UiT The Arctic University of Norway

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Limitations of Ice Accretion on Offshore Aquaculture Facilities

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Benjamin Marsden

Abstract

Sea spray icing is a constant risk for fish farms operating in cold climates, such as on the Northern Norwegian coast, and there must therefore exist methods to reduce this risk. This thesis discusses the consequences of ice accretion to the traditional plastic circular fish cage design, and how the cage reacts under the pressure of added mass from sea spray icing. The prediction of sea spray icing events and sea spray icing rates is paramount for predicting the risk of large quantities of ice build-up that can be a danger to the cage and fish escaping. Multiple methods and models exist and are compared throughout this thesis. Feeding barges hold a particularly important role in the everyday operations of fish farming, and should not be neglected when sea spray icing events are at risk of occurring, possibly resulting in a loss of stability. Icing can also create difficulties to routine operations and dangers to workers.

1 Introduction

1.1 Background

Norway has a total coastal perimeter of 2650km long, which naturally has resulted in a large percentage of Norwegian industries taking advantage of the coast, e.g., the petroleum industry, transportation, sea fishing, and offshore fish farming to mention some. Norway, situated relatively far north, parts of its coastline is located north of the Arctic Circle and where the continental shelf is rich in seafood resources.

According to SalMar (2020), the world needs to produce 70% more food within the next ten years compared to today’s situation, and at the same time reduce resources and environmental footprint. The world oceans cover two thirds of the Earth’s surface, however only 2% of food energy for human consumption is sourced from the sea. There is therefore a possibility to vastly increase seafood production to provide the population’s increased need. SalMar (2021) also claims that aquaculture is more environmentally friendly and uses less resources compared to livestock farming. However, this is debatable: for example, livestock farming uses manure to improve soil quality, whereas fish farming dumps fish excrement and excess food directly on the seabed, potentially destroying life under the farms (Gudmestad, 2021).

Aquaculture is one of the largest industries in Norway, with a total of 986 sites producing Atlantic salmon and rainbow trout along (and onshore) the Norwegian coast. As of2020 196 of these sites are located in Troms & Finnmark (Directorate of fisheries, 2021). In 2019, the aquaculture industry alone accounted for 8201 jobs in Norway in the production of Atlantic Salmon (Directorate of Fisheries, 2019) and estimated thousands of additional jobs in other domains of the industry (e.g., business, sales, transportation, biology). In Norway by 2019 numbers, this industry produced 1 357 304 tons of farmed salmon, selling for 68 115 302 000 NOK (Directorate of Fisheries, 2019). As seen in the following chart (Figure 1) from the Directorate of Fisheries, the production of Atlantic salmon in Norway has been steadily increasing over the past decade.

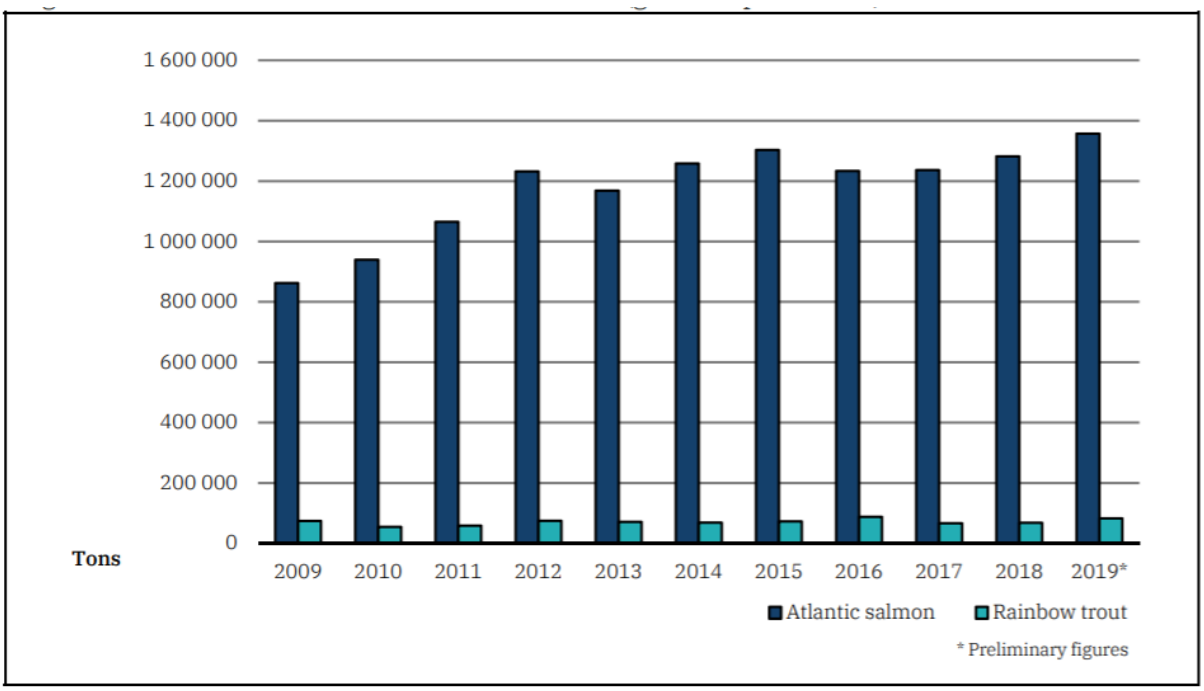


Figure 1: Production of Atlantic salmon in Norway over the past decade. Figure modified from Directorate of Fisheries (2019)

With an increase in demand for offshore produced fish, it follows an increase in demand for improved structures, systems and safe operating conditions for workers. Fish farms need to provide larger cages and better infrastructure, all whilst maintaining or improving operations without severely increasing the total costs. The increase in size and quantities of fish cages result in farms being often moved further out in to more exposed areas, away from civilization, more spacious and a better-quality environment where farming will have a lower impact on the environment. Larger cages must be able to withstand the harsh offshore climates, which is often the ideal climate for many farmed breeds of fish (e.g., Atlantic salmon and trout). Arctic areas experience harsh winters and tough cold climates, with frequent polar low pressures, resulting in strong wind velocities, large waves, and heavy atmospheric- and sea spray icing phenomena. Marine fish farming is considered one of the most dangerous industries in Norway (Utne et al., 2015) and relies strongly on human influence and interaction. These interactions involve maintenance, cleaning and surveillance to mention some. Workers are often operating in exposed, high-risk situations (Utne et al., 2015), see for example Figure 2, Icing on fish cage in Kaldfjord, Tromsø, 1977. With 9058 employees working in this industry in 2019 (Directorate of Fisheries, 2019), there are a large number of workers regularly exposed to these exposed environments and therefore exposed to the risk of injury (1400 reported injuries, and 33 deaths from 1988-2013, Utne et al., 2015).

Figure 2: Icing on fish cage in Kaldfjord, Tromsø, 1974 & 1977. Licensed photos by Andersen (1974), Andersen (1977)

1.2 Statement of Relevance

1.2.1 Causes of Escaping Fish

The escape of fish from these farms is considered an environmental crime, and can occur from many causes. Structural failures can be caused by large low-pressure systems bringing strong winds, currents and large waves. Errors and failures, mechanical or human, in routine operations (e.g., feeding, cleaning, moving fish) can also be causes to escaping fish. Large scale escape events, considered over 10 000 individuals, can be seen in a seasonal pattern, most often occurring in the autumn months, where storm systems are larger and most frequent according to Jensen et al. (2010). An anchoring failure is a possible failure mode in case of large forces from waves and currents.

Jensen et al. (2010) also mention that these large-scale events represent only 19% of reported escape events, but caused a total of 91% of the number of escaped fish. Although relatively outdated, these numbers are severe and still relevant today. Structural failures are the most common and cause of this. Whilst relatively infrequent, the consequences can be at a much larger scale. Errors in routine operations are much more frequent, but the scale of escaping fish at each incident is much smaller, often only a few fish to a few thousands (Jensen et al., 2010). Structural failures have therefore much greater focus in the prevention of escapes (Jensen et al., 2010).

Cold climates are presented with additional risk of ice build-up, which can be a challenge for operations in the wintertime, and a danger to the structure of the cage, increasing the risk of escaping fish. The escaping of Atlantic salmon, as well as other farmed species varies each year, but the Directorate of Fisheries' reports show that this phenomenon is globally on the decline. The situation in Norway is demonstrated in figure 3.

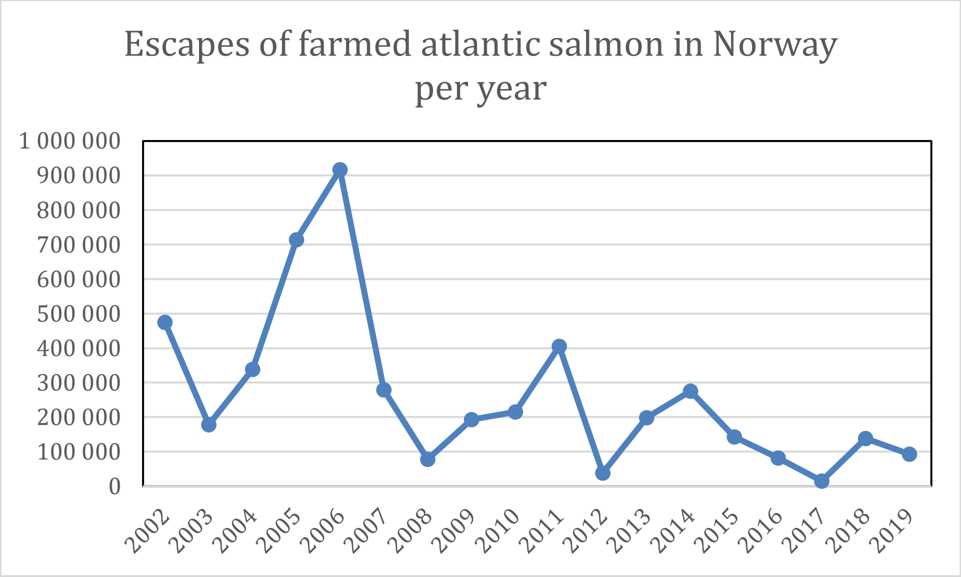


Figure 3: Escapes of farmed Atlantic salmon in Norway per year. Figure made from escape statistics from Directorate of Fisheries (2002-2019)

1.2.2 Environmental impact of escaping farmed fish

The escape of fish can have dramatic effects on the environment. The newly increased interest in the environmental impact has led to several studies being published on the environmental issue related to the escaping of genetically modified farmed Atlantic Salmon and its negative impact on the local wild salmon population in several parts of the world (e.g. Crosier et al,. 1993; Fraser et al,. 2008 Keyser et al,. 2018,. Diserud et al,. 2019 to mention some). Some of the most severe impacts are listed below:

Genetic impact of escaping fish

Through regular monitoring from the Institute of Marine Research in Bergen, Norway (Havforskningsinstituttet, 2019), it has been shown that escaped farmed Atlantic salmon, through breeding, has affected the genetic make-up of wild salmon in Norwegian rivers. Wild salmon have gene pools adapted to the area and conditions they live in. The alteration of their gene pool can cause the wild salmon to be less well adapted and therefore less likely to survive (Havforskningsinstituttet, 2019).

Transfer of diseases and pathogens

Jensen et al., 2010, explain that the transmission of diseases and pathogens from farmed salmon to wild salmon has been well documented. It is known that fish farms are considered a reservoir for sea lice, and escaped fish can easily transmit this to wild salmon. Other diseases can also be transmitted. In 2007, an outbreak at a farm in southern Norway, caused the escape of 60 000 salmon carrying infectious salmon anaemia, and 115 000 salmon infected with pancreas disease (Jensen et al., 2010), although the extent of transmission to wild salmon is still unknown.

Competition for food

Wild and farmed Atlantic salmon, have same dietary needs, and can therefore eat much of the same diet (Jensen et al., 2010). In Open Ocean, and in coastal areas, the salmon can be competing for the same food. However, in open oceans, this competition is unlikely to have an effect, as the mortality rate appears to be independent to the density of salmon (Jensen et al., 2010). This is however unknown for coastal areas.

1.3 Fish farm layout

Figure 4 “Products offered by Akva group”, shows a standard layout for a fish farming site. The cage itself is built up from multiple floating rings holding up a net containing the fish, and a heavy sinker tube at the bottom maintaining the structure and integrity of the net. This circular cage is a commonly used design, often made with polyurethane plastic tubes. Steel circular and rectangular cages are also used. The cages are most commonly moored to the seabed with large chains. In proximity to the cage, there is a feeding barge. The feeding barge is connected to the cage by tubes, floating or submerged in the water, that provide fish food to the cage. There are often multiple fish cages on one site that can be supplied by the one feed barge. The feed barge also carries fuel to supply the service boats and office space for work, with computers for planning automated feeding and camera surveillance. Modern feed barges are adapted to provide living space for longer stays. The feed barge is usually anchored in position, but is designed to travel to and from land. Service boats are often present to transport employees from land to the feed barge, and to the cages for inspection, maintenance to mention some.

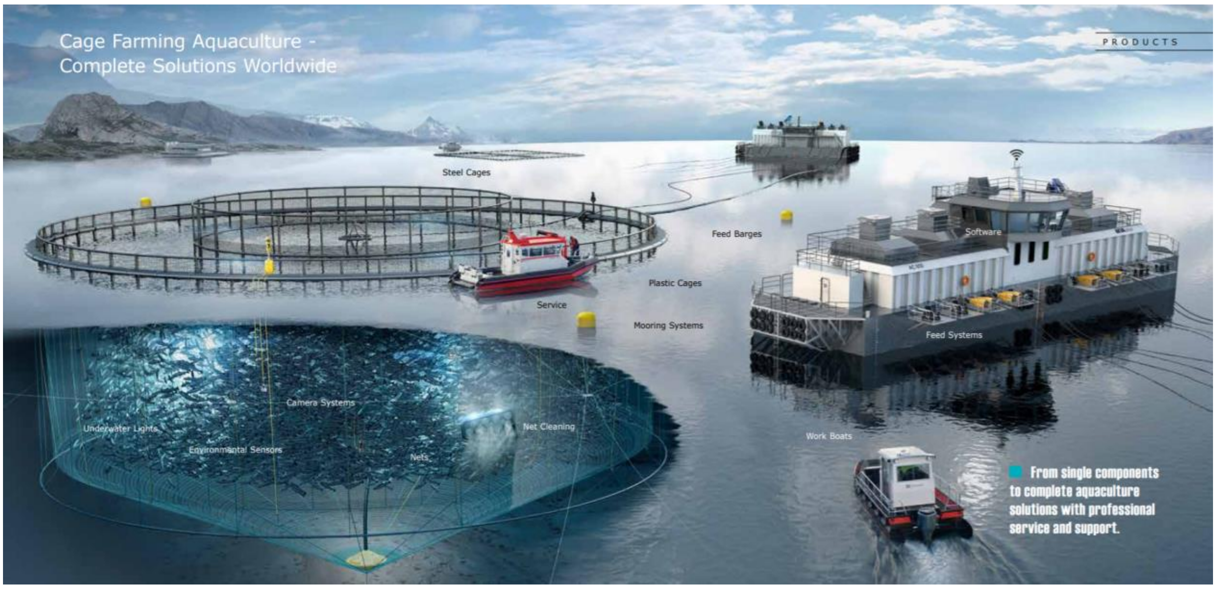


Figure 4: Products offered by Akva Group. Figure is modified from Akvagroup (2021a)

1.4 Previous incidents related to sea spray icing

1.4.1 Sinking of an Icelandic feeding barge

Figure 5: Icelandic feeding barge, Muninn, half submerged. Photo from RUV (2021)

Figure 6: Location of Reyðarfjörður, image modified from google maps

On the night of the 10th January 2021, an Icelandic patrol ship, Þór, was called to a fish farming site in Reyðarfjörður (Figure 5 and 6), where a feeding barge was reported sinking, by employees of the fish farming company Laxar. Severe weather conditions made operations difficult. The Coast Guard launched a lifeboat, carrying powerful sea pumps, but the barge was almost completely submerged and there was little that could be done to save it

Over that weekend, Iceland was affected by heavy storms including strong winds, combined with high tides and severe icing (Fish Farmer Magazine, January 2021)

The feeding barge named Muninn, measured 25m in length and was 12m wide, and was thought to have taken on water causing it to list, and therefore sank rapidly. 10 000 litres of diesel fuel were stored on the barge at the time, and was contained during the sinking. It is thought that heavy icing caused the feed barge to take on water, but this has not been concluded.

Laxar is a large fish farming company that operates multiple farming sites around Iceland, including that at Reyðarfjörður. The site in Reyðarfjörður is large and technically advanced and has a production permit for 16 000 metric tons per year (Laxar, 2021).

The fjord Reyðarfjörður is located on the eastern coast of Iceland, and is 20km long. Icelandic winters can be harsh, and it’s location out in the middle of the ocean between two continents makes Iceland subject to heavy storms. The length and geography of the fjord inland on Iceland, therefore means farms will not be affected by offshore swell and as subject to the weather.

1.4.2 Loss of 100 000 salmon in Western Iceland

The fish farming company Anarlax, owned by SalMar, had long delays in harvesting salmon from their site in Arnarfjörður in Western Iceland (Figure 7). These delays occurred due to severe weather conditions. During a period of a few days, the severe weather brought considerably colder sea temperatures. According to Iceland’s food safety inspectorate, MAST, this caused the salmon to move lower down in the cages. This movement resulted in the salmon to be in close contact, rubbing themselves on each other and the netting of the cage. This close contact resulted in around 500 tonnes, or 100 000 salmon, to die or suffocate (Fish farmer magazine, 2021).

