well as automation, is the key element regarding present and future innovative opportunities for more automated, autonomous and remotely operated systems and operations in the fish farming industry. Autonomization is the process of making something autonomous. When something is autonomous, a process or system operates without or with minimal human interaction. This could be work processes, a sequence of tasks, industrial processes, machine learning and improving, or context informed decision making. The main difference between autonomy and automation is that automation requires some operator performance or input before and after the automated sequence, while autonomy is the capacity to accomplish defined tasks without operator interaction. Automation has been around in industries for centuries, including fish farming, while autonomization is a further development of automation that will impact and change the fish farming industry over the years to come.

As mentioned regarding the PFF concept, fish farming consists of four phases which all has the potential to improve from current state to an increased level of monitoring, control and autonomy in fish farming solutions and management. While sensorization and connectivity covers the first two operational phases in fish farming, *observe* and *interpret*, autonomization is the key trend in making the *decide* and *act* phases more automated, self-dependent and knowledge-based. With the use of artificial intelligence, independent decision making, and autonomous perceiving and acting - unmanned and remotely operated fish farms can be feasible through the development of robotics and autonomous systems for general farming operations and monitoring of fish and environment.

Existing solutions in today's salmon farming depend on manual labour and crew/operators on the cage rings. The trend will be that fish farms will move farther at sea, where existing technology and methods are insufficient in relation to the challenges of harsher environment and where staffing at site is difficult. In addition, the methods of which salmon lice and environmental issues are handled are also insufficient. To address these challenges, there are several players already well in the process of utilizing autonomization to develop innovative systems and methods for remote and sustainable fish farming. All the upcoming examples of innovative solutions for improved monitoring and control in fish farming are based on PFF principles, as well as the mentioned technology trends.

4.4.1 ARTIFEX and CageReporter

SINTEF Ocean has through several research projects been working on development of new robot technology above and below water, for unmanned surveillance and operations of offshore fish farming. The autonomous fish farm is based on SINTEF's two projects, ARTIFEX and CageReporter.

ARTIFEX

ARTIFEX is an ongoing project started in the beginning of 2016 by SINTEF Ocean in collaboration with Maritime Robotics, Argus Remote Systems and other industry partners. ARTIFEX is built on autonomization to solve the challenges associated with future fish farming and allows for unmanned monitoring and operation of offshore based fish farms. By the development of a robot system it will allow for daily and periodic operations for inspection, maintenance and repair to be carried out from a land-based facility and without staffing at the site. The robot system consists of 3 systems in interaction, where an Unmanned Surface Vehicle (USV), Figure 18, functions as a platform and carrier of a Remotely Operated Vehicle (ROV) for underwater operations, and Remotely Piloted Aircraft Systems (RPAS) for inspection tasks from the air (SINTEF, 2016). The USV will move between the different sea cages and the land base. While the drone (RPAS), will inspect conditions on the surface, the ROV swims around in the cage and checks for holes in the net pen. Using autopilot functions, the ROV can inspect the entire net pen systematically and efficiently, where a computer vision hole detection system will alert the pilot if there are any holes in the net. The ROV provides 3D visualization of the net pen, showing the ROV's position relative to the net, and which areas that have been inspected. In addition to performing underwater inspections, the ROV can repair weaknesses in the net before the hole becomes of such size that there is a risk of the fish escaping.

Figure 18: Illustration of an Unmanned Surface Vehicle (USV) carrying ROV and drone (RPAS) between sea cages for various farming operations as inspection, maintenance and repair. Photo: Maritime Robotics (SINTEF, 2016).

CageReporter

In addition to being able to perform unmanned operations on the site, a remotely-operated fish farm must also be able to monitor and control key variables such as feeding conditions and feed waste, fish amount, average weight and growth, lice infestation status, and health conditions. SINTEF's CageReporter project addresses these challenges with the development of technology for autonomous, bio-interactive and high-quality data acquisition. CageReporter consist mainly of an Autonomous Underwater Vehicle (AUV), which is a carrier of sensor systems for data acquisition, where the data is transferred from the sea cage to land-based control room (SINTEF, 2017). Each sea cage is equipped with a self-controlled and self-operating AUV, with underwater docking for 24/7 data collection on sea cage and fish conditions. The AUV is bio-interactive, and swims around with the fish with sensors that obtain information on fish behaviour, health status, lice levels and feeding activity. This project was started in the summer of 2017 in collaboration with Water Linked AS and Sealab AS and is expected to be completed in 2019 with demonstration in a full-scale sea cage (SINTEF, 2017). Figure 19 illustrates how CageReporter is composed.

