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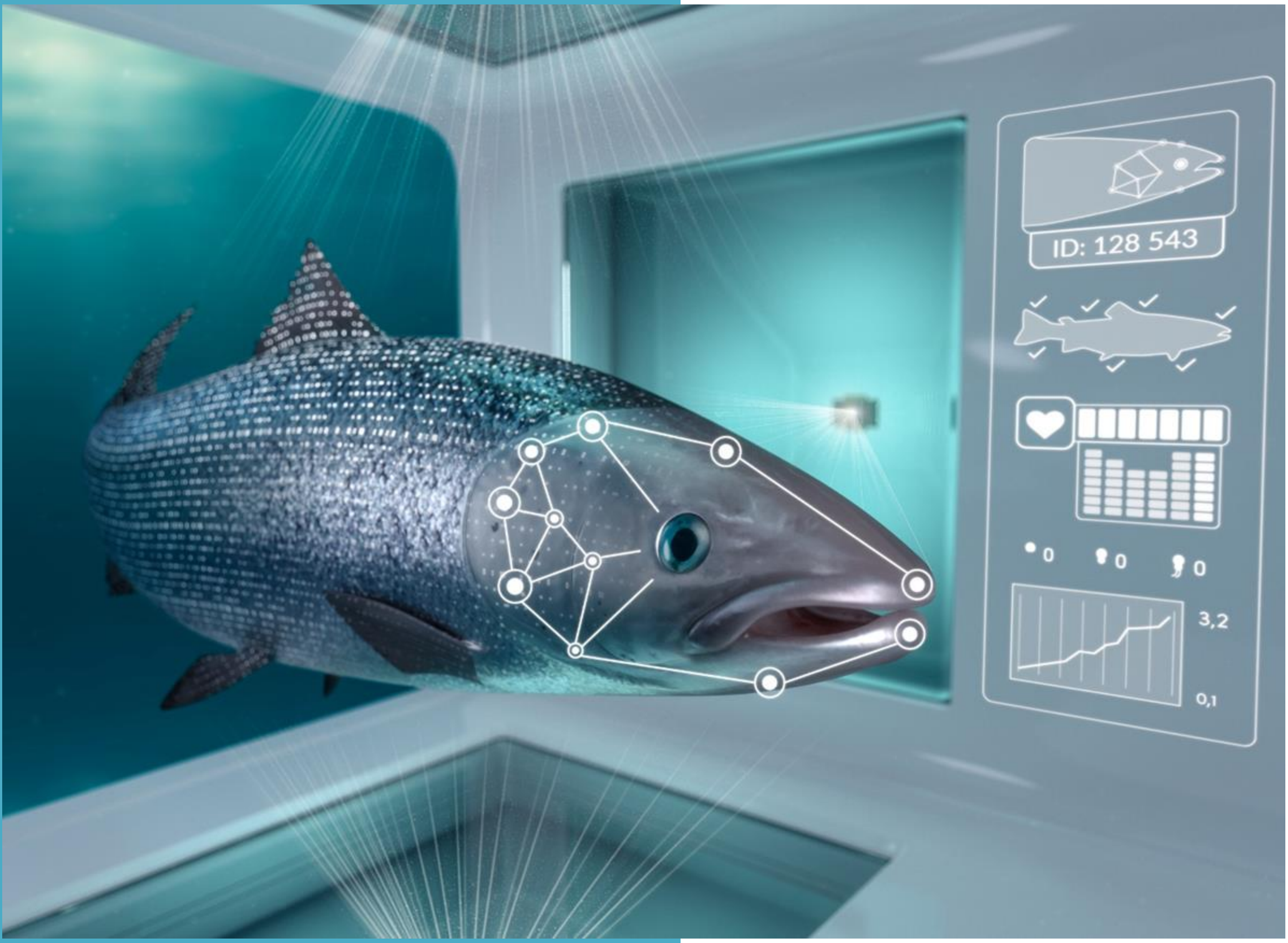
iFarm: Final report documenting the biological and technological results from Phase 1 (Concept-test) – Cermaq Utvikling AS avd Martnesvika



Cermaq Norway

12.07.2022

Innhold

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Summary

The iFarm aquaculture concept, being developed by BioSort AS in partnership with Cermaq Utvikling AS was granted four development licences by the Norwegian Directorate of Fisheries in 2019. The iFarm concept is a novel production system that aims to introduce individual-based Precision Fish Farming (Føre et al., 2018) to Atlantic salmon aquaculture. It aims to use advanced illumination/camera technologies and computer vision algorithms to identify individual fish, as well as counting lice on the fish and other parameters related to health, welfare and growth on individual salmon held within adapted aquaculture sea cages from smolt transfer to slaughter. The development licence project also aims to grade and sort fish based on their size.

The iFarm production system in Phase 1 consists of adapted snorkel cages that hold fish 10 – 15 m below the ocean surface to limit their interactions with potential lice rich surface waters. Cages were also fitted with lice skirts around the main cage collar (not the adapted snorkel) down to a depth of 5 meters. The fish can access the ocean surface via the snorkel to refill their swim bladder with air. Each time the fish swims to the surface it must pass through the iFarm sensor which aims to identify it and measure various performance, welfare and health parameters. Three phases of the iFarm project are planned from 2020-2024.