Once the severe weather had passed, Arnarlax called in multiple local fishing boats and the Norwegian Gannet (a hi-tech slaughter vessel) to rapidly slaughter the remaining salmon. The remaining salmon were of decent quality, but the whole event caused a financial loss of ISK 435 million (over 28 million NOK).

Figure 7: Location of Arnarfjörður, image modified from Google maps

1.4.3 Sinking of Scottish feeding barge

At a Mowi (formerly known as Marine Harvest ASA) farm near Lochboisdale, Uist, Scotland (Figures 8 and 9), a feeding barge sunk in the night of the 17th January 2019, during a storm generating 2-meter swell. This feeding barge was of cylindrical shape, containing 170 tons of fish feed and 1000 litres of diesel. All fish feed and diesel was sealed and contained at the time of the sinking to the seabed 20m.

Figure 8: Feeding barge from Lochboisdale farming site, under normal condition. Photo from Salmon Business (2019)

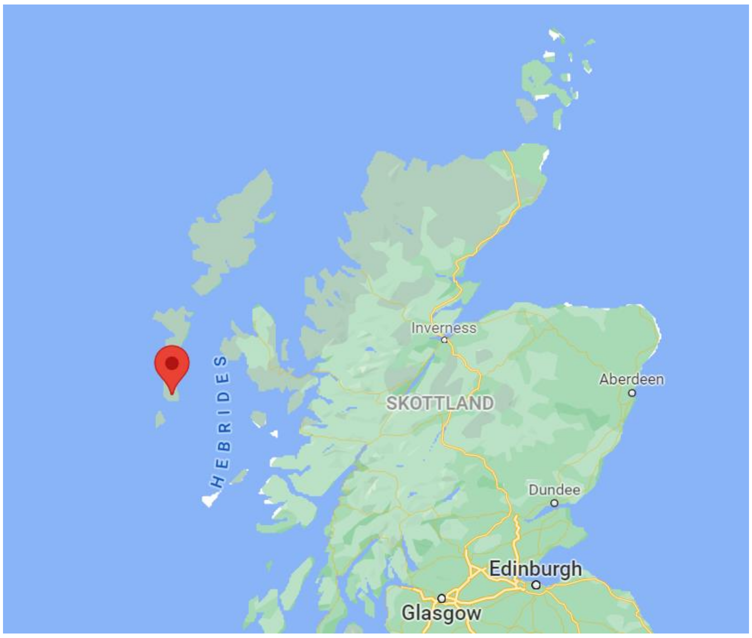


Figure 9: Location of Lochboisdale. Image modified from Google Maps

1.5 Problem Statement

Aquaculture is raising in demand to nourish a constantly increasing world population. But this increase in quantity and size of farms raises the risk of large quantities of Atlantic salmon escaping. As structure failures are being the dominating factor in large-scale escapes of Atlantic salmon, it is essential that they are focused on to control and continuously improve, in order to reduce this risk of damage and eventually fish escape. Icing is an additional factor to structure failures in cold climates, and could also cause structural failures due to increased weights, and should be included in this focus.

1.6 Aims and Objectives

This thesis is aimed on creating a better understanding of the impact of cold climates and ice on fish farming, with the overarching goal of creating a safer and more secure environment for the future fish farming industry.

More specifically, the objectives of this thesis are:

- To study the impact of icing on structural failures of fish cages causing large scale escapes.
- To assess the impact of operations in winter that can result in fish escapes.
- To show how ice accretion can be predicted.
- To discuss the stability and motions of feed barges.

1.7 Research questions

Based upon the aims and objectives of this thesis, the following research questions can be identified:

- How much ice can a commonly used plastic circular cage withstand?
- How can icing be predicted to lower the risk of structure failure and escaping fish?
- What are the impacts of ice on commonly used feed barges?
- How can cold climate and ice impact routine operations, and the risk of escaping fish?

1.8 Organisation of thesis

Chapter 1, Introduction to the fish farming industry, and the importance of avoiding escapes.

Chapter 2, Methodology, will present the Standards used in the fish farming industry, and how they are regulated. The basics of ice accretion, and a presentation of multiple ice accretion models, for predicting or estimating the quantity or rate of sea spray icing.

Chapter 3, presents a traditional fish cage structure, with its limitations from ice accretion, and a case study on a new type of offshore fish cage, by Norway Royal Salmon.

Chapter 4, Results and Discussion, presents the results of the thesis, and discusses the structure of traditional fish cages, ice prediction methods and models, the limitations to operating and running farms in cold climates, and the importance of the design of feeding barges.

Chapter 5, Conclusion of the thesis, with recommendations for future work.

2 Methodology

2.1 Norwegian Marine fish farming Standards

Farmed fish escaping can be an economical problem, but also a risk for the surrounding ecosystem. Farmed fish are genetically different to those in the wild, and can alter wild fish genes when breeding. Escaping fish is considered an environmental crime, and should be prevented at all costs.

With an increase in aquaculture, the Norwegian Aquaculture Act was written in 2006 (Regjeringen, 2006).

Section 31 of the Regulations for Operating Aquaculture placed a ban on the release of farmed fish into the wild. The Norwegian standard NS 9415 (Standard Norge, 2009), covers this issue of escaping fish.

NS 9415 (Standard Norge, 2009) covers the requirement necessary to reduce the risk of escape down to an acceptable level. It covers requirements for the design of cages, operations and documentation. The standard sets requirements to all of the main components of the cages: netting, framing and the general functionality of the farm to mention some. The farm operations can cause the escape of fish, from (but not limited to) technical failures, boat collisions or poor operations. The farms design and its operability will be certified so that it is acceptably escape-proof in accordance with the NS 9415 standard (Standard Norge, 2009).

Norwegian Standard NS 9415 requires that sea structures must be dimensioned to withstand 30kg/m^2 for horizontal surfaces and 7,5kg/m^2 for vertical surfaces.

The “PolarCirkel” cages developed by Akva Group follow also the ISO 9001 (ISO, 2015) and ISO 14001 (ISO, 2015) standards for quality assurance: Akva Group’s Quality Assurance System (Akvagroup, 2017). This system is certified by Det Norske Veritas (DNV).

ISO 9001 (ISO, 2015) is developed and maintained by the International Organization for Standardization (ISO) and was published in 2015. It is useful for reducing errors, by preventing errors from occurring and identifying possible errors. Reduction of errors can be a financial benefit.

The ISO 9001 is general and can be used in all business domains. The International Organization for Standardization created this standard to set international requirements for a quality management system. It covers many domains, such as quality management system, management responsibilities, resource management, product sales, measurement, analysis and improvement to mention some.

ISO 14001 (ISO, 2015) is an internationally recognized standard for environmental management. It can be used within all industries, and has been developed by the International Organization for Standardization based on continuous improvement & compliance with regulations

This standard was created to ensure effective environmental management, in both the service sector, and in production companies. Companies must prepare environmental objectives, and management systems for these objectives. The main elements of the standard are:

- Environmental policy
- Planning
- Implementation and operation
- Control and Remediation
- Management evaluation

The standard demands that all environmental impacts are to be reported by the company, that measures to improve procedures are implemented.

All of Aker Group’s “PolarCirkel” Cages are manufactured and assembled in accordance with Akva group’s Quality Assurance System (Akvagroup, 2017) which follows standards ISO 9001 and ISO 14001 (ISO, 2015) and is certified by DNV.

NORSOK N-003 (Standard Norge, 2017)

NORSOK N-003 (Jensen et al., 2005) covers the design of facilities in use on the Norwegian continental shelf (NCF) and the continental shelf of Svalbard. It applies to all types of offshore structures in the petroleum industry, but and also applies to the aquacultural industry. It covers standards for bottom founded structures, and floating structures. The standards are related to cold climate conditions (e.g., sea ice, icebergs, icing, and snow). This standard covers principles and guidelines for the design of structures like vessel hulls, mooring systems and subsea installations,

2.2 Directorate of fisheries

The Directorate of Fisheries was founded in 1900 to regulate, guide, supervise and control quality in the sea fishing and aquaculture industry. As a part of regulating fish farming in Norway, they published the Aquaculture Act no. 79, on 17 June 2005, to set requirements and standards within the industry. For example, paragraph 12, chapter 3, Environmental Standards, expresses that any new installations and equipment must be designed with appropriate characteristics (Aquaculture Act no. 79, 2005). This means that all new installations must follow the standards.

Whilst regulating wild fishing and farmed fishing licences, the Directorate of Fisheries holds statistics for many aspects. For example: number of licences, number of fish cages, quantity of livestock, quantity of losses and quantity of sold slaughtered fish. Throughout these statistics they can decide on the quantity of quotas sold each year and regarding the losses of fish, in production or from escape whether standards, regulations and procedures are sufficient.

The Directorate of fisheries have published their vision of no escapees, as shown in figure 10. They have chosen a step-by-step method to educate, raise awareness, and recommendations to reduce the escaping of fish.

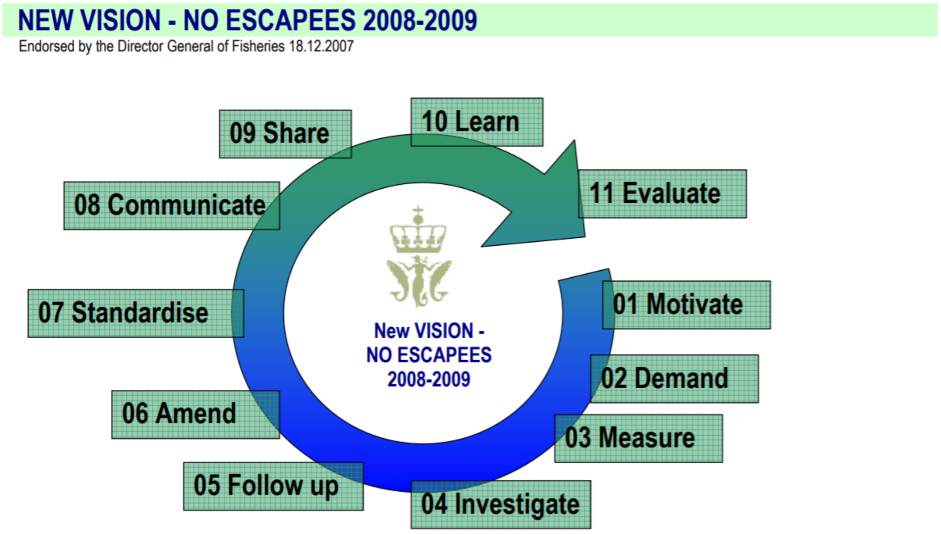


Figure 10: Directorate of Fisheries model for reducing escaping fish. Figure taken from Directorate of Fisheries (2007)

Although the document is slightly outdated, The Directorate of fisheries' ambition to stop fish escaping should not be reduced. The steps are listed as followed (Directorate of Fisheries, 2007):

1. Motivate: Obtain a positive focus and incitement for desirable action and attitude
2. Demand: Examine possible regulation amends with the intention of preventing escapes
3. Measure: Follow up the agreement regarding monitoring and make visible the need for suitable effect monitoring of escaped fish
4. Investigate: Perform investigations into escape episodes and collect information in harmony with the RKA and also on own accord.
5. Follow Up: Ensure that the provisions for technical demands in the regulations are respected by the industry
6. Amend: Better implements for the administration
7. Standardize: Initiate standardizing within own areas for the achievement of better security measures regarding escapes
8. Communicate: Implement dialogue and communication that sets focuses on the work against escapes through appropriate measures
9. Share: Communicate important knowledge concerning practise, which reduce the risk of escapes to staff members, producers and contractors
10. Learning: Implement competence requirements
11. Evaluate: Evaluate and report the efforts made visually in Vision NO ESCAPEES through practical methods

2.3 Sjømat Norge

Sustainability has been defined by UN World Commission for the Environment and Development (1987) as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Sjømat Norge, 2011). The Norwegian Seafood Federation, or Sjømat Norge, holds an important role in the sustainability of aquaculture, and in 2011 they committed themselves to multiple new initiatives including measures against salmon lice, and measures to deal with escape (Sjømat Norge, 2011).

The Norwegian Seafood Federation’s measures to deal with escaping fish involve (Sjømat Norge, 2011):

- The prevention of escapes, by analysing risks, use of surveillance (CCTV), divers to assess damage of netting or other equipment.
- Marking and tracking of salmon to enable distinguishing escaped farm salmon to wild salmon.
- Enhanced preparedness to facilitate catching of escaped fish.
- Creating fines for companies for escaped salmon caught in rivers (NOK 500 per escaped fish in 2011).
- An environmental fund of NOK 30 million to aid in catching escaped fish from watercourses.

The main purpose of these measures is the prevention of farmed salmon escaping and affecting wild stocks of salmon and sea trout.

2.4 Ice

2.4.1 Ice accretion

Ice accretion on vessels and structures is generally caused by two phenomena in cold regions: sea spray icing and atmospheric icing. Both phenomena can have large consequences, but according to Dehghani-Sanij et al. (2017), sea spray is the main reason of icing in cold regions. According to their observations, sea spray icing is the cause of more than 80% of reported icing cases on marine platforms.

2.4.2 Sea spray icing

Sea Spray icing is caused by a combination of the following meteorological and oceanographic factors:

- Atmospheric temperature
- Waves
- Wind

- Seawater temperature

Sea spay occurs in windy conditions typically over 7 m/s (Andreas et al,. 1998). This sea spray contains small droplets of sea-water, which is carried by the wind. In cold enough air temperatures (sub-zero), the water droplets landing on objects will freeze. This is a common and important hazard within cold climates. Sea spray icing can be generated by wind and waves (wind-generated spray and wave-generated spray). Wave-generated spray can become a large source of icing, as water is washed directly onto the structure, wetting the surface ready to freeze, but this is generally closer to the water level. Wind-generated spray is usually a smaller source of icing, but can be carried with the wind to higher levels.

There are many year-round marine operations in the Arctic, especially on the Norwegian coastline. The oil industry and fishing industry are two examples of industries that cannot suspend operations during the winter, and therefore the operators must have a strong focus on the prevention or limitation of sea spray icing, on offshore rigs, fish cages and vessels.

In figure 11, we can see that the cargo vessel has experienced large quantities of sea spray icing. This has resulted in an increase in weight and large decrease in stability. For the vessel, there is a large risk of capsizing, but for fish cages, the risk is the cage sinking to or below the water level, or damage to the structure, enabling fish to escape.

Figure 11: Sea spray icing on vessel. Modified from Group Ocean (2010)

On 26 February 1987, the vessel KV Nordkapp was on a voyage from Tromsø towards Bjørnøya and Hopen, when it sailed into a polar low-pressure storm. During this polar low, the ship experienced up to 30 m/s winds from the north-west, air temperatures below -12 degrees Celsius, water temperature around 3-4 degrees Celsius, and a significant wave height of up to 7.5 m. With these combining factors, the icing accumulated on the vessel to over a cover of over 20 cm in measured places, and the overall ice load was estimated to 110 tons based on readings on the draft water level, which occurred within a 17-hour period. The following figure 12 shows the sheer quantity of icing present after the polar low-pressure event.

Figure 12: Icing on KV Nordkapp on the 27th February 1987, Barents Sea (Samuelsen et al., 2015)

2.4.3 Sea spray ice density

According to NORSOK N-003 (Standard Norway, 2017), at North of 68º we have different sea spray ice densities dependent on the height above sea level. They have set the density of 850 kg/m^3 for 5-10m, and 850-500 kg/m^3 for 10-25m. The density seems to decrease with altitude. These rates are suggested for vessels, but can be used for aquaculture (Jensen et al., 2005).

2.4.4 Atmospheric icing

Atmospheric icing is considered as the icing of fresh water, which is precipitation from rain, snow and fog. This form of icing can occur on much higher areas of structures than sea spray icing, which can raise the centre of gravity, and cause a large decrease in stability, especially for vessels. Figure 13 demonstrates the general areas prone to different types of ice accumulation on an offshore rig. Atmospheric icing tends to occur on top of surfaces and on higher areas due to the freezing of precipitations. Sea spray icing occurs on low altitudes, that are more frequently impacted by waves and wind sprayed seawater.

Figure 13: Potential areas for ice accretion (Ryerson, 2010)

2.5 Ice accretion models

2.5.1 Overland Formula

The Overland 1990 formula (Overland, 1990) can be used to predict sea spray icing:

$$PPR = \frac{Va(Tf - Ta)}{1 + 0{,}3(Tw - Tf)}$$

PPR=icing predictor

Va = wind speed [ms^{-1}]

Tf = Freezing point of seawater [ºC]

Ta = Air temperature [ºC]

Tw = Seawater temperature [ºC]

Designed for vessels from 20 m to 75 m in length, in the North Pacific Ocean, it is widely used to predict ice accretion. Taking into consideration wind speed, water temperature, air temperature and the freezing temperature of the sea-water, which is mostly dependant on the salt concentration, this formula is quite thorough. It is however conservative, as it does not regard the vessel’s velocity.

The dimensions of the vessels this formula is designed for can be comparable to those of fish cages, and considering cages are moored, the vessel velocity is not necessary within the equation and can be omitted.