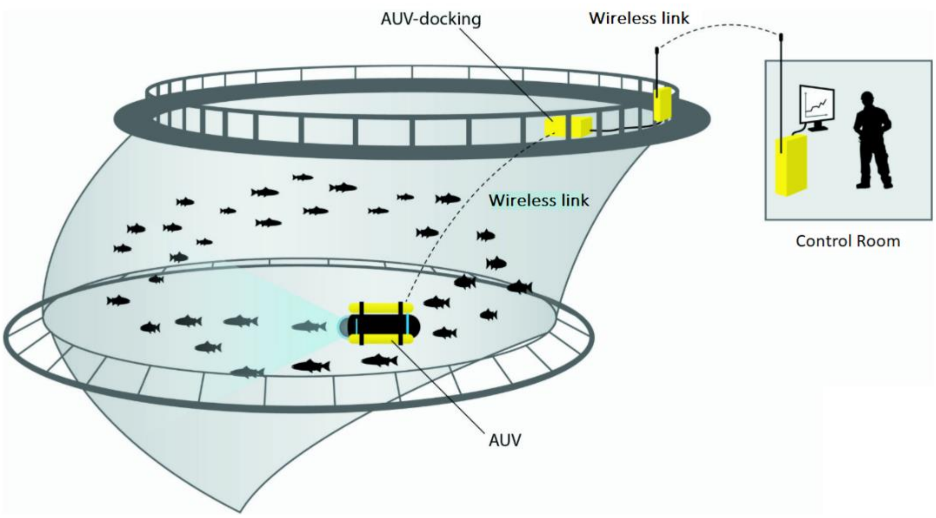


Figure 19: Illustration of SINTEF's CageReporter project, with AUV immersed in the sea cage for 24/7 monitoring of fish health, fish welfare and environment conditions (SINTEF, 2017).

4.4.2 Stingray

As previously mentioned, sea lice remain the biggest challenge in the fish farming industry and is often the most common reason to loss of resources. In addition to the fact that sea lice weaken and kills the salmon, the way lice counting, and delousing operations are carried out today are both very time-consuming and expensive. The cost of combating salmon lice has exploded to over NOK 10 billion annually for the Norwegian fish farming industry (Stensvold, 2017). Apart from being labour intensive and costly, the present methods of counting and delousing involves crowding and handling, which negatively affects the fish's health and welfare. Based on advanced sensorization, laser and autonomization technology, Stingray Marine Solutions has developed a solution that eliminates all these challenges regarding sea lice.

The intelligent Stingray system shown in Figure 20 consist of mechanical components computer applications/software that allows for optic delousing, as well as data retrieval from the pens. With laser technology and advanced software and camera vision, the sea lice can be quickly analysed, identified and shot with laser, without causing any harm to the fish. The laser identifies the louse, locks on it, and follows it before the laser fires a pulse which is powerful enough to make the louse coagulate within milliseconds (Stingray Marine Solutions, 2018). The salmon will not take any harm from the laser as the salmon's skin reflects the light, while the louse absorbs it. The smallest louse can look like the black dots of the salmon skin, and the Stingray technology can separate lice and dots down to 2 – 3 mm (Stensvold, 2017). The process is completely automated, and the laser works continuously and preventively 24/7, throughout the year.

As well as the Stingray uses LED lamps, sensors, cameras and lasers to detect and shoot lice, the system is capable of machine learning, which allows for extended application towards lice counting and biomass measurement. Norwegian fish farmers are obliged to report both sea lice levels and number of fish in each pen to the authorities regularly. The Stingray technology is also capable for continuous and automatic lice counting and biomass measurement with the use of camera vision and software. Not only will this eliminate how these manual and labour-intensive controls are performed today, but it has also proven to show more accurate results as the Stingray node performance take measurements on a larger scale of fish and in an extended area in the pen.