2.5.2 Kulyakhtin et al. (2013) experiment

Kulyakhtin et al. (2013) explains that there are two main scenarios of ice accretion in accordance with the factors limiting the growth rate. Firstly, the Mass Limited scenario: the total water mass landing on the object is frozen due to the cooling. In this case, the water mass is the limiting factor of the ice accretion rate. The second case, the Thermally Limited scenario: the impingement of water is large, and the heat flux of the object is not able to freeze all of the water. In this case, the heat flux is the limiting factor for the ice accretion rate. Their study in Longyearbyen on Svalbard showed that this scenario is independent of the spray period and quantity of water arriving on the object.

$$Icalc = \frac{Qc + Qe}{Lf(1-k)}$$

Icalc = Ice accretion rate

Qc = convective heat flux

Qe = evaporative heat flux

Lf = latent heat of pure ice freezing

k = mass of entrapped unfrozen brine in the ice, which according to Kulyakhtin and herein, can be approximately 0,26

During their experiments they concluded that the experimental results support this theoretical equation.

2.5.3 K. Jones (1998) method

There exist multiple models to determine the ice loads from freezing rain, and with very different results. Kathleen F. Jones (1998) proposes a simplified, conservative model to calculate ice accretion, dependent on the precipitation rate and wind speed.

$$Req = \frac{N}{\rho_i \pi} \left[(P\rho_0)^2 + (3.6VW)^2\right]^{\frac{1}{2}} [mm]$$

Were:

N= number of freezing rain hours

p_i=0.9 [g/cm^3] ice density

P= precipitation rate [mm/h]

p_0=1.0 [g/cm^3] uniform ice accretion

V= wind speed [m/s]

W=0,067P^{0,864} [g/m^3] related liquid water content to precipitation rate

This equation estimates the radius of ice accretion on the cylinder of radius 1 unit [mm]. This is however an estimation considering a constant precipitation rate and constant wind state. During a storm, the precipitation and wind will be irregular. The equation can be generalized:

$$Req = \frac{1}{\rho_i \pi} \sum_{j=1}^{N} \left[(P_j \rho_0)^2 + \left(3,6V_j W_j\right)^2 \right]^{\frac{1}{2}}$$

This model is for horizontal circular cylinders and is based on 3 assumptions:

1. Collision efficiency of the raindrops with the cylinder is 1
2. All the rainwater impinging the cylinder freezes to the cylinder

3. The ice accretes uniformly around the circumference of the cylinder.

The first two assumptions are conservative, but this is a reasonable approach to being on the safe side. The third assumption is a simplification. In reality, ice accretion to a cylinder will not be perfectly circular. The assumption of a uniform radial accretion is sufficient for this simple model, and is regularly assumed in detailed models (Jones, 1998), see Figure 14.

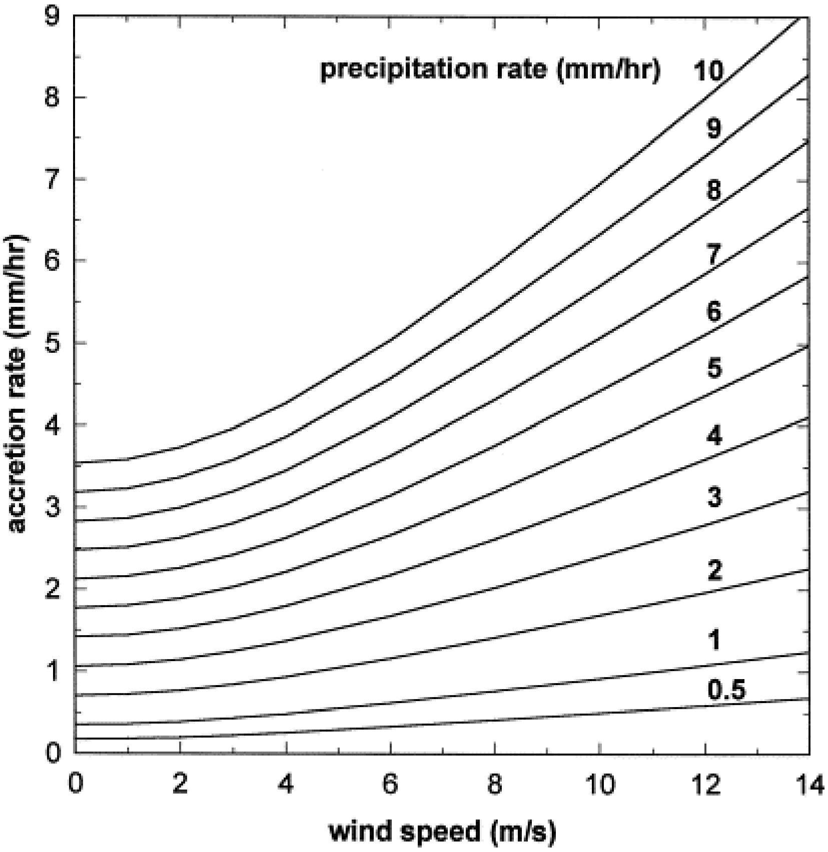


Figure 14: Ice accretion rate. Figure modified from Atmospheric Research, (K. Jones, 1998): Uniform radial ice accretion rate for the simple model as a function of precipitation rate (0<P<10 mm/h) and wind speed (0<V<14 m/s).

For a precipitation rate of 5mm per hour and over 12 hours, and a wind speed of 5 m/s, the ice accretion rate will be estimated, according to this model, to be at approximately 2.2 mm/h. Over 12 hours this will build up to 26.4 mm, or 2.64 cm radius on the cylinder. This is a very plausible amount of ice build-up over one night of constant heavy rain. This results in a very small additional weight to the cylinder, which we can compare to the structural cylinders, and will not result in a danger to the buoyancy of the cage. This freezing rain can be considered negligible compared to sea spray icing.

2.5.4 Fukusako et al. (1989) experiment

Fukusako et al.(1989) conducted an experimental investigation, to determine the characteristics of sea spray icing on a horizontal circular cylinder. The measurements were taken for multiple different conditions including wind velocity, air temperature, droplet diameter, initial droplet temperature and mass flow rate of the droplets. They also determined the salt content of the ice layer built up on the cylinder.

The test consisted of the following 7 major components:

- Tunnel
- Test section
- Fan
- Refrigeration system
- Spray generation system
- Heaters
- Measuring instruments

The wind tunnel, of square cross section, was built of 15 mm thick wood, and 25 mm thick Styrofoam on the outer surface to avoid heat loss. The test section was a cylinder with dimensions of 800 mm long, and a cross section of 150 mm by 150 mm, exposed to a centrifugal axial fan (0.75kW) producing winds speeds of up to 25 m/s. The test cylinder was positioned 600 mm vertically below the fan.

Fukusako et al.'s experiment uses multiple variables:

- Wind speed
- Air temperature
- Droplet mass flow rate
- Droplet size
- Droplet temperature

Fukusako et al. discusses that the wind speed has a large effect on how the spray freezes to the cylinder, e.g,. Lower wind speeds tend to leave a thin layer of water on the cylinder which will run down the cylinder and freeze partially as icicles below the cylinder, whereas with higher wind speeds, the spray will be more spread around the cylinder, including to the downwind side of the cylinder due to drag, and will freeze in a different pattern.

The effect of temperature on the freezing rate can be seen in figure 15 as calculated by Fukusako et al. (1989). The experiment, over an elapsed time of 20 minutes, shows the substantial increase in ice accretion for lowers temperatures. For a temperature of -5ºC, 50 g of ice had accreted, whereas for -15ºC, there was 100 g of ice accretion.

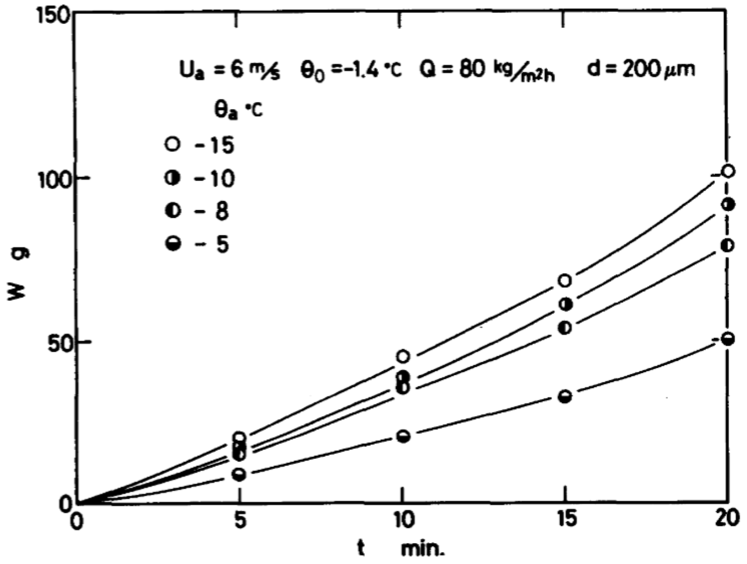


Figure 15: Ice accretion on cylinder, with set parameters for wind speed, droplet temperature, spray flux and droplet diameter, in function of time. Figure is modified from Fukusako et al., 1989.

When considering the droplet mass flow rate, or the flux of spray, they observed that more icicles tend to appear when the spray flux is higher. This was observed because of a larger amount of water landing on the cylinder, and the heat transfer insufficient to freeze all the water. A smaller spray flux tends to freeze faster and more evenly to the cylinder.

The droplet temperature and droplet diameter played an important role in the pattern of ice accreting to the cylinder, leaving a more or less even surface.

2.5.5 Ryerson (1995) observations

Ryerson studied ice accretion of sea spray deflected from the bow of a 115meter long Coast Guard vessel in the North Pacific Ocean and the Bering Sea. The sea spray icing events occurred during February and March 1990. The study took into considerations measurements of the duration of the sea spray events, concentration of sea spray drops and sea spray-drop sizes.

The icing accreting on the ship's superstructure could be considered similar to that of freezing rain, as the spray drops had been carried in the wind from the bow, to where they land on the superstructure, causing the drops to instantly cool. Under these conditions, the icing could be considered similar to atmospheric icing. Due to the size of the vessel, the ice accretion rate could vary considerably, when considering the quantity of sea spray, or water delivery rate (Ryerson, 1995).

Ryerson claims that the dimensions of a vessel play a large part in ice growth rates. Small vessels receive more frequent spray events due to their increased pitch frequency. Larger vessels rotate slower, meaning longer spray periods. Larger vessels will also receive sea spray on only a portion of the vessel.

Icing accretion was generally small during the observed events, in the order of a few centimetres, but this can result in multiple tons of added mass.

Through observations and measurements, the icing rate was able to be measured for different positions of the vessel, for each sea spray icing event. The largest icing rate observed was during a 24-hour event in March. This rate was 13.3 mm/h.

2.5.6 Makkonen (1989) method

According to Makkonen (1989), wet snow accretion can occur when the air temperature is close to 0ºC, and a high humidity rate of over 92% (cases with humidity below 92% were excluded from their study). Colder, dry snow will not stick to vertical surfaces, will be extremely limited to angled surfaces and sometimes even limited to horizontal surfaces, due to the non-effective bouncing of dry snow (Makkonen, 1989). When snow particles fall from a cold air mass at altitude, to a warmer air near the surface of the earth, the snow particles hitting the surface will be melted due to the heat flux of the environment, and therefor become wet (Makkonen, 1989). This wet surface is the condition necessary to create sticky snow that can accrete to structures.

This condition is common of the Norwegian coast, which is often milder due to the impact of the Gulf Stream. Troms for example is therefore commonly experiences wet snow.

Makkonen and references herein propose an estimation of wet snow accretion using only the visibility in a snowstorm V [m]:

$$I = 2100V^{-1,29}$$

Where:

I = wet snow accretion rate $[gm^{-2}s^{-1}]$

V = visibility [m]

This equation assumes that the temperature and humidity parameters allow for wet snow accretion. It is also independent of the wind speed. Although this equation is an approximation, it is very simple to use and can be an effective technique for rapidly assessing the possible quantity of wet snow that will build up over for example one night. This method suffices only a visual observation to assess the visibility.

Example: visibility of 100m, no wind, and correct temperature and humidity for wet snow accretion.

$$I = 2100.100^{-1,29}$$

$$I = 5{,}52\ [gm^{-2}s^{-1}]$$

Over one night of 12h:

$$I = 238{,}4\ [kgm^{-2}]$$

Over a period of 12 hours with these conditions, the fish cage structure could receive an additional weight of wet snow of 238,4 kilograms per square meter. This wet snow can be a relatively large factor to consider for the safety of the fish cage, considering the NS 9415 standard for withstanding 30 kg/m^2.

On the fish cage, the vertical surface of the handrail is small, so wet snow accretion should not be large, but can be significant on the walkway over the two floating tubes. For Akva Group's "PolarCirkel 450" cages, the walkway is 1 m wide (see appendix 1). This cage can therefore be subjected to nearly 240kg per meter of the circumference of the cage. However, considering this to be almost at water level, the weight will cause the floating tubes to sink just below the surface, and the sea-water, above freezing, should slowly melt the wet snow. Not causing the cage to sink below the height of the netting.

3 Farming types / Case study

3.1 Traditional cages

Cages for fish farming have been used for decades. Cages have been modified over the years but the principle has remained the same: floating geometrical structure holding a net containing the fish. The whole structure is anchored to the seabed to maintain its position. The most commonly used cage consists of a floating collar, supporting the net, which is also held down by a sinker tube.

The floating collar:

The floating collar consists of two main pipes for buoyancy, and a higher handrail, also holding the top of the net above the surface of the water, and a sinker tube holding the bottom of the net in position. This main structure of three surface pipes (floating pipes and handrail) are joined together with strong brackets. This whole system is made of polyethylene (PE) plastics. Polyethylene pipes have a high strength to weight ratio, good resistance to corrosion and a good moisture resistance (Omnexus, 2021).

PE plastics have a very good resistance to cold, with very low glass transition temperature of Tg= -120 to -100^{0}C, compared to PVC with Tg=+90^{0}C. (Zeus, 2005).

At temperatures below the glass transition temperature, the plastic becomes stiff (compared to glass) and has a large decrease in impact resistance. Polyethylene’s extremely low Tg makes it very resistant to cold compared to most other commonly used plastics.

Polyethylene’s high strength to weight ratio also means the structure is built much lighter than with other materials, resulting in a more buoyant structure.

The net:

The netting is usually made of nylon and Dynema technology, or PET (Polyethylene Terephthalate) netting. The netting is technically designed to prevent the escape of fish. It is secured to strong PE brackets on the floating tubes, which hold the weight of the net and sinker tubes. This system of nylon netting and PE brackets is designed to result in a low maintenance and long-lasting reliable solution.

The sinker tube:

The sinker tube is a PE tube covering the full circumference of the net. This tube is filled with chain or wire rope to maintain a large enough weight to hold the netting in position (Figure 16).

Figure 16: Description of circular fish cage framing. Figure modified from Akvagroup (2021c)

With all parts assembled, we obtain a large circular fish cage with a diameter of up to 83 m (Akvagroup, 2021c). A centre support stand is commonly used to hold a bird net over the farm to protect the fish. This centre support stand can hold the netting 4 to 5 meters above the water as demonstrated in figure 17.

Figure 17: Image of complete "Polarcirkel" cage from Akvagroup (2021c)

3.2 Steel cages

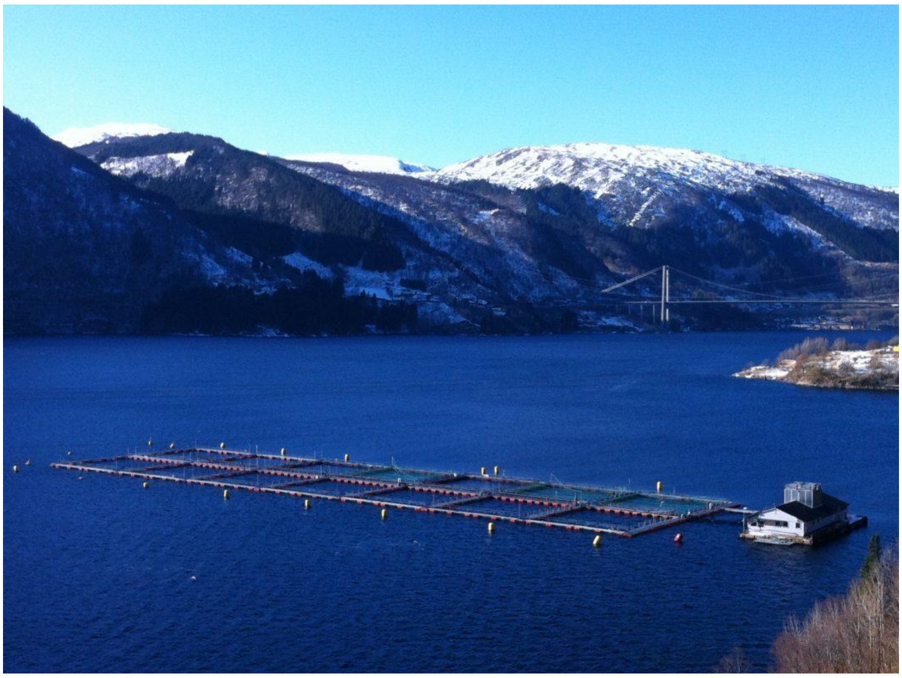


Figure 18: Steel cage design. Image taken from Ilaks (2015)

Steel cages are also a commonly used type of cage (Figure 18). This type of cage is rectangular shaped and usually multiple cages connected together with the use of hinges. The benefit of this type of farming site is that it can be easier for employees to work on. However steel cages are far less flexible that plastic circular cages. For this reason, rectangular steel cages are mostly located in more sheltered sites, so will not be further discussed in this study. This does not however exclude the possibility of escaping fish, and there has been reported escapes from these types of farm sites. For example, in 2015, there were four separate reports of escaping fish from sites in Hordaland, Norway, due to bad weather (Ilaks, 2015).

3.3 Case Study: Norway Royal Salmon (NRS) Arctic Offshore Farming (AOF) Cage

Figure 19: Photos of NRS AOF cage A, taken by Benjamin Marsden during visits in September 13, 2021

In 2015, Norway Royal Salmon and Aker Solutions united their expertise to develop offshore technology for aquaculture, and in March 2016, they sent an application to the Directorate of Fisheries for permits to develop this cage. After long going investigations for multiple locations, Norway Royal Salmon were granted permits in March 2018 by the Directorate of Fisheries, for a total of 5990 tons. In other words, a permit for two offshore cages with a capacity each of 3000 tons: Cage A & Cage B (Arctic Offshore Farming, 2021).

Models for this cage design were tested throughout the summer of 2018, and came out with positive results. The cage model was very stable in rough waters and behaved as they were designed for (Arctic Offshore Farming, 2021).

The fish cage consists of a semi-submersible floating steel construction, holding a fish net. The structure consists of two circular rings, or pontoons, one at the base, and one near the top of the structure. These are held in position by 16 steel pillars, making the whole structure a floating collar. The fish net is approximately 67m diameter and 34m depth. This net is designed to hold

3000 tons of fish, roughly 600 000 salmons at 5kg each (Arctic Offshore Farming, 2021).The whole structure is a semisubmersible, with the use of ballast tanks in the base ring and pillars.

Figure 20: Norway Royal Salmon AOF Cage construction. Image taken from Salmon Business (2021)

3.3.1 Location of AOF

Norway Royal Salmon's Arctic Offshore Farming (AOF) site is located near Fellesholmen Island, approximately 20 kilometers offshore from Tromvik, a small fishing village located on Kvaløya, roughly one hour's drive from the city Tromsø, northern Norway. Tromvik is a preexisting fishing village, and the use of this village in connection with the farming will offer multiple full-time jobs, and help in the development of Tromvik. The construction and installation of the cages has been underway throughout the year 2021 and is planned to be complete, with fish, by the end of 2021 (Arctic Offshore Farming, 2021).

The map in figure 21 shows the tracked route of M/S Frøy Finnmark, a service boat owned by Norway Royal Salmon, between Tromvik port and the AOF Fellesholmen site.

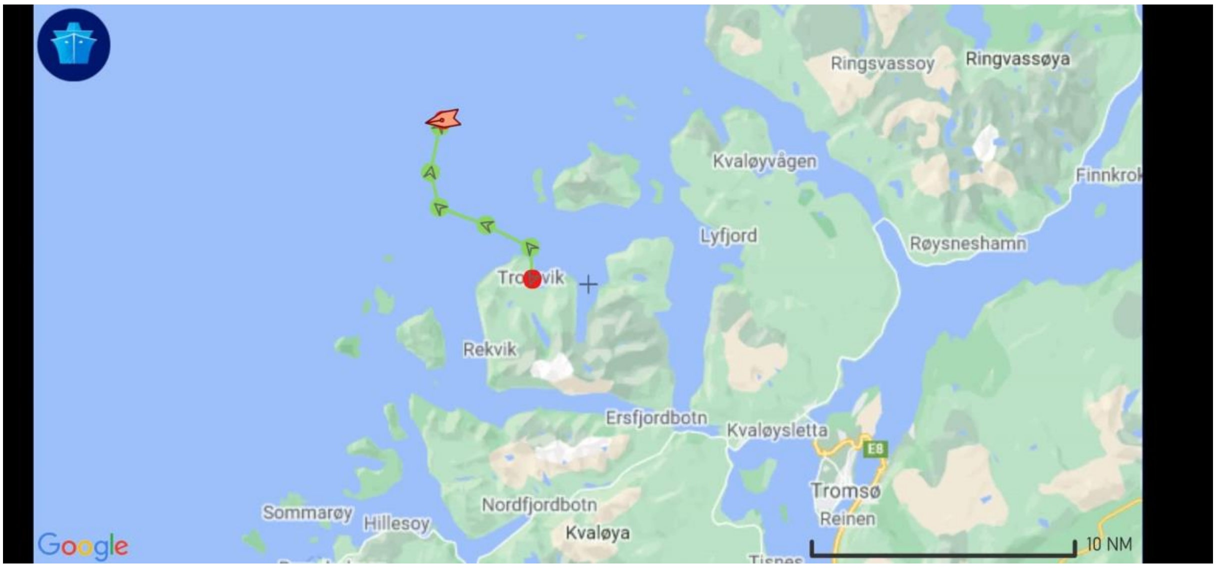


Figure 21: Service vessel M/S Frøy Finnmark's route from Tromvik to AOF Cage A. Vessel tracking taken from Marine Traffic (2021)

3.3.2 Level of Exposure

Due to the increasing demand for farmed fish, the aquaculture industry is starting to design and install farm sites further out in the ocean, where water quality can be cleaner and exchanged due to natural currents, decreased exposure to sea lice and less impact on the Norwegian coastline and wildlife. However, moving cages further offshore comes means of creating cages that must withstand more exposed conditions.

In the Norwegian standard NS 9415 (Standard Norge, 2009), on the technical and operational requirements for aquaculture sites and structures, there are five exposure classes. The largest exposure class, E: "extreme exposure", consists of sites with more than 3 m significant wave height (Hs) and mid-water-currents above 1.5 m/s. Utne et al. (2015) defines offshore aquaculture, among other things, as locations further than 2 km from the coast, with Hs of 5 m or more, and inshore aquaculture in between 500 m – 3 km from shore with Hs usually <=1 m, but up to <=3-4 m.

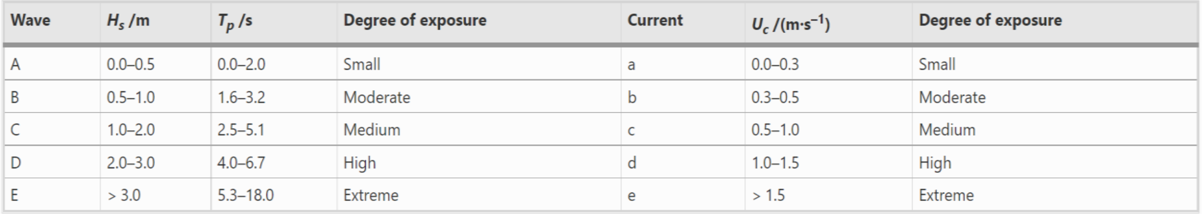
According to Faltinsen et al., 2018, the following table can be used to classify exposure of aquaculture sites into 5 degrees. With:

H_s - significant wave height

T_p - peak wave period

U_c – water current speed

Table 1: Norwegian aquaculture site classification for waves and currents (Faltinsen et al., 2018)



Wave	H_s /m	T_p /s	Degree of exposure	Current	U_c /(m·s^{-1})	Degree of exposure
A	0.0–0.5	0.0–2.0	Small	a	0.0–0.3	Small
B	0.5–1.0	1.6–3.2	Moderate	b	0.3–0.5	Moderate
C	1.0–2.0	2.5–5.1	Medium	c	0.5–1.0	Medium
D	2.0–3.0	4.0–6.7	High	d	1.0–1.5	High
E	> 3.0	5.3–18.0	Extreme	e	> 1.5	Extreme

Exposed Aquaculture Operations is a new research center, created to help improve offshore aquaculture. Their research is focused on technological innovations to improve safety and reliability of operations in four areas: autonomous systems for remote operations, monitoring and decision support of fish, site and operations, structures for exposed locations and vessel design for exposed locations. They also focus on improving sustainable production within two areas: Safety and risk management, and fish behavior and welfare (Exposed Aquaculture, 2021).

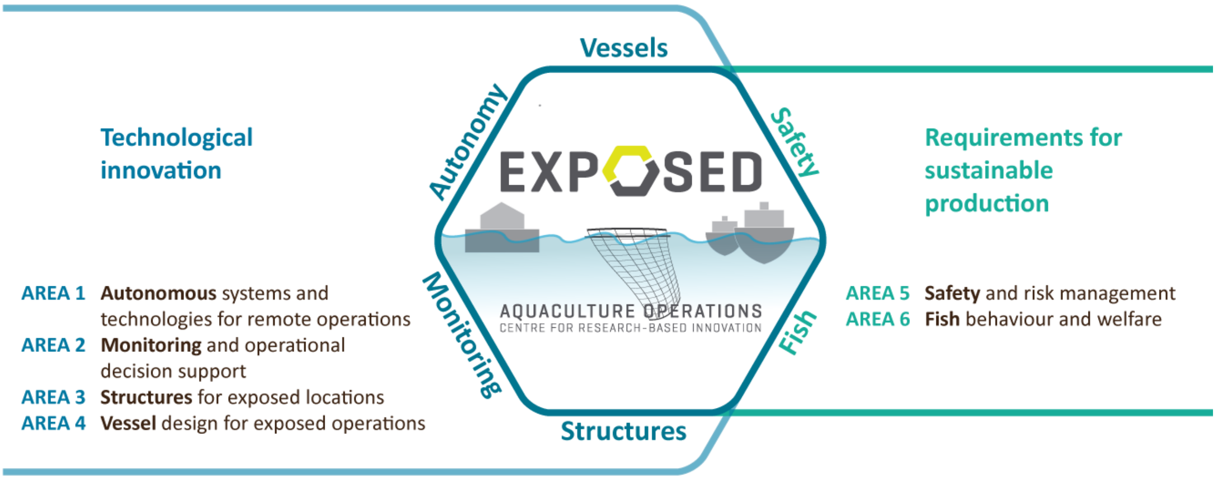


Figure 22: Exposed Aquaculture Operations research domains for improving offshore aquaculture. Image taken from Exposed Aquaculture (2021)

Bjelland et al. (2015) identify these areas of research as crucial for the challenges of aquaculture operations in exposed locations.

The areas of focus by Exposed Aquaculture (2021) are explained:

Creating autonomous systems will reduce the need for manual human labor, increasing safety of routine operations. Improving monitoring and operational decision support, with for example improved sensors and numerical models for predicting conditions on site (weather, fish health, etc.) can help improve maintenance and operations to better fish health, whilst also reducing human risk on operations and operating costs. Improving structures for exposed locations will result in structures designed to withstand exposed conditions, and enable safer and more reliable operations. Vessels must be designed to withstand, but also operated safely, in exposed conditions. For safety and risk management, identification of hazards and risks must be efficient in order to limit risk within operations. Methods and procedures must be improved to optimize safe operations. The study of fish behavior and welfare is extremely important. For example, the tolerance of fish to specific situations, in particular to the acceleration of cages, will affect the way offshore cages are designed and the location chosen.

3.3.3 Exposure of Fellesholmen site

The choice of the Fellesholmen site for the AOF Cages, is due to its level of exposure. The cages are designed for a highest significant wave height (Hs) of 6.6 m, and a maximum current exposure (under operation) of 1.46 knots, or 0.75 m/s (NRS, 2021).

NORSOK Standard N-003 (Standard Norge, 2017) suggests that it should be expected a significant wave height (Hs) of 14 m, for the area offshore of Troms region, and a maximum tidal current of 0.5 m/s. See following figure 23.

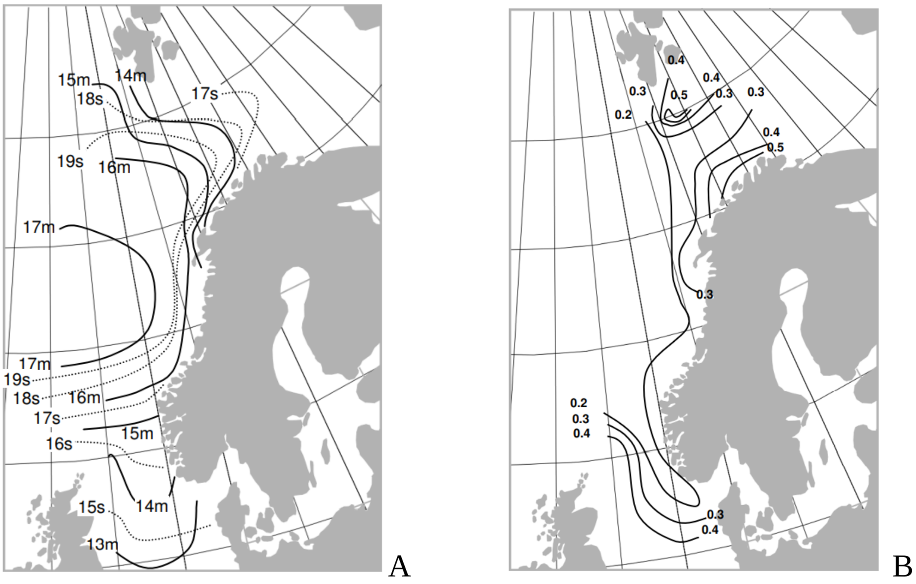
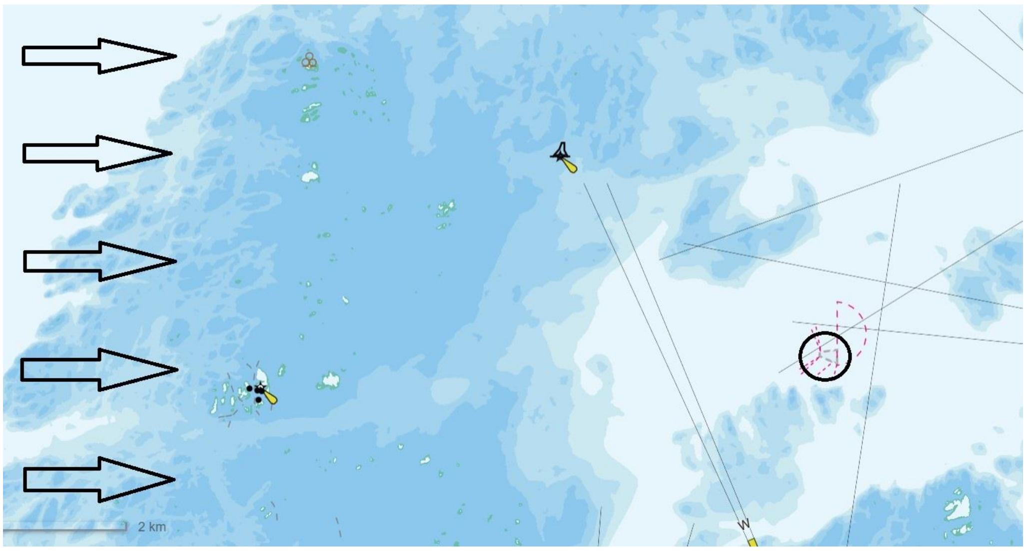


Figure 23: Figure A, Significant wave height and maximum peak period for the coast of Norway. Figure B, Maximum 100-year tidal surface current in m/s. Figures modified from NORSOK standard N-003, Edition 2, (Standard Norge, 2017)

The Fellesholmen site, although located on the outer coast of Kvaløya, where the sea can be rough, is also located inshore from an archipelago named Auvær. It is a cluster of many small islands and reefs. This provides a great deal of shelter from large swells coming from the open sea. The following figure 24 (A) shows the visible islands of the archipelago. The arrows to the left represent a common swell from the west, and the circle to the right is the location of the AOF site. Figure 24 (B) represents the same location but includes all submerged shallow points (i.e., Rocks), most of which are at depths of less than 10 meters below the water surface.

A



B

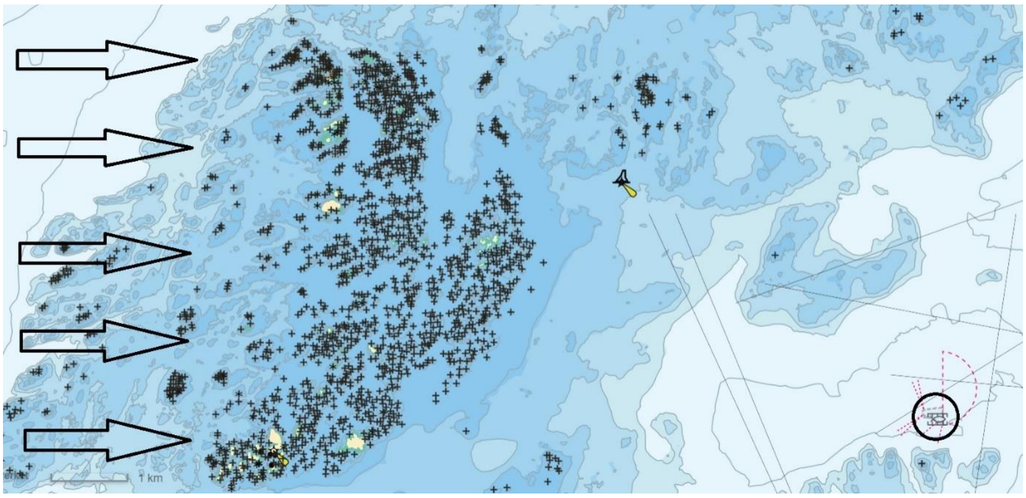


Figure 22: Figure A, Map of Auvær archipelago sheltering Fellesholmen site from offshore swells. Figure B, revealing subsurface shallow points in the Auvær area sheltering Fellesholmen from offshore swell. Maps modified from DNL (2021)

Although it is unclear if there is a calculated or measured maximum significant wave height for the location of the fish cages, the islands and shallow waters of Auvær archipelago will attenuate the ocean swell, meaning the swell will have to be regenerated between those islands and the cage. Considering the distance between Auvær and the cages being only approximately 6km, and a relatively shallow water depth in between, it may be comparable to a reservoir. In this case, we can compare to Pullen et al's (2018) simplified relationship between fetch length, wind speed and significant wave height (Figure 25). For example, a storm bringing 20m/s winds from the west and the fetch is 6000 m. The significant wave height will be at Hs=0.85 m. This is far under the design limit of Hs=6.6 m (NRS, 2021).