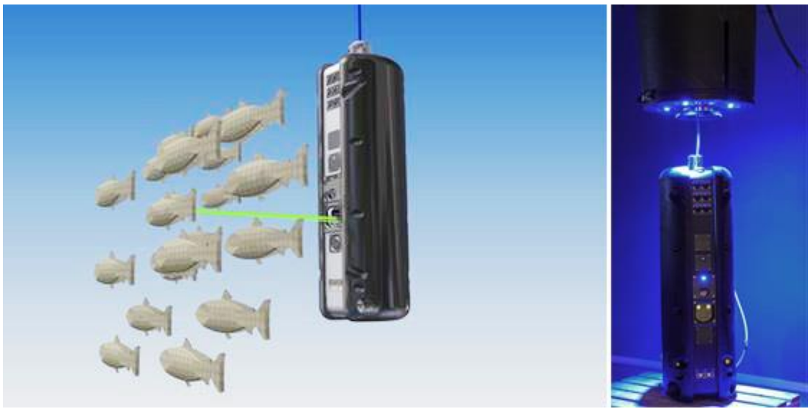


Figure 20: Illustration of Stingray laser node. Photo: Stingray Marine Solutions

The development of Stingray started in 2010, of which the first sea lice was killed in 2013. First commercial laser node was sold in 2014, and by the end of 2015 there were 48 operating lasers (Stingray Marine Solutions, 2018). Stingray is expanding rapidly, and only within the first quarter of 2018, Stingray have sold as many laser nodes as in 2017, which corresponds to more than 200 operational units (Moore & Hosteland, 2018). From the end of May 2018, every laser node is delivered with optical and automatic louse counting applications. Stingray sells a laser node with a 4-year warranty and operating agreements and service programme for NOK 1.3 million, or NOK 325,000 per year (Stensvold, 2017).

4.4.3 Echofeeding

The Norwegian Institute of Marine Research has taken on another challenge, namely zero feed waste. As well as feed waste negatively affects the surrounding environment, feed spills is a major loss of resources for the farmers, as pellets accounts for 60 – 90% of production costs. To achieve zero feed waste, they have developed an automated technology that uses an echo sounder connected to an advanced software that monitors the fish's behaviour and appetite for automatically control of the feeding process. The echo sounder shows the amount of fish that is gathering around the feed, and when the feed pellets dissolves. The echo-feeding principle uses the echo sounder to observe the amount of fish that responds to feeding, where the analysis software automatically stops feeding at a predetermined critical value when the fish is saturated and swims away from the feed (Norwegian Institute of Marine Research, 2018).

4.4.4 Autonomous net cleaning

Another extensive task and challenge the breeders are daily exposed to in cage farming is algae growth in the net pen. In the cages it is crucial to have clean nets and proper waterflow so that the fish has sufficient oxygen in the surrounding water. To maintain good waterflow through the nets, breeders may have to wash the nets several times a month. Traditional net cleaning procedures are mostly manually performed and so labour intensive that some companies choose to pay other companies for net cleaning services. Not only does this initiate prohibitive cost, but it also limits the number of treatments per cage. Thus, several companies have researched and developed net cleaning systems that will make this process more automatic or autonomic, as well as easier, cheaper and more sustainable.

One of the most promising net cleaning innovation at present times in Norwegian aquaculture is the Halo Net Maintenance System developed by Aqua Robotics. This Halo system was launched in August

2017, and is a patented, fully automatic robotic system that is mounted on rails in each cage, with a rolling brush unit that keeps the net clean by automatically moving up and down along the net (Erik-Blaalid, 2017). The robot unit moves automatically around the cage via railing system, and with reversible wings/foils, the brush is pressed close to the net wall. With an integrated net cleaning system permanently in each cage, the Halo system can maintain constantly clean nets as it can operate up to several times per day, giving the fish optimal growth conditions. This patented technology is also the most promising regarding offshore based fish farms that are remotely operated, since the net washing system is integrated and self-controlled, as well as the system does not need to be moved from cage to cage or operated from the site.