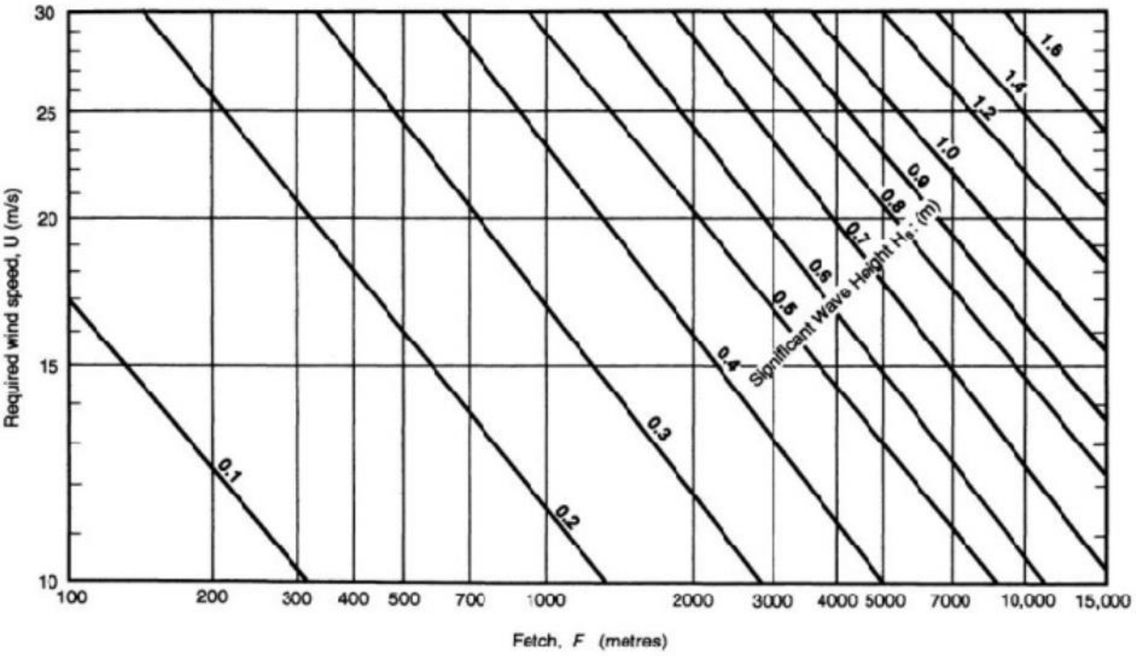


Figure 25: Simplified relationship between fetch length, wind speed and significant wave height. (Pullen T. et al., 2018)

During a visit to Fellesholmen site on October 13th 2021, relatively strong winds of 15 m/s from the west were present. In the following photograph, the Auvær archipelago is visible, with large crashing waves. It is clear here that the archipelago attenuates the swell from the ocean. Around the cage site was visually observed an approximate significant wave height of less than 1 meter. If we compare to Pullen et al.'s chart, 15m/s wind would generate a significant wave height of 0.65 m for a fetch of 6000 m. This result is in accordance to the visually observed significant wave height. The cage is therefor in no danger to a standard swell from moderately strong winds. If we take an extreme weather situation with 30 m/s winds, the cage should still be submitted to a significant wave height of 1.3m. This is still below the design limit.

Figure 26: Visit of Norway Royal Salmons AOF site, Fellesholmen on October 13th 2021. Photo of the Auvær islands to the west, with approximately 15m/s wind from the west. Taken by Benjamin Marsden (2021)

It is relevant to note that the Fellesholmen site is not located within the areas of dense sea fishing activity or dense vessel traffic. See following map from Norges Kart:

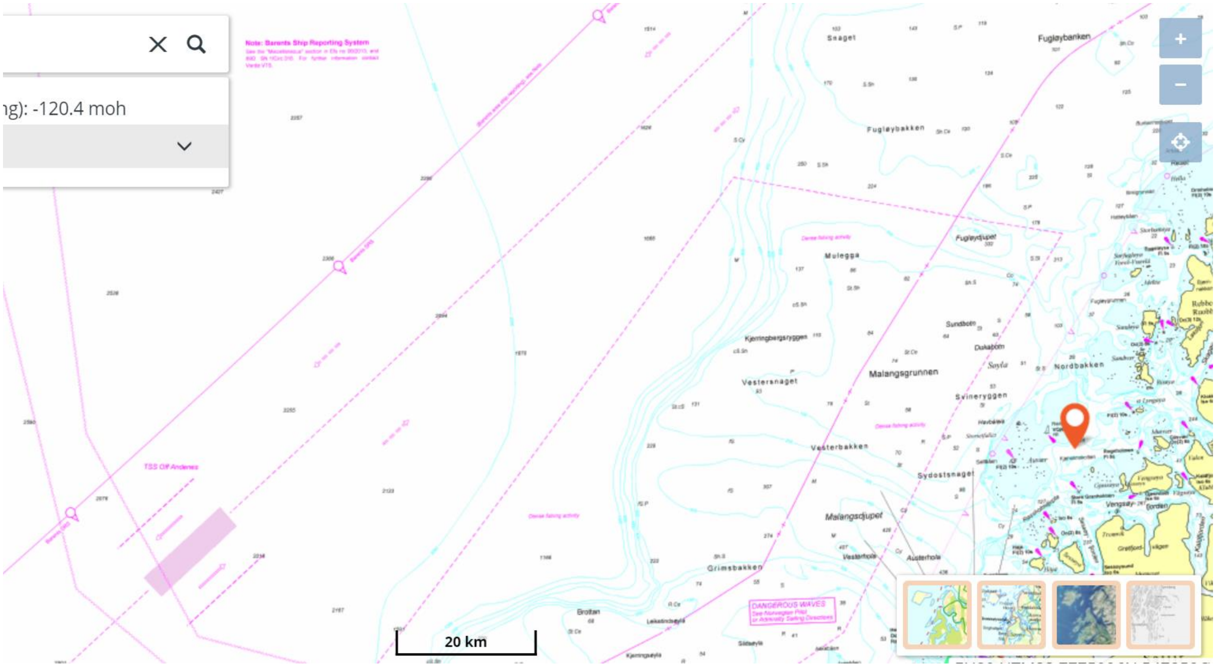


Figure 27: Map of vessel activity in the vicinity of the Fellesholmen cage site. Dotted lines box in a zone of dense fishing vessel activity. Map taken from Norges Kart (2021)

3.4 Feeding barge supplying the NRS AOF Cages

Figure 28: Photo of AC800PVDB feeding barge at Fellesholmen site. Taken by Benjamin Marsden (2021)

The feeding barge, AC800PVDB, supplying the two cages is designed and built by Akva Group. It is a brand-new type of feeding barge, designed for offshore rough conditions and for a significant wave height of up to 6 m (Salmon Business, 2021). This maximal significant wave height is similar to that of the cages themselves. It is a very large barge, with a length of over 64 meters and 12 meters in width, and is capable of supplying both cages thanks to its total capacity of 800 tons of fish feed. This new barge allows for waterborne feeding, with feeding pipes connected under the barge, transporting food at a rate of up to 200 kg per minute (Akvagroup, 2021d). This feeding solution is extremely environmentally friendly, using 70-90% less energy than with traditional airborne feeding systems (Akvagroup, 2021d). Waterborne feeding also gives the possibility to feed at lower depths than just at the surface, allowing for a more efficient dispersion of food. Feed tubes being attached below the barge, allows other vessels (service vessels, workboats, etc.) to access the barge from both sides. The barge also has a boat garage at the stern, to receive work-boats. This system allows boats to enter the barge with maximal safety, and is a secure place to store the boat during severe weather. This however has not yet been tried in rough conditions and it is debatable as to whether this system will be possible to use (NRS, 2021)

3.5 Ice accretion on the NRS AOF Cage design

There is little available information regarding the prevention of ice accretion on this cage design, or on other new offshore steel cages. However, this type of structure resembles production units from the Oil and Gas industry, where much work has been done regarding marine icing (Edmond Hansen, Multiconsult).

In the case of these Arctic Offshore Farming cages by Norway Royal Salmon, during operation, the cage is semi-submersed, so that only the higher ring is visible above the water surface. Figure 29 demonstrates how the cage appears when submersed to the maximum, under ballasting, and with empty ballast tanks (during installation and servicing).

Figure 29: NRS AOF cage, under operation (semi submerged), under ballasting and de-ballasted for servicing: Image modified from Arctic Offshore Farming (2021)

When semi-submersed, only the upper ring and the top of the towers are visible. The sides of the ring are vertical. This geometry is particularly difficult for ice to accrete to, but it could accrete on top of the ring. However, with the height of the ring measuring 3 meters, and a few meters of this visible above the water surface, larger waves and a longer fetch of sea spray would be necessary to reach the top of the ring or towers.

The allowed load per axle is at maximum 6 tons (NRS, 2021). If we consider the Overland (1990) formula, it expresses severe icing up to 40mm/h. This is the equivalent of 34 kg/m^2 of icing, which is negligible to the overall buoyancy of the structure. Considering the geometry of this structure, even a substantial added mass from ice accretion would be negligible to the stability of the cage.

The use of ballast tanks to make this cage semisubmersible could play a large part in sinking the cage so that sea spray icing is lowered below the surface will allow the above freezing sea water to slowly defrost.

The waterborne feeding system keeps all feeding tubes fully submerged, which eliminates all risk of ice build-up.

This Arctic Offshore Farming Cage is built to withstand rough conditions, and appears to be suitable for operating during winter months and under-sea spray icing conditions.

4 Results & Discussion

The consequences of ice accretion on fish cages and equipment can be severe. Small or large-scale escapes, regardless of the quantity of escaping fish, is considered an environmental crime. However, this will also become a financial burden to any company owning the farm, with a loss of income due to smaller numbers of remaining on site, reparations of damage to the farm, and possible fines. The prevention of this is there for critical, and models for predicting ice accretion should be used for minimizing the risk of escape. Ice accretion on cages can present a direct link to escaping fish, for example by sinking the net low enough that fish can escape, but is not the only cause. Icing on the structure of the cage, netting, service boats, etc. can have a large impact on operations, especially regard the human factor. Ice accretion to fish barges can also be a problem, as seen in the introduction, but the risk of damage is more related to waste or leakage of fuel and fish feed, and the risk of danger to employees working on the feeding barge. The loss of a functional feed barge, or problems regarding routine operations, can have a direct link to the health of the fish, which can also cause grave problems for the company. This chapter aims to discuss the main questions of the thesis.

4.1 4.1 Impact of icing on structural failures of fish cages

Ice accretion to traditional circular fish cages can cause major structural failures, to the floating framework, made up of PE pipes and brackets, and to the netting.

The frame for a standard plastic circular cage consists of two floating pipes (the inner and outer rings), a plastic hand-rail (also holding the top of the net), plateform (walk-way) over the floating rings and multiple vertical plastic tubes holding up the handrail. All is assembled together with strong plastic brackets.

Figure 30 represents the cross section of Akva Group’s Polarcirkel cage frame design. This is a standard structure and can be represented as a simplified 3-point system: point A being the handrail (net holder), point B the inner ring, and point C the outer ring.

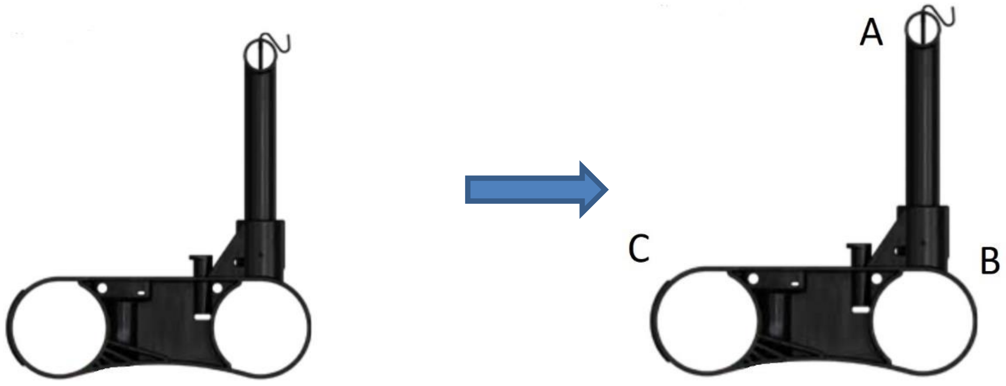


Figure 30: Cross section of a standard plastic circular cage, image of a cage from Akvagroup's Polarcirkel range, modified from Akvagroup (2021c)

In Jensen et al's. (2005) Sintef report, it is explained that as the ice builds up on the frame (floating rings), it will start to sink. When this happens, the floating rings and platform will be below the water surface. The sea-water, above freezing temperature and usually around +4°C in the offshore Troms area, will defrost the sea spray ice, and the floats will then re-rise to the surface, ice free. This process can be repeated as long as the amount of ice does not damage the plastic structure Jensen et al. claim that the brackets between the floating ring and the vertical pipes are the most likely parts that could be damaged from this event.

Figure 31: Sea spray icing on fish cage. (Jensen et al., 2005)

As we can see in figure 31, extreme ice loads can cause the cage structure to collapse. This is caused by breakage of the brackets (Jensen et al., 2005). This however will not necessarily sink the netting. The floating pipes on the perimeter of the cage, will sink below the surface of the water in presence of ice loads, but the sea water temperature will soon defrost the ice on these pipes allowing them to resurface once again (providing this doesn't cause permanent damage to the pipe). This submersion is not critical in the relation to increased risk of fish escape (Jensen et al., 2005). However, under a heavy sea state, with large waves, the immersion could be critical for fish escape (Jensen et al., 2005).

The more important factors in the situation of heavy ice loads, are the vertical pipes and handrails. Unlike the floating pipes that will submerge, defrost and resurface, these pipes cannot. The ice accretion will continue until it melts, breaks, or is manually removed. The main focus for ice build-up on the cage structure is there for on the handrail. As ice builds up on the hand rail, a heeling moment is created around the inner rail.

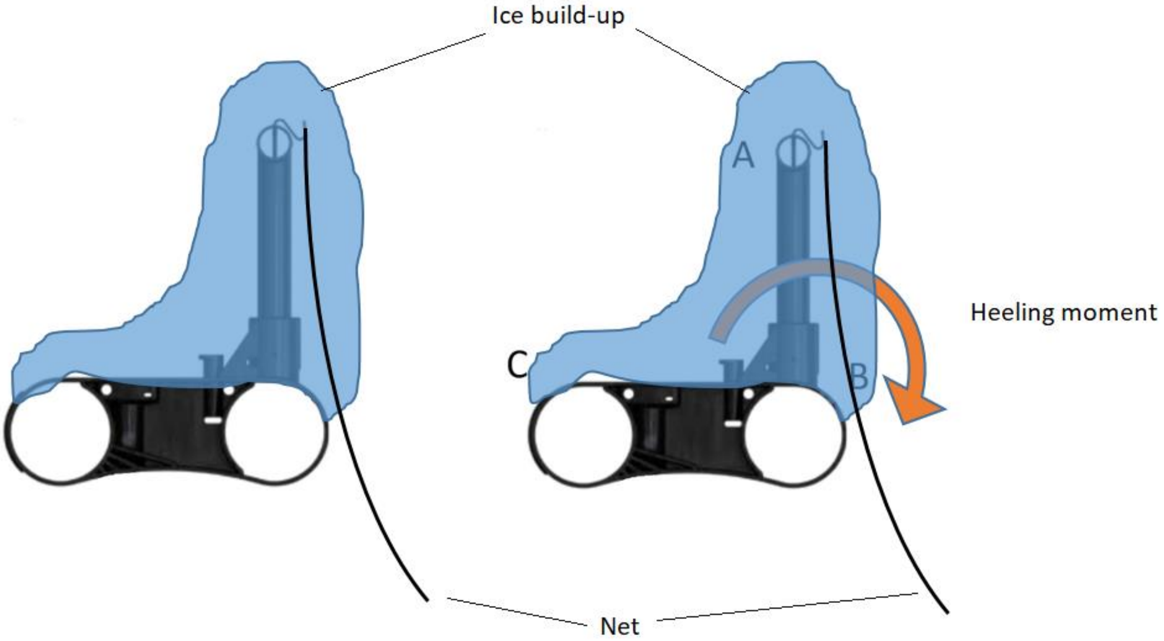


Figure 32: Cross section of standard plastic cage from Akva Group Polarcirkel, with presence of accreted ice. Image modified from Akvagroup (2021c)

The heeling moment from ice build-up on the handrail and netting, will cause the whole section of the structure to lean inwards, lowering the net height and exerting much pressure on the vertical tubes and brackets between points A and B. The strength of the bracket is therefore an important factor here.

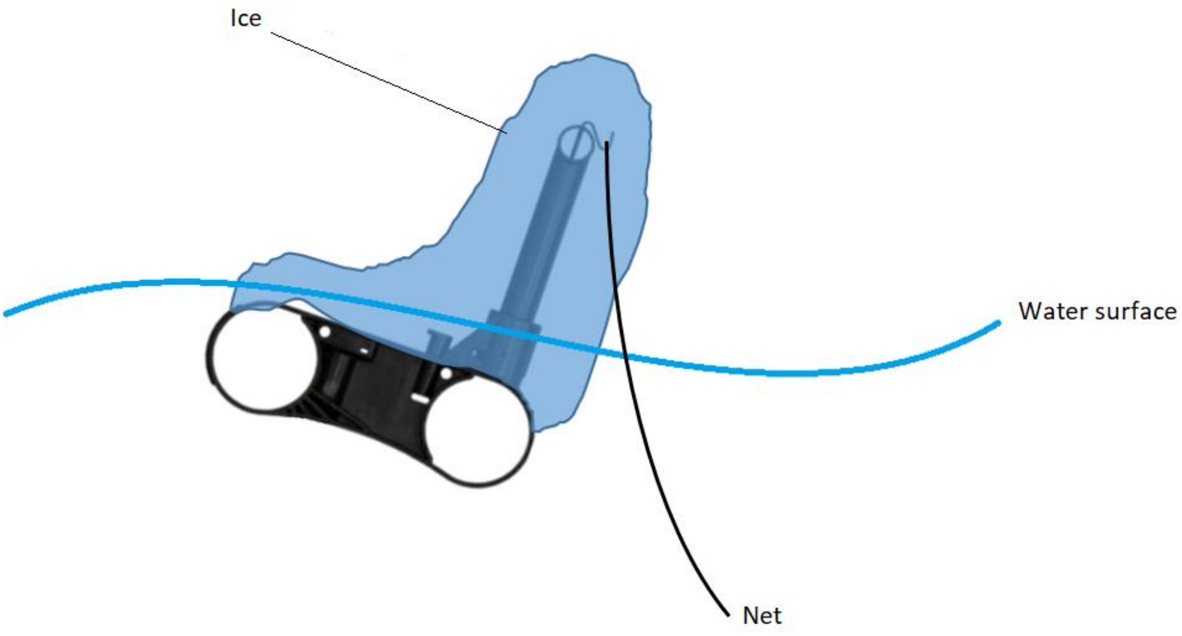


Figure 33: Cross section of standard plastic cage from Akva Group Polarcirkel, and the movement of the cage in presence of accreted ice. Figure is modified from Akvagroup (2021c)

According to Jensen et al. (2005), as long as the structure does not collapse, the frame will just sink partially below the water level, when the seawater will slowly defrost the sea spray ice, allowing the frame to rise once again. Therefore, the frame and net should not sink low enough that fish can swim out, but the question is whether the net can sink enough that the fish can easily jump over.

Some sources claim that during these periods creating large amounts of sea spray icing, the water temperatures will be lower, and the fish will therefore be lower in the cage, and the risk of fish jumping out and escaping will be minimal (Jensen et al., 2005). As seen earlier in this thesis (previous incidents related to sea spray icing), severe weather brought colder sea temperatures, causing salmon to swim lower in the cage. The higher density of fish in close contact at the bottom of the net, resulted in the death of 100 000 salmon for the fish farming company Anarlax.

In the following table from SINTEFs report, Islaster – isvekst og forslag til tiltak (Jensen et al., 2005), an estimation can be made for the maximal ice load permitted be meter of floating pipe. For three common pipe diameter dimensions: 250 mm, 315 mm and 400 mm, the buoyancy increases with the dimensions of the tube (respectively 40 kg/m, 60 kg/m and 100 kg/m). From this can be deducted the weight of the net and other loads (20 kg/m, 30 kg/m and 40 kg/m. The remainder is the addition load that can be added to the pipe without submersion of this pipe: in this case this can be the total ice load permitted on the frame without risk of submersion. The smallest 250 mm pipe can therefore withstand 20 kg/m, 30 kg/m for the 315 mm pipe, and 60 kg/m for the largest 400 mm pipe. Although this is only an estimation, it can help in choosing pipe dimensions when creating new plastic circular cages.

Table 2: Buoyancy capacity of cage pipes, dimension depending (Jensen et al., 2005)

Pipe dimension	Buoyancy capacity	Net weight	Estimated permitted ice load
250 PN4	~ 40kg/m	~ 20kg/m	~ 20kg/m
315 PN6	~ 60kg/m	~ 30kg/m	~ 30kg/m
400 PN6	~ 100kg/m	~ 40kg/m	~ 60kg/m

Considering the NS 9415 (Standard Norge, 2009) standard for additional ice loads (horizontal load of 30 kg/m^2, and vertical load of 7.5 kg/m^2). This table by Jensen et al. show that the cages are designed to be conform to this standard. However, various models for predicting sea spray icing show that in presence of the right weather conditions (e.g., wind, sea temperature, air temperature and waves), the ice accretion rate can be up to multiple kilograms of icing per hour. It is therefore possible in severe weather that the ice load can rapidly exceed the NS 9415 standard (Standard Norge, 2009), resulting in a potential risk for damage and escaping fish.

4.2 Ice accretion prediction models

In cold climates, any vessel or offshore structure can be at risk of experiencing sea spray icing, and predicting this ice accretion is important for the safety of workers, equipment, operations, and in the case of fish farming, avoiding damage that can result in escaping fish.

Jensen et al. (2005) explain in the report for SINTEF Fiskeri og Havbruk AS, that to ensure that a cage will not collapse due to icing, one must have the knowledge to know how much ice build up to expect in a unit of time, for example per hour.

Although literature on the sea spray icing rate is limited (Jensen et al., 2005), this section of the thesis will focus on comparing the six models presented earlier: Overland formula (1990), Kuyakhtin et al. (2013), Jones (1998), Fukusako et al. (1995), Ryserson (1995) and Makkonen (1989).

4.2.1 Overland Formula (1990)

The formula by Overland (1990), has been designed for use on vessels in North America, but today, according to a "Survey among Operational weather forecasters at MET Norway" in 2014, is most used among weather forecasters in Norway (Samuelson et al., 2015). However, the Overland formula (1990) has not been tested with real life sea spray icing observations in the Barents Sea (Samuelson et al., 2015).

The formula is based on reports from vessels in North America with lengths measuring between 20 and 75 meters, and applies for vessels travelling against the wind direction. The formula takes into account the wind velocity, freezing point of the water, air temperature and sea temperature. Considering this formula is designed for use on vessels, it is somewhat conservative as it does not take into consideration the velocity of the vessel itself (O. Gudmestad, 2020). However, the formula considers that the quantity of water present for freezing is always sufficient, regards of the speed of the vessel, or the sea state.

For vessels heading into the wind, the icing rates can be put into five classes, according to MET Naval Posgraduate School NPS:

Table 3: Icing classes from Guest (2008)

Icing Class	**None**	**Light**	**Moderate**	**Heavy**	**Extreme**
Icing Rate (cm/hour)	0	<0.7	0.7<2.0	2.0<4.0	>4.0

For the Troms coastal region, a normal seawater temperature during the winter months is usually around 3-4 ºC. The following figure 34 generated by MET NPS show the ice rate curves for set seawater temperatures of 3 and 4 degrees Celsius, in function of the air temperature (ºC) and wind speed (m/s). The difference in curves between that of 3ºC and of 4ºC is only small, but it is clear that with slightly warmer water, the limits between the ice rate classes has shifted, meaning colder air temperature and or higher wind speed is necessary to produce the same quantity of sea spray icing.

We can take a few weather scenarios for example:

To put ourselves on the limit between light icing and moderate icing, at a set wind speed of 10m/s: for a sea temperature of 3ºC, we will need an air temperature of approximately -6ºC to achieve an icing rate of 0.7 cm/h, but for a sea temperature of 4ºC, we will need an air temperature of -8ºC.

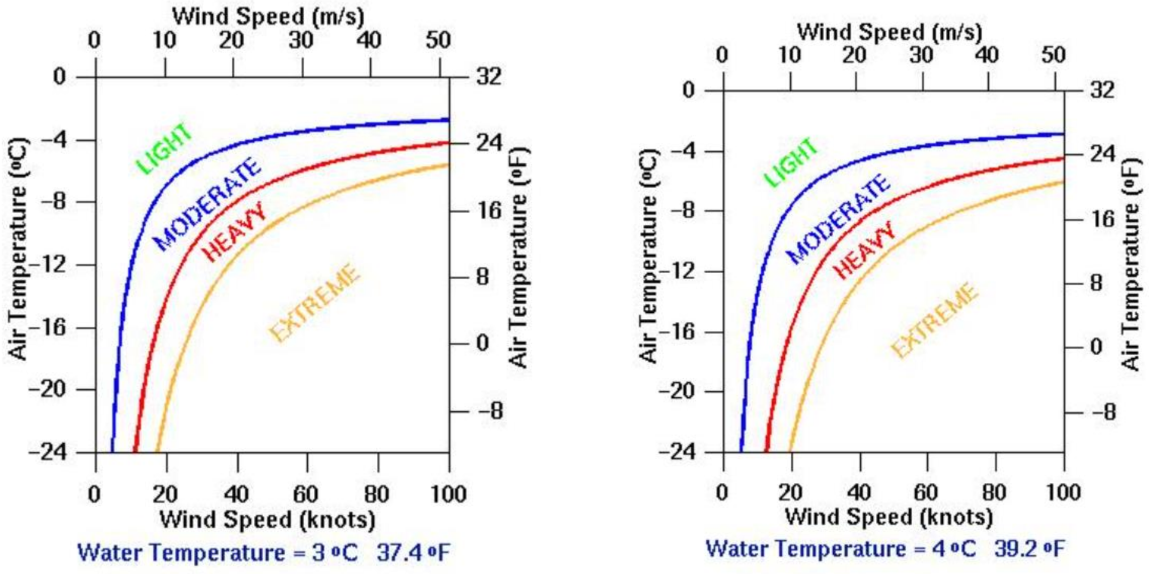


Figure 34: Overland icing classes for water temperatures 3 and 4 C. in function of air temp, wind speed. Graphs taken from Guest (2008)

4.2.2 K. Jones (1998) method

Jones model for predicting ice loads from freezing rain is a simple model. It is conservative, but Jones claims the model is explicitly dependent on meteorological parameters, so is therefore reasonable model, considering ice loads are commonly modeled with meteorological data.

This model does not depend on the diameter of the cylinder in presence of ice accretion, but this ice growth remains regular around the cylinder. In reality, it is possible that the dimensions of the cylinder can have an effect on the shape of the ice growth during the freezing rain-storm

(Jones, 1998). However, this model designed to be conservative, simple and easy to use (Jones, 1998).

The important factors taken into consideration in this model are precipitation rate, and wind speed.

With a precipitation rate varying from 0.5 to 10 mm/h, and wind speeds varying from 0 to 14m/s. Jones model represents an ice accretion rate for freezing rain from 0.25 to 9 mm/h.

4.2.3 Kulyakhtin et al. (2013) experiment

Kulyakhtin's model focusses on heat conductivity and heat capacity of the ice accretion. Heat conductivity is an important factor when in presence of irregular spray events (non-continuous). Heat capacity of sea ice accretion is far more important than that of fresh water ice. Their model showed that 90% of the ice accretion occurs between 4.5 - 9.5 s after the spray event. Longer periods between sea-spray events. Due to the heat capacity of the ice, longer delays between spray events results in larger and more even ice accretion. Their experiments showed the mean spray flux to be at 300 g/m^2/s. Due to the difference in heat conductivity between the metal pipe in the experiment, and that of the sea ice accreted to the pipe, the ice growth rate will decrease over time.

Kulyakhtin's model is the only model referenced within this thesis that considers heat conduction as a factor for ice accretion. The experiments took place with rather large periods between spray events, up to 147.8 s. Kulyakhtin et al. claim that previous experiments do not take into account heat conductivity, as these experiments took place with shorter and more realistic spray periods, from 5 to 20 s, which would most likely have obscured the effect of heat conductivity (Kulyakthin et al. 2016).

4.2.4 Ryerson (1995) observations

Ryerson's observations on a Coast Guard vessel provided icing measurements over different locations of the vessel, for each icing event. These measurements were however limited due to problems with instruments, and limitations due to weather conditions (Ryerson, 1995). The factors measured were the duration of the sea spray events, water concentration of spray clouds, time average and instant spray clouds. In addition to this, the number of spray-drops and the size of these drops was measured. The thickness of sea spray ice after sea spray events were small, but still sufficient for observations of differences regarding time, position and surface orientation. The largest ice rate observed was of 13.3 mm/h.

4.2.5 Fukusako et al. (1989) experiment

Fukusako et al. (1989) experiment included multiple factors for ice accretion to a cylinder: air temperature, wind speed, spray flux, droplet size, droplet temperature, salt concentration.

The effects of these factors were observed during their experiment concluded that the morphology of the ice depended mainly on the wind speed and droplet size, and the surface pattern of the ice depended more on the size and temperature of the droplets. Ice accretion increased when in presence of a larger spray flux; however, the spread of ice was less even.

4.2.6 Makkonen (1989) method

Makkonen’s (1989) method for predicting accretion of wet snow (atmospheric icing) uses visibility during a snow as the main factor in their estimation. The unit of the result is grams per square meter per second, which is relatively easy for public to visualise. This estimation only applies in conditions of high humidity and temperatures close to 0ºC, that are important parameters for wet snow. However due to the Gulf Stream, the coastline of Norway commonly experiences these parameters and in consequence often large quantities of wet snow falling.

This icing rate can be very helpful to workers on fish farms, as this estimation requires only a visual observation. It can be enough for workers to just look out the window, or look at a surveillance camera on site, and estimate the visibility (in meters) and quickly calculate the potential added mass of wet snow to the cages per second, easily converted into hours or a day period.

However, this method is independent of wind, which can play a large part in how wet snow settles on the cage. This method should therefore be used only during snowfalls with little or no wind, or should be compared to windy conditions to see whether or not this method is applicable when windy.

4.2.7 Comparison of icing rates

Table 4: Icing rates for different ice prediction models

Method	**Conditions**	**Icing rate (mm/h)**	**Weight (kg/m^2) 12 hours**	**Weight (kg/m^2) 24 hours**	**Weight (kg/m^2) 48 hours**
Jones (1998)	Freezing rain	0.25-9	2.55-91.8	5.1-183.6	10.2-367.2
Fukusako et al. (1989)	Salt water icing on cylinder	2-17	20.4-173.4	40.8-346.8	81.6-693.6
Ryerson (1995)	Vessel icing	13.3	13.26	26.52	53.04
Makkonen (1989)	100m visibility ($5.52g/m^2/s$)	2.3	237.6	475.2	950.4
Overland (1990)	Vessel icing	7-40	71.4-408	142.8-816	285.6-1632

This table represents the icing rate for the multiple models studied in this thesis. For the models by Jones (1998), Fukusako et al. (1989) and Overland (1990), the icing rates chosen are the limits of their models. For example: Jones (1998) limits are chosen from their graph, with weather limits set at precipitation rates of 0.5 to 10 mm/h and wind speeds of 0-14 m/s. Ryerson's (1995) model is the maximum icing rate observed during their observations of the Coast Guard vessel. Makkonen's (1989) visibility dependant ice rate was set with weather conditions allowing for 100m visibility. Kulyakhtin et al. (2013) does not conclude with simple icing rates, as there are many factors within their experiments.

Each model presents different results, but all are of similar order, with icing rates only varying by up to a few centimeters per hour (from 0.25 mm/h (Jones, 1998) to 40 mm/h (Overland, 1990).

Many factors influence the rate of ice accretion, making it very complicated to provide good prediction, even with decent meteorological data. All of these models can be related to traditional circular fish cages, but not all in relation to sea spray icing. Makkonen's (1989) icing rate prediction relates to atmospheric icing (snow). This is however relevant to fish cages as they are also submitted to atmospheric icing. Jones' (1998) model of freezing rain accretion on cylinders is relevant as in some conditions sea spray icing can be considered as freezing rain, for example, with long airtime for sea spray, the spray droplets are cooled and can be considered freezing rain (Ryerson, 1995).

Fukusako et al. (1989) and Kulyakhtin et al. (2013) both presented experiments submitting a metal cylinder to sea spray fluxes. Under different weather conditions (temperature, wind speeds, etc.), different spray densities, etc. However, Kulyakhtin et al. (2013) is the only model to consider heat conductivity. Kulyakhtin et al. claim that heat conductivity is an important factor. This determines how fast and how much of the sea spray flux will actually accrete as ice, and not run off the target as water. The importance of heat conductivity can only be clearly noticed for long spray periods, allowing more time for the spray to freeze evenly around the cylinder. Other models use a more rea- life spray period 5 to 20 seconds, where the difference in this period does not show clear differences in ice accretion (Kulyakhtin et al., 2013).

Ryerson's (1995) results can be considered relevant, as they are observations from actual icing events. Ryerson explains, however, that the icing rate varies substantially regarding the location on the vessel. The rate presented in the previous table (13.3 mm/h) is the maximum observed during his time on the vessel, but is an average rate when compared to the other models in the table. This makes for a very relevant and conservative maximal icing rate.