5 Evaluating innovation opportunities

The innovation opportunities derived from the technology trends in energy, sensorization and connectivity, and autonomization was in the previous chapter identified and described in terms of their composition and structure, functionality, improvement potential and ability to solve existing and future challenges in the fish farming industry. For further evaluation of the technology trends and their opportunities to effect fish farming, a breakdown of each technology trend is carried out in Table 7. The table illustrated how the technology trends and their associated innovation opportunities can affect the fish farming industry in terms of value creation flow, market, solving key challenges and their feasibility.

Table 7: Effect of technology trends on the fish farming industry

Technology trends		**Energy: Renewable energy, grid independence and battery storage**	**Sensorization and connectivity**	**Autonomization**
Value creation flow	Changes to production cycle - Are there possible improvements from this technology to the production cycle?	Solutions from energy trends have no direct impact on the production cycle. However, renewable energy and self-sufficient energy systems reduce CO_2 emissions as well as reduce maintenance needed on diesel systems.	Opportunities from sensorization and connectivity improves the level of monitoring and control of following biological processes and environmental parameters in the production cycle; - Lice infestation and lice counting - Biomass monitoring; total weight and number of fish, individual fish weight and size - Environmental parameters as algae growth, oxygen level and cage conditions - Feeding process and feed waste	Opportunities based on autonomization opens the possibility for offshore based fish farms, as well as unmanned and remotely operated fish farming. This involves that there will be reduced human interaction during the production cycle, and reduced handling of the fish. Together with the improved environment for fish at offshore locations, the fish health and welfare will improve, as well as increase growth.
	Changes to required skills - Are there possible changes to the required skills from the fish farmers with this technology?	With implementation of renewable power generation as wind turbines and solar panels etc., this requires operators with skills within renewable energy to operate and perform maintenance and repair on these systems.	Requires more technical skills regarding monitoring systems as sensors and monitoring software, as well as skills regarding interpretation of informative data on fish and marine parameters	Implementation of more automatic and autonomization requires more technical knowledge, competence and skills in areas as automation, electronics and engineering. Autonomous vehicles such as USV, ROV and drones requires pilots. These autonomous systems also require personnel and technicians to perform maintenance and repair.
	Changes to cost - Are the production costs changing from this technology trend?	Renewable energy systems and electric workboats will save costs compared to diesel generators and diesel boats. However, renewable energy is	More advanced sensory and equipment software tools will increase tangible costs at fish farms. However, it will reduce cost in relation to reduced	More autonomous and advanced technology will increase tangible costs considerably, as for example the Stingray node. However,

		more expensive compared to on-grid solutions.	manual labour, as well as improved monitoring and control over the fish and farming processes can induce actions that reduce the loss of resources such as feed waste, fish mortality and escapes.	implementation of more autonomous systems and processes will reduce costs related to manual labour (from lice counting, repair, inspection etc.), delousing operations, and net cleaning etc. Autonomization will also improve the level of monitoring and control of farming processes, which induces more accurate and precise decision making and actions, which again can reduce loss of resources.
Market	New needs - Can this technology trend contribute to covering potential new needs?	The renewable energy system as Salmo Solar can also function as an energy station for passing electric boats in the area. The technology and concept for power generation can also be implement in other offshore businesses for reduced CO2 emissions, as for example the oil & gas industry.	Sensorization and connectivity trends already plays an important role in other industrial contexts where machinery, equipment and processes must be monitored and controlled. So, development of sensory systems in the fish farming industry can also be applicable for other industries where condition monitoring is applicable.	The technology in fish farming emerged from the autonomization trends can contribute to replace human labour in other industries as well. In other maritime industries such as oil & gas, fisheries and shipping, where human safety can be a risk, autonomous system can be a solution.
	New customer groups - Can this technology trend help attract other customer groups	The technology in electric workboats for fish farming can be used in the maritime market in general. As for example private boats, ferries, and workboats in other industries.	The principles and methods from the PFF concept are also relevant for general monitoring of biological processes and animal welfare as agriculture and the fishing industries.	Autonomous technology developed for fish farming can be applicable for the maritime environment. USV, ROV and drones are commonly used in other industries, and can also be attract more customers in the maritime industries. As an example, there are research on autonomous boats for developing unmanned supply ships.
Key	Solving key challenges - Which challenges will the technology trend help to solve?	As the government are demanding cuts in CO2 emissions, renewable energy sources will reduce greenhouse gases and contribute to a sustainable future. Offshore power generation will also solve the challenges regarding electricity grid.	Application of trends in sensorization and connectivity, such as the PFF methods, will solve challenges related to monitoring and control of biological and production processes, and improve precision and accuracy of farming operations, as well as provide more reliable decision support and facilitate more autonomous animal/biomass monitoring. - More precise and automated lice counting, which eliminates physical handling of salmon - Improved feeding control and feeding regimes	The Stingray technology are already implemented and has the potential to solve or minimize all challenges related salmon lice, such as lice counting and delousing. The technology has also the potential to improve biomass measurements. The use of autonomous systems as USV, ROV and drones can solve challenges related to crew at site on future offshore fish farms. Autonomous feeding control as the Echofeeding technology contributes to reduced feed waste and

			- Improved control of biomass parameters, inducing improved decision making	challenges related to environmental pollution and loss of resources. Autonomous net cleaning can be a solution for fish farms on exposed locations, where access for manual operated net cleaning can be challenging.
	Implementability - Are the innovative opportunities from this technology trend feasible to implement?	Salmo Solar are the first concept of this kind and are not yet fully implemented. However, with the recent development in offshore wind power, solar power and battery storage, this concept should be feasible for future offshore farming. Electric workboats are already implemented, so this trend will probably increase in the future due to stricter requirements for CO2 emissions.	The methods of PFF and the use of sensorization to and algorithms to induce automatic and improved decision-making are already well established in several industries such as oil and gas, finance and medicine, as well as measurement of animal parameters are common in agriculture. The recent development in sensor systems are therefor feasible to implement in the fish farming industry for improved monitoring and more precise and automated decision-making.	The use of autonomous vehicles such as in the ARTIFEX and CageReporter projects are still ongoing and not fully exploited. However, it is expected to be implemented during the next years. The Stingray technology was recently implemented and is expected to expand rapidly in the future. Autonomous net cleaning is already practiced and can be expected to more implemented in the future. Automated feeding processes are already well established in the industry, and a shift to more autonomous feeding process can be expected to be common practise in the years to come.

After a thorough research and an evaluation of all listed opportunities, it is clearly that the ability to innovate in the fish farming industry is considerably high. The evaluation of the innovation opportunities derived from the three different technology trends are further discussed in the next chapter.

6 Conclusions

The fish farming industry is an important supplier of fish food for human consumption, and due to the significantly increasing worldwide demand for food, fish farming will play an even greater role in feeding future generations. This increasing demand will force the industry to grow and expand production, which will threaten the sustainability of fish farming due to space limitations and emergence of already major challenges such as salmon lice and environmental pollution. An upscaling in production will lead to an upscaling of existing problems, causing the fish farming industry in need to improve their current solutions in line with evolving challenges and increased production demand.

To comprehend with these emerging biological, economic and social challenges, the study shows that fish farming is assumed to be moved farther out to sea, as well as making future methods for farming more advanced and smarter, to achieve growth and maintain sustainability. When fish farming is increasing production and is moved more offshore and in exposed locations, the fish farms will increase in size and in complexity, as well as being more exposed to harsher environment. There will still be more fish farms a in the fjords nevertheless, and with an expansion of fish farms along the coast, the challenges related to sea lice and environmental will increase significantly. The industry is therefore required to adapt to modern technology trends and aspire to more sophisticated technology to improve farming solutions and operations, as well as realization of offshore based fish farms.

This study identifies and evaluates several innovation opportunities that are emerging from modern technology trends, that has the potential to make fish farming sustainable and more future-oriented. The main goal of the thesis is to provide an assessment on how trends in technology can affect the fish farming industry, as well as determine how the innovation opportunities derived by these trends can and will improve current solutions and improve fish farming in relation to monitoring and control of biological processes, net pens and surrounding environments, feeding processes, lice infestations, as well as the realization of offshore based fish farms with more automatic/autonomous, unmanned and remotely operated systems and operations.