Overland's (1990) model, although designed for medium sized vessels (20-75 m long), is widely used, especially in Norway, for weather forecasters (Samuelson et al., 2015). Dependant of the sea temperature, air temperature, wind speed and sea-water freezing point, the model seems to be quite an interesting model, and covering standard meteorological factors, it is an effective model for weather forecasts. The Overland formula is conservative as it does not take into consideration the speed of the vessel, but this is nevertheless irrelevant for fish cages, as they are anchored at a set position. The values of icing rates from this formula are set into multiple classes: none, light, moderate, heavy and extreme. This is an effective way to categorize the severity of potential ice accretion, resulting in an easier risk assessment for a more general public. However, the formula does not take into account the limited accretion in case one is close to the ice-edge with a short fetch length.

Norwegian Standard NS 9415 (Standard Norge, 2009) requires that sea structures must be dimensioned to withstand 30kg/m^2 for horizontal surfaces and 7,5 kg/m^2 for vertical surfaces.

Although all icing rate models differ, it is clear through all models, that ice accretion can become critical even after just a few hours.

For traditional circular fish cages, the distance of the walkway (or between the two floating rings) can often measure around 1 meter. The Norwegian standard NS 9415 (Standard Norge, 2009) therefore demands that the cage can support horizontally 30 kg per meter around the cage. Due to the sinking and defrosting of the lower parts of the cage, for example the walkway, from the above freezing seawater, we have seen earlier that the handrail, vertical tubes and brackets are more critical to ice build-up. However, these parts of the cage are considerably smaller in dimensions, so are most likely not expected to withstand the same quantity of ice as the floating rings. The surface area of the cage parts will have an important influence on the amount of ice accretion.

4.3 Impact of ice on winter operations

Icing can have a large impact on safety and efficiency of operations. There are many operations evolving around fish farming that must continue throughout the winters. To make this possible, ice build-up must be prevented or controlled.

Human Factor and Error:

Since the creation of the Norwegian Standard NS 9415 (Standard Norge, 2009), there has been a larger investment and improvement in fish farming technology. Thorvaldsen (2015) states that human errors are becoming the main challenge regarding the prevention of fish escape.

There are currently 4000-5000 persons working in this industry in Norway. There are daily tasks that are performed to maintain the welfare of the fish. These include feeding, maintenance of the cages, lice treatments, net cleaning, transfer of fish from the cages and boats. This means that the employees must work with the handling of fish, machinery, equipment and chemicals in a challenging environment. Fish farmers carry a great responsibility for the welfare of fish and should therefore not be overworked to exhaustion that can put them at risk, endangering themselves and others (Høyli, 2016).

According to interviews within Thorvaldsen (2015), poor interaction between humans and machinery is a factor in fish escape. This has been put down to the possibility of equipment being difficult to operate or handle.

The winter climate will add an important element of risk to these routine operations:

- Cold temperatures can add discomfort to employees during operations, with the most common issue of loss of sensibility of the hands due to the cold. This can make operations particularly difficult even with suitable clothing. Cold wind will cause wind chill effect, rapidly cooling the employee, and surrounding materials, and it is often not possible to be sheltered from this. The cold-water temperatures will be extremely dangerous when working around the cages.
- Ice build-up can make operations more difficult, for example ice on structural parts that need to be replaced, ice blocking hinges, etc. This may need to be removed before operations start, resulting in extra work time and effort. This ice build-up can occur not just on the fish cages, but also on the workboats, barges, etc. The ice can also reduce safety. Ice on walkways, stairs, handrails, etc. can make movements and operations hazardous.

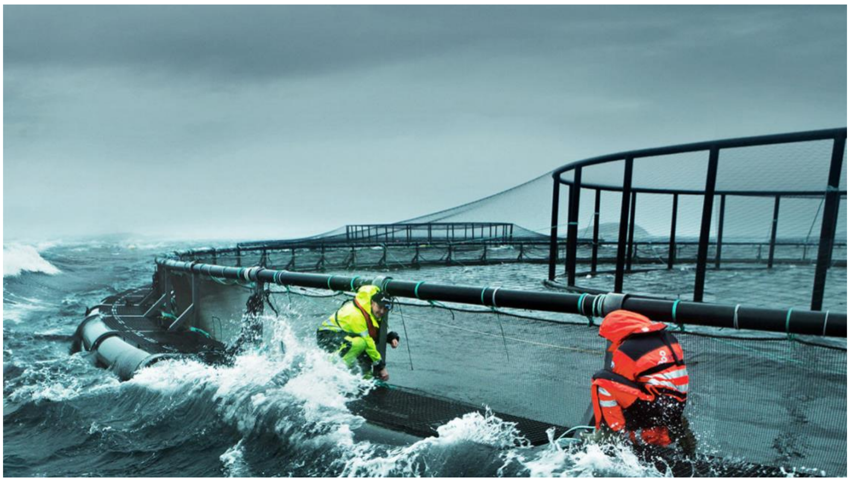


Figure 35: Human operations on cage. Photo taken from Høyli (2016)

Autonomous systems:

Currently, there is a high dependency on human interactions for operations. Which brings an important safety risk factor into the workplace, and to the escape of fish. With a growing industry, there is a growing demand for autonomous systems and integrated operations, to reduce manual workloads and the workers time spent on the facilities at sea (Utne et al. 2015). This can equally be beneficial to the efficiency of the industry.

According to Utne et al. (2015) and herein, there are four levels of autonomy:

1. Manual and automatic operations, requiring human control of all functions
2. Automatic systems that only require management authorization
3. Semi-autonomous systems that can make decisions when management is not present, but can be manually overridden
4. Fully autonomous in operations and decisions.

In offshore aquaculture, many operations, for example feeding and net cleaning, can be classed in level 2 autonomy. The feeding is autonomous, but orders are given by the worker from the feeding barges (on/off, dispersal rate of food (kg/s).), the net cleaning is often remotely operated, but must be installed manually. Many other operations are considered fully manual and are classed in level 1, for example ice removal.

Remotely Operated Vehicles (ROV’s) are starting to be used more than the traditional diving operations, for inspecting and maintaining the fish cage, removing the necessity for humans diving within or around the cage.

The increase in autonomy will reduce the need for workers to be present on site, where weather can be harsh, and high risk. There are currently multiple cameras and sensors allowing the farms to be monitored remotely, but operations and problem solving currently still rely on human interactions. Utne et al. (2015) show that there has been a large improvement in autonomy to raise health and safety in the aquaculture industry, but fish cage structures are not completely designed for autonomous systems, and that optimization of these structures, tools and systems is necessary for the future of autonomy in aquaculture.

4.4 De-Icing

The traditional and most commonly used method for removing ice from cages, is the use of wooden or rubber mallets. This is physically demanding work, with a risk of injury to the workers, but is also potentially dangerous. This method can only be done once a storm has passed, and the sea state is calm enough to access the cage, which could potentially be damaged from large amounts of sea spray ice and therefor unstable.

On vessels, some chemicals can be used for removal of ice build-up. However, chemicals should not be used on fish cages as it will have an impact on the water quality and a potential impact on the health of fish within the cage, and the surrounding wildlife.

4.5 Feeding barge

Feeding barges are an indispensable part of fish farming sites, as they must provide fish food, at all times, as well as fuel for generators, work boats to mention some. They often also include office space and living space for sites where it is necessary for employees to visit, or remain on site for longer periods including multiple days. The safety of feeding barges is there for equally important. Sea-spray icing can have a severe impact on the stability of the barge, as well as reducing the safety of operations on deck, access to equipment, etc. Unlike other vessels, in situations of severe weather and sea spray icing conditions, the barge cannot sail to shelter as it is moored and must continue its supply of food to the cages.

When designing a vessel, determining the shape should be an important factor the designed use of the vessel. For example, a fishing vessel will generally be designed for easy manoeuvring, with enough stability from frequent crane operations. When it comes to vessels designed as feeding barges, they are usually moored for long periods of time, or even permanently, on a fish farming site, and are not commonly used for travelling. Feed barges must store many hundred tons of fish feed, and often large quantities of fuel. For this use, feeding barges are often designed rather box like.

If we consider basic ship stability, there are three important variables in the stability equation: buoyancy B, centre of gravity G, and the metacentre M. The metacentre being the point about which the body starts oscillating. The metacentric height GM is a variable that is used to characterise the stability of a vessel.

In presence of added mass on the top of the barge, the centre of gravity and centre of buoyancy will increase drastically causing a decrease in the metacentric height. This resulting in a decrease in stability. However, with presence of uneven or non-symmetrical icing, the centre of gravity will shift away from the centre line, resulting in a far more important decrease in stability and an increased risk of capsizing. In presence of swell, the vessel will gently roll. This phenomenon is normal for any vessel, and the centre of gravity will remain on the centreline of the vessel. However, in case the natural frequency of the barge in roll gets in resonance with energetic waves, the roll amplitude will increase considerably. Combined with icing, capsizing could occur.

As seen earlier in the thesis, winter storms and sea spray icing has resulted in the sinking of feed barges. The design of a box shaped barge is generally very stable, due to its width, and shallow draft.

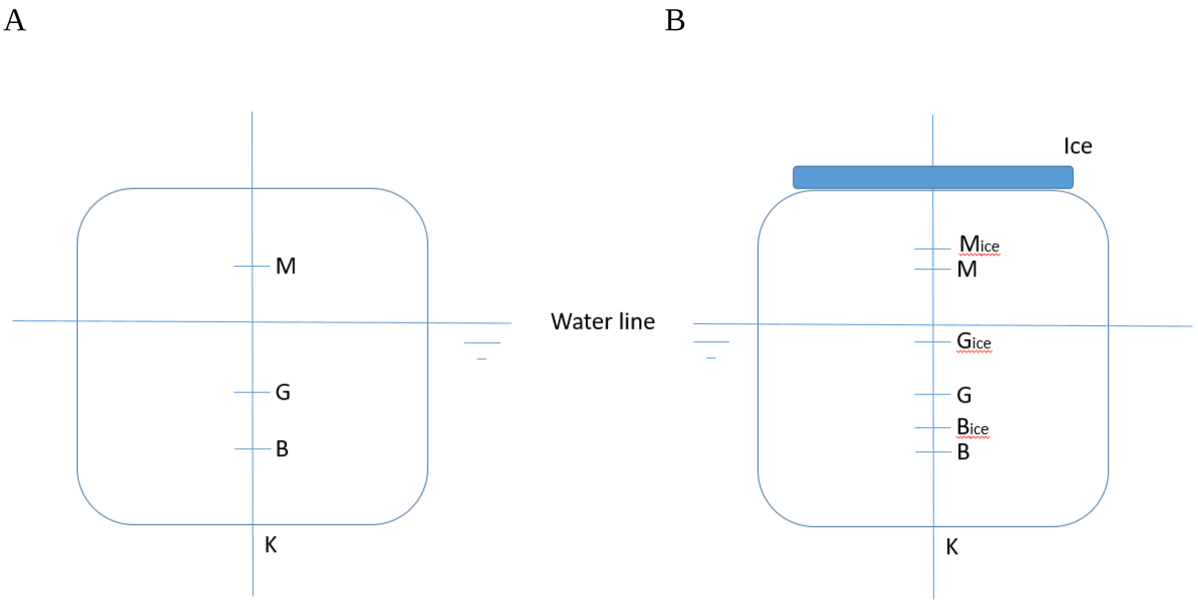


Figure 23: Cross section of a vessel. Figure A: Under normal buoyancy. Figure B: in presence of sea spray icing

M: Metacentre

G: Centre of gravity

B: centre of buoyancy

K: Keel

An equation for the stability of a vessel is as follows:

$$GM=KB+BM-KG$$

During an icing event, the centre of gravity will move upwards, increasing the distance KG from the keel and GM will be reduced. Any vessel shall have an absolutely lowest value of GM equal to 0.15m

If we take into consideration the natural frequency in roll of a barge $\omega_{\eta 4}$ (Pedersen, 2019):

$$\omega_{\eta 4} = [\frac{\rho g \nabla GM}{1.2{I_{44}}^2}]^{1/2}$$

This equation is under the following assumptions:

- Small roll angle
- No external forces
- $I_{44} = \nabla \rho (0.35B)^2$ is an estimation for hull vessels

$$\omega_{\eta 4} = [\frac{\rho g \nabla GM}{1.2\nabla \rho (0.35B)^2}]^{1/2}$$

We will choose dimension the following vessel dimensions to resemble a large and modern feeding barge:

B=10m

GM=1m

$$\omega_{\eta 4} = [\frac{gGM}{1.2(0.35B)^2}]^{1/2}$$

$$\omega_{\eta 4} = [\frac{9.81 \times 1}{1.2(0.35 \times 10)^2}]^{1/2}$$

The natural frequency of the barge is:

$$\omega_{\eta 4} = 0.817\ [s^{-1}]$$

The roll period of the barge will therefore be:

$$T_{\eta 4} = \frac{2\pi}{\omega_{\eta 4}} = 7.7\ [s]$$

We can now use the same equation of natural frequency for the same barge, but with a decreased metacentric height (GM=0.5m) due to ice accretion:

$$\omega_{\eta 4\mathrm{ice}} = [\frac{gGM_{ice}}{1.2(0.35B)^2}]^{1/2}$$

We will therefore have:

$$\omega_{\eta 4\mathrm{ice}} = 0.577\ [s^{-1}]$$

And:

$$T_{\eta 4\mathrm{ice}} = \frac{2\pi}{\omega_{\eta 4\mathrm{ice}}} = 10.9\ [s]$$

This significant increase in roll period results in a very different behaviour of the barge in a rough sea state, as the barge now gets in resonance with more energetic waves with higher wave periods. This, in consequence, will result in a largely increased risk of capsizing. This increase of roll period is often a first warning sign for workers on vessels that there could be presence of ice build-up with a reduction in GM. If no action is made to remove the ice, or to prevent more ice build-up, the barge could become a danger.

Figure 37 represents the range of feeding barges designed by Akva Group. (All of the barges designed by Akva Group are in accordance to the Norwegian Standard NS 9415 (Standard Norge,2009)).

Figure 24: Akva Group's available feeding barges. Image taken from Akvagroup (2021b)

The choice of feed barge is extremely important depending on the location of the farm site and the designed use of the barge. As seen earlier, the new offshore site in Fellesholmen uses a new design, the AC800 PVDB. This, whilst designed for the standard use of supplying the farm with food and power, is also built to withstand harsh offshore sea states. A traditional fish farm located in a sheltered area of a fjord, would not need such a large barge, as the sea state will be much calmer and the risk of sea spray icing much lower.

The box-like design for feed barges, whilst allowing for large storage capacities for fish food and fuel, is highly functional for fish farming. Its stable design allows for continuous use even during harsh weather. However, in the case of long swells, roll motions can become severe, in particular during icing events.

5 Conclusion

The fish farming industry is endlessly expanding, and with that, an increase of farming sites in cold climates at risk of ice accretion from sea spray icing, as well as atmospheric icing.

Traditional circular plastic fish cages are the most commonly used, due to their relatively small and flexible design, but hold their share of limitations when it comes to icing. The Norwegian Standard NS9415 (Standard Norge, 2009) demands that cages withstand an addition weight of 30 kg/m² horizontally and 7.5 kg/m² vertically, however this can be easily exceeded during events of severe sea spray icing. The prediction of sea spray icing is therefore paramount. Few methods or models exist to predict ice accretion rates, and are all dependent on many factors. The Overland formula (1990) is the most commonly used, as it considers simple weather-forecast data (wind speed, sea temperature, air temperature and sea-water freezing temperature). Due to the difficulty of predicting ice accretion, a simple and conservative method like the Overland formula is currently the most effective. For example, Makkonnen's (1989) visibility dependant ice rate is effective for wet snow accretion as this has the possibility to be used within the industry by workers.

Feeding barges play an important role in routine operations and should not be neglected when it comes to sea spray icing. Damage or loss of a feed barge can result in harm to the fish within the cage due to lack of food, and possible pollution to the environment considering the vast amounts of food and fuel stored onboard these barges. The design and stability of the barge should be chosen carefully when planning a new fish farming site.

Icing can have a large impact on safety and efficiency of operations, resulting in potentially dangerous situations to workers, and possible delays in operations which can result in harm to the fish, and financial losses to the farming company. Autonomous solutions can reduce the need for workers to be present on site during harsh conditions and therefore reduce hazards in the workplace. Fish cage structures are not completely designed for autonomous systems, and optimization of these structures, tools and systems is necessary for the future of autonomy in aquaculture.