After carrying out a thorough overview of the fish farming industry and all products, technologies and processes involved in the salmon production cycle, as well as an identification of all related challenges, it was concluded that there are essentially three different technological trends that can contribute to solving emerging challenges and create future growth and sustainability. These are respectively energy, sensorization, and autonomization. Within all these trends, several innovation opportunities have been identified and evaluated essentially in terms of their potential to reduce the impacts of existing challenges and achieve the goals for offshore based and remotely operated fish farming.

The results from the evaluation suggests that the greatest opportunities from trends in energy is to implement renewable energy sources and battery storage to generate power for offshore fish farms. As fish farms located at exposed areas will have challenges with connecting to the onshore electricity grid, Salmo Solar and the exploitation of both wind turbines, solar panel and wave power will solve the challenges of offshore power supply and eliminate the use of diesel generators and emissions of greenhouse gasses. For fish farms located along the coast, where the possibilities for power generation is not sufficient and connection to the electricity grid are not possible, a hybrid solution combining both wind turbines, solar panels and a diesel generator backup system may be the best alternative.

In sensorization, methods from the Precision Fish Farming (PFF) concept was assessed, which showed potential effects and opportunities with implementation of several sensory systems. Table 5 and Figure 17 illustrates how four distinct sensor systems can be deployed and arranged in a commercial sea cage to improve the two first operational phases in fish farming, observation and interpretation. This involves improved monitoring, control and feeding regimes by continuous data collection of biological processes as lice counting, biomass monitoring (fish weight, size and total biomass), feeding activity, surface activity and swimming activity. Since sensorization are well established in other industries as oil & gas, finance and medicine, it is concluded that implementation of advanced sensor technology is feasible for fish farming, as well as it will induce more opportunities for autonomous fish farming innovations.

The thesis shows that sensorization and the principles from PFF is the foundation for autonomization in the fish farming industry. After reviewing considerable ongoing research and recently implemented projects, it was found that there are several promising opportunities for innovation in fish farming emerging from this technology trend. The already implemented Stingray technology has the potential for both autonomous sea lice counting and delousing. With laser technology and advanced software and camera vision, a node submerged in the net pen identifies and shoots louse that are attached to salmon with a laser beam, without causing harm to the fish. With this technology and in combination with cleaner fish, fish farming can cope with sea lice challenges without chemical treatment and manual counting of lice, which cause damage to the surrounding environment and increased stress levels on the fish. The Stingray is developed to cope with higher environmental loads, it can just as well be applicable in more exposed locations as in the fjords.

ARTIFEX and CageReporter are two highlighted projects that utilizes autonomous vehicles for realization of offshore and unmanned fish farms controlled from a land-based control centre. With the use of autonomous vehicles, an Unmanned Surface Vehicle (USV) will carry a Remotely Operated Vehicle (ROV) and a drone between sea cages, the ARTIFEX concept will perform inspection, maintenance and repair on the offshore fish farm. The CageReporter concept consist of an Autonomous Underwater Vehicle (AUV), which perform 24/7 data collection on sea cage and fish conditions. With a combination of these two concepts, it will be possible to perform all monitoring and control form a land-based facility and avoid having crew on the farming site to carry out daily operations.

To carry out remaining tasks such as feeding and net cleaning operations, autonomous technologies such as Echofeeder and Halo Net Maintenance Systems are suggested solutions. Echofeeder is automated technology that uses echo sounder and advanced software to monitor the fish's appetite and generate a feeding regime, with the intention of solving challenges with pollution and loss of resources with zero feed waste. The Halo system is autonomous net cleaning that uses a robotic system integrated on rail in each cage, with the possibility to clean each pen up to several times per day, for optimal growth conditions.

As a concluding remark, there are major opportunities to apply emerging technological trends to innovate in the fish farming industry, particularly within energy, sensorization and autonomization. However, the industry is very aware of this opportunity and necessity, which results in multiple players in the segment performing research and technology development on these trends with the intention to create innovative solutions that will contribute to growth and sustainability in the future of fish farming.

Future studies on this topic may include a specific proposal on a future-oriented and offshore fish farm, with more detailed description of its composition, technology used, mode of operation, production cycle, and operating methods, as well as further research on how the farm will cope with emerging challenges in offshore farming. Figure 17: Illustration of how four sensor systems and monitoring methods can be deployed in a commercial sea-cage .

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