The main contributions of the thesis are given as:

- Giving an overview of agrégation of ice on fish farms, using different sea spray icing models

- Discussing of the impact of ice on feeding barges
- Giving an overview of the impact of ice on farming operations

6 References

People:

Edmund Hansen, Multiconsult

Ove. T. Gudmestad, UiT

Egil Pedersen, UiT

Benjamin Marsden, photos taken and copyrighted in figures 19, 26 & 28

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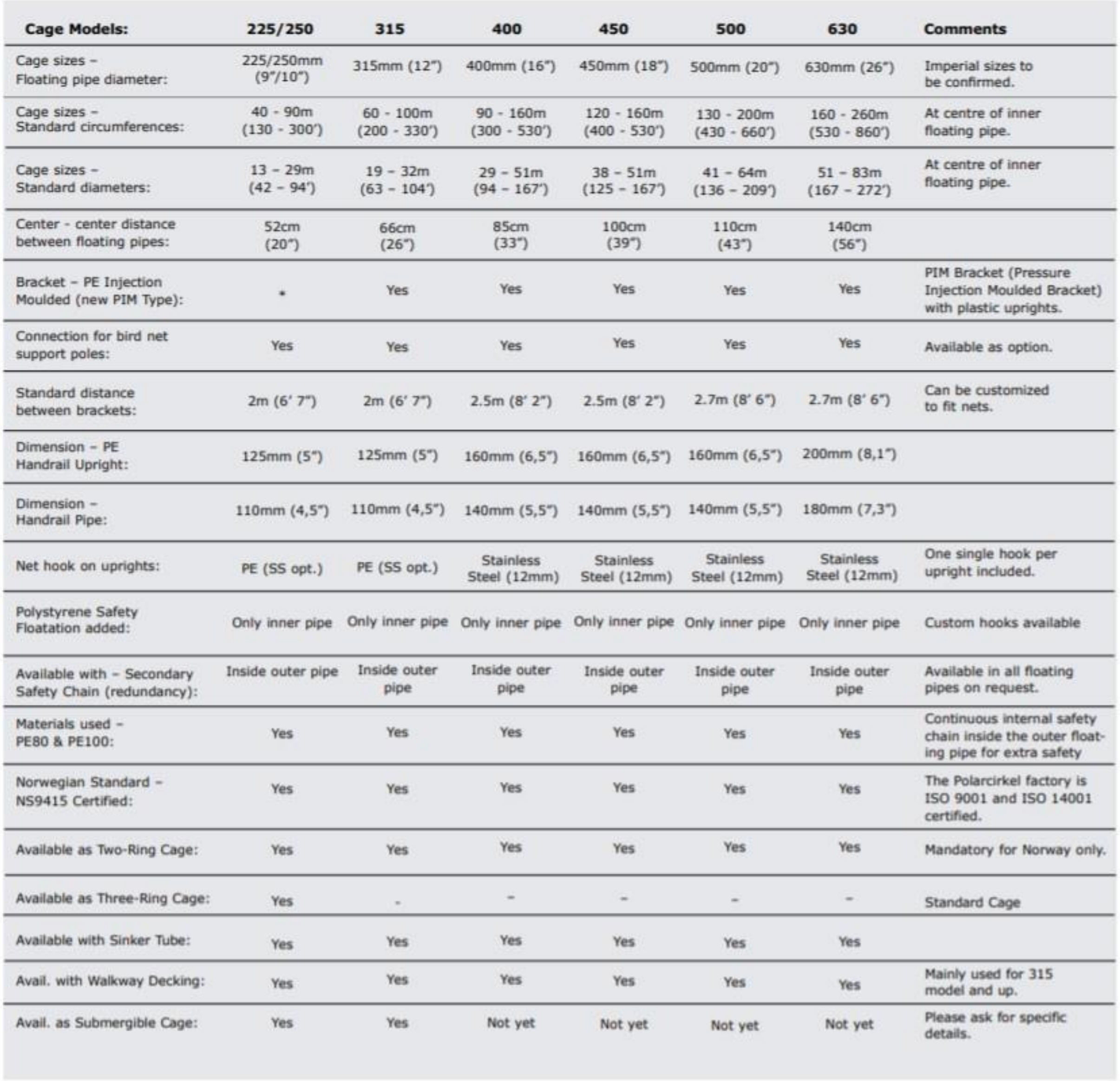
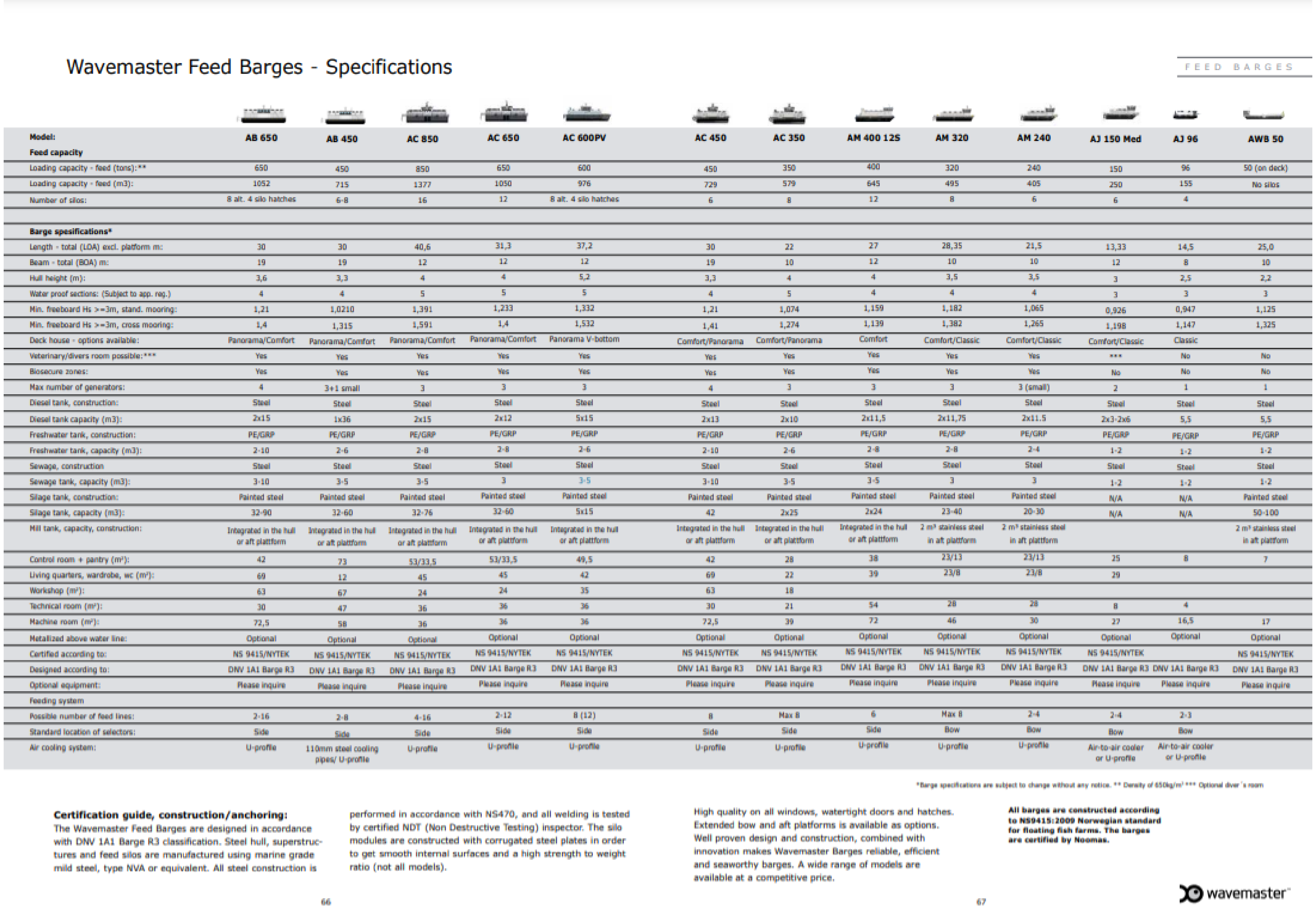
Appendix 1: Plastic Cage dimensions and specifications from Akva Group PolarCirkel



Cage Models:	225/250	315	400	450	500	630	Comments
Cage sizes – Floating pipe diameter:	225/250mm (9"/10")	315mm (12")	400mm (16")	450mm (18")	500mm (20")	630mm (26")	Imperial sizes to be confirmed.
Cage sizes – Standard circumferences:	40 - 90m (130 - 300')	60 - 100m (200 - 330')	90 - 160m (300 - 530')	120 - 160m (400 - 530')	130 - 200m (430 - 660')	160 - 260m (530 - 860')	At centre of inner floating pipe.
Cage sizes – Standard diameters:	13 – 29m (42 – 94')	19 – 32m (63 – 104')	29 – 51m (94 – 167')	38 – 51m (125 – 167')	41 – 64m (136 – 209')	51 – 83m (167 – 272')	At centre of inner floating pipe.
Center - center distance between floating pipes:	52cm (20")	66cm (26")	85cm (33")	100cm (39")	110cm (43")	140cm (56")	
Bracket – PE Injection Moulded (new PIM Type):	*	Yes	Yes	Yes	Yes	Yes	PIM Bracket (Pressure Injection Moulded Bracket) with plastic uprights.
Connection for bird net support poles:	Yes	Yes	Yes	Yes	Yes	Yes	Available as option.
Standard distance between brackets:	2m (6' 7")	2m (6' 7")	2.5m (8' 2")	2.5m (8' 2")	2.7m (8' 6")	2.7m (8' 6")	Can be customized to fit nets.
Dimension – PE Handrail Upright:	125mm (5")	125mm (5")	160mm (6,5")	160mm (6,5")	160mm (6,5")	200mm (8,1")	
Dimension – Handrail Pipe:	110mm (4,5")	110mm (4,5")	140mm (5,5")	140mm (5,5")	140mm (5,5")	180mm (7,3")	
Net hook on uprights:	PE (SS opt.)	PE (SS opt.)	Stainless Steel (12mm)	Stainless Steel (12mm)	Stainless Steel (12mm)	Stainless Steel (12mm)	One single hook per upright included.
Polystyrene Safety Floatation added:	Only inner pipe	Only inner pipe	Only inner pipe	Only inner pipe	Only inner pipe	Only inner pipe	Custom hooks available
Available with – Secondary Safety Chain (redundancy):	Inside outer pipe	Inside outer pipe	Inside outer pipe	Inside outer pipe	Inside outer pipe	Inside outer pipe	Available in all floating pipes on request.
Materials used – PE80 & PE100:	Yes	Yes	Yes	Yes	Yes	Yes	Continuous internal safety chain inside the outer floating pipe for extra safety
Norwegian Standard – NS9415 Certified:	Yes	Yes	Yes	Yes	Yes	Yes	The Polarcirkel factory is ISO 9001 and ISO 14001 certified.
Available as Two-Ring Cage:	Yes	Yes	Yes	Yes	Yes	Yes	Mandatory for Norway only.
Available as Three-Ring Cage:	Yes	-	-	-	-	-	Standard Cage
Available with Sinker Tube:	Yes	Yes	Yes	Yes	Yes	Yes	
Avail. with Walkway Decking:	Yes	Yes	Yes	Yes	Yes	Yes	Mainly used for 315 model and up.
Avail. as Submergible Cage:	Yes	Yes	Not yet	Not yet	Not yet	Not yet	Please ask for specific details.

Appendix 2: Akva Group's Wavemaster Feed Barges and Specifications



Wavemaster Feed Barges - Specifications

FEED BARGES

Model:	AB 650	AB 450	AC 850	AC 650	AC 600PV	AC 450	AC 350	AM 400 12S	AM 320	AM 240	AJ 150 Med	AJ 96	AWB 50
Feed capacity													
Loading capacity - feed (tons):**	650	450	850	650	600	450	350	400	320	240	150	96	50 (on deck)
Loading capacity - feed (m3):	1052	715	1377	1050	976	729	579	645	495	405	250	155	No silos
Number of silos:	8 alt. 4 silo hatches	6-8	16	12	8 alt. 4 silo hatches	6	8	12	8	6	6	4	
Barge spesifications*													
Length - total (LOA) excl. platform m:	30	30	40,6	31,3	37,2	30	22	27	28,35	21,5	13,33	14,5	25,0
Beam - total (BOA) m:	19	19	12	12	12	19	10	12	10	10	12	8	10
Hull height (m):	3,6	3,3	4	4	5,2	3,3	4	4	3,5	3,5	3	2,5	2,2
Water proof sections: (Subject to app. reg.)	4	4	5	5	5	4	5	4	4	4	3	3	3
Min. freeboard Hs >=3m, stand. mooring:	1,21	1,0210	1,391	1,233	1,332	1,21	1,074	1,159	1,182	1,065	0,926	0,947	1,125
Min. freeboard Hs >=3m, cross mooring:	1,4	1,315	1,591	1,4	1,532	1,41	1,274	1,139	1,382	1,265	1,198	1,147	1,325
Deck house - options available:	Panorama/Comfort	Panorama/Comfort	Panorama/Comfort	Panorama/Comfort	Panorama V-bottom	Comfort/Panorama	Comfort/Panorama	Comfort	Comfort/Classic	Comfort/Classic	Comfort/Classic	Classic	
Veterinary/divers room possible:***	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	***	No	No
Biosecure zones:	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No
Max number of generators:	4	3+1 small	3	3	3	4	3	3	3	3 (small)	2	1	1
Diesel tank, construction:	Steel	Steel	Steel	Steel	Steel	Steel	Steel	Steel	Steel	Steel	Steel	Steel	Steel
Diesel tank capacity (m3):	2x15	1x36	2x15	2x12	5x15	2x13	2x10	2x11,5	2x11,75	2x11.5	2x3-2x6	5,5	5,5
Freshwater tank, construction:	PE/GRP	PE/GRP	PE/GRP	PE/GRP	PE/GRP	PE/GRP	PE/GRP	PE/GRP	PE/GRP	PE/GRP	PE/GRP	PE/GRP	PE/GRP
Freshwater tank, capacity (m3):	2-10	2-6	2-8	2-8	2-6	2-10	2-6	2-8	2-8	2-4	1-2	1-2	1-2
Sewage, construction	Steel	Steel	Steel	Steel	Steel	Steel	Steel	Steel	Steel	Steel	Steel	Steel	Steel
Sewage tank, capacity (m3):	3-10	3-5	3-5	3	3-5	3-10	3-5	3-5	3	3	1-2	1-2	1-2
Silage tank, construction:	Painted steel	Painted steel	Painted steel	Painted steel	Painted steel	Painted steel	Painted steel	Painted steel	Painted steel	Painted steel	N/A	N/A	Painted steel
Silage tank, capacity (m3):	32-90	32-60	32-76	32-60	5x15	42	2x25	2x24	23-40	20-30	N/A	N/A	50-100
Mill tank, capacity, construction:	Integrated in the hull or aft plattform	Integrated in the hull or aft plattform	Integrated in the hull or aft plattform	Integrated in the hull or aft plattform	Integrated in the hull or aft plattform	Integrated in the hull or aft plattform	Integrated in the hull or aft plattform	Integrated in the hull or aft plattform	2 m³ stainless steel in aft plattform	2 m³ stainless steel in aft plattform			2 m³ stainless steel in aft plattform
Control room + pantry (m²):	42	73	53/33,5	53/33,5	49,5	42	28	38	23/13	23/13	25	8	7
Living quarters, wardrobe, wc (m²):	69	12	45	45	42	69	22	39	23/8	23/8	29		
Workshop (m²):	63	67	24	24	35	63	18						
Technical room (m²):	30	47	36	36	36	30	21	54	28	28	8	4	
Machine room (m²):	72,5	58	36	36	36	72,5	39	72	46	30	27	16,5	17
Metalized above water line:	Optional	Optional	Optional	Optional	Optional	Optional	Optional	Optional	Optional	Optional	Optional	Optional	Optional
Certified according to:	NS 9415/NYTEK	NS 9415/NYTEK	NS 9415/NYTEK	NS 9415/NYTEK	NS 9415/NYTEK	NS 9415/NYTEK	NS 9415/NYTEK	NS 9415/NYTEK	NS 9415/NYTEK	NS 9415/NYTEK	NS 9415/NYTEK		NS 9415/NYTEK
Designed according to:	DNV 1A1 Barge R3	DNV 1A1 Barge R3	DNV 1A1 Barge R3	DNV 1A1 Barge R3	DNV 1A1 Barge R3	DNV 1A1 Barge R3	DNV 1A1 Barge R3	DNV 1A1 Barge R3	DNV 1A1 Barge R3	DNV 1A1 Barge R3	DNV 1A1 Barge R3	DNV 1A1 Barge R3	DNV 1A1 Barge R3
Optional equipment:	Please inquire	Please inquire	Please inquire	Please inquire	Please inquire	Please inquire	Please inquire	Please inquire	Please inquire	Please inquire	Please inquire	Please inquire	Please inquire
Feeding system													
Possible number of feed lines:	2-16	2-8	4-16	2-12	8 (12)	8	Max 8	6	Max 8	2-4	2-4	2-3	
Standard location of selectors:	Side	Side	Side	Side	Side	Side	Side	Side	Bow	Bow	Bow	Bow	
Air cooling system:	U-profile	110mm steel cooling pipes/ U-profile	U-profile	U-profile	U-profile	U-profile	U-profile	U-profile	U-profile	U-profile	Air-to-air cooler or U-profile	Air-to-air cooler or U-profile	

*Barge specifications are subject to change without any notice. ** Density of 650kg/m³ *** Optional diver´s room

Certification guide, construction/anchoring:
The Wavemaster Feed Barges are designed in accordance with DNV 1A1 Barge R3 classification. Steel hull, superstructures and feed silos are manufactured using marine grade mild steel, type NVA or equivalent. All steel construction is performed in accordance with NS470, and all welding is tested by certified NDT (Non Destructive Testing) inspector. The silo modules are constructed with corrugated steel plates in order to get smooth internal surfaces and a high strength to weight ratio (not all models).

High quality on all windows, watertight doors and hatches. Extended bow and aft platforms is available as options. Well proven design and construction, combined with innovation makes Wavemaster Barges reliable, efficient and seaworthy barges. A wide range of models are available at a competitive price.

All barges are constructed according to NS9415:2009 Norwegian standard for floating fish farms. The barges are certified by Noomas.

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