This report covers the whole of Phase 1 of the development project from September 2020 until March 2022 and summarises the technological developments that occurred during the report period, in addition to results from the monitoring of biological (fish health and welfare) and production performance during the reporting period.

Background

Cermaq's vision for the Age of Aquaculture

The Norwegian Atlantic salmon farming industry is over 50 years old, beginning in the late 1960's where annual production was very limited, amounting to ca. 100 tonnes in 1970 (Hersoug, 2021 and references therein). Steady growth, seeing annual production reach over 200,000 tonnes in the mid 1990's soon accelerated in the early and mid-2000's reaching an annual sales tonnage of over 1.0 million tonnes in 2011. However, growth has somewhat stagnated over the last decade, with annual sales ranging from 1.1 – 1.4 million tonnes per year (Norwegian Directorate of Fisheries, 2021).

The drivers for this stagnation are wide-ranging and multi-factorial, and also manifest themselves in other Atlantic salmon production regions around the world (see e.g., Iversen et al., 2020). These drivers consider socio-environmental impacts of aquaculture addressing sustainability and co-existence, including the potential transfer of disease and pathogens to wild stocks, and the potential genetic and ecological impacts of escaped farmed fish upon wild stocks amongst others (see e.g., Young et al., 2019; Hersoug, 2021).

A central objective in Cermaq's operations is to continuously work to minimize the negative environmental footprint of the company while lifting Cermaq's own and the industry's standards. Farming salmon is an efficient way of producing healthy and nutritious food with a smaller ecological footprint compared with other animal proteins. Cermaq aligns its focus areas with the UN Sustainable Development Goals (SDGs) but growing sustainable salmon farming comes with challenges. Through dedicated R&D, Cermaq are always searching for new ways to improve animal welfare, salmon quality and make the task of farming more sustainable and take great interest in innovative ways to use new technologies to enhance nature and ensure salmon health and welfare.

Regulatory frameworks for promoting sustainable and innovative Norwegian salmon farming

The Norwegian Atlantic salmon farming industry is subject to a robust and far-reaching management and regulatory framework to promote sustainability, to regulate total production and address the concerns of interested parties and stakeholders (Young et al., 2019; Hersoug, 2021). The regulatory framework has been developed and adapted over the years, with two recent regulatory instruments, the 'Traffic Light System (TLS)' and 'Development licences' being recently introduced (Hersoug et al., 2021). Growth under the Traffic Light System is regulated by sea lice abundance on out-migrating wild salmon smolts and the potential mortality risk on these smolts within a specific salmon farming region (Young et al., 2021).

The Development Licence regulatory instrument is specifically designed to encourage innovation and help the aquaculture industry develop new and innovative production technologies (see Hersoug et al., 2021 and https://www.fiskeridir.no/Akvakultur/Tildeling-og-tillatelser/Saertillatelser/Utviklingstillatelser). The aim of the licence instrument is to reduce the risks connected to the development and implementation of large scale innovations and are initially granted freely but do require the awardee to make significant investments in the projects (see Hersoug et al., 2021 for more details).

The iFarm concept

The iFarm aquaculture concept, currently being developed by BioSort AS and brought to fruition in partnership with Cermaq Norway AS was granted four development licences by the Norwegian Directorate of Fisheries in 2019 (see https://www.fiskeridir.no/Akvakultur/Tildeling-og-tillatelser/Saertillatelser/Utviklingstillatelser/Status-ja-nei-antall-og-biomasse).

The iFarm aquaculture concept is a novel production system that aims to introduce individual-based Precision Fish Farming (Føre et al., 2018) to Atlantic salmon aquaculture. It aims to use advanced illumination/camera technologies and computer vision algorithms to identify individual fish (similar to facial recognition), as well as counting lice on the fish and other parameters related to health, welfare and growth on individual salmon held within adapted aquaculture sea cages from smolt transfer to slaughter. The development licence project also aims to grade and sort fish based on their size. The iFarm production system consists of an adapted snorkel cage that holds fish 10-15m below the ocean surface to limit their interactions with potential lice rich surface waters. Cages are also fitted with lice skirts around the main cage collar (not snorkel) down to a depth of 5 meters. The fish must be able to access the ocean surface to refill their swim bladder with air and can do so by swimming up through the snorkel to the surface (see Stien et al., 2016a). Each time the fish swims to the surface it will pass through an iFarm sensor house who's technologies aim to identify it and measure various performance, welfare and health parameters.

The iFarm development licence Phase 1

Pilot and commercial testing of the iFarm concept

The iFarm concept was initially pilot-tested at the Institute of Marine Research and a report of the 2017 trials from January 24th – March 28th 2017, was submitted to the Directorate on June 27th 2017, as part of "tilleggsopplysninger til søknad", vedlegg 7.

Development of the iFarm concept for commercial scale cages, within the development licence project, was started in January 2020. In September 2020 a full-scale testing of two iFarm systems with a strong focus on operations, technology and fish welfare and health monitoring was carried out to initiate the first full-scale "proof of concept" for the iFarm system and also to instigate the initial full-scale implementation and application of the farming system and take the first steps to realise it as an innovative product. This testing was carried out in tandem with monitoring a third, adapted 'associate' snorkel cage at the same farming site.

Technical design and cage set-up Phase 1

Geographical location

This proof of concept commercialisation study was carried out at Cermaq Utvikling AS's Martnesvika production site 67.76705° N, 15.580867° E (see Figure 1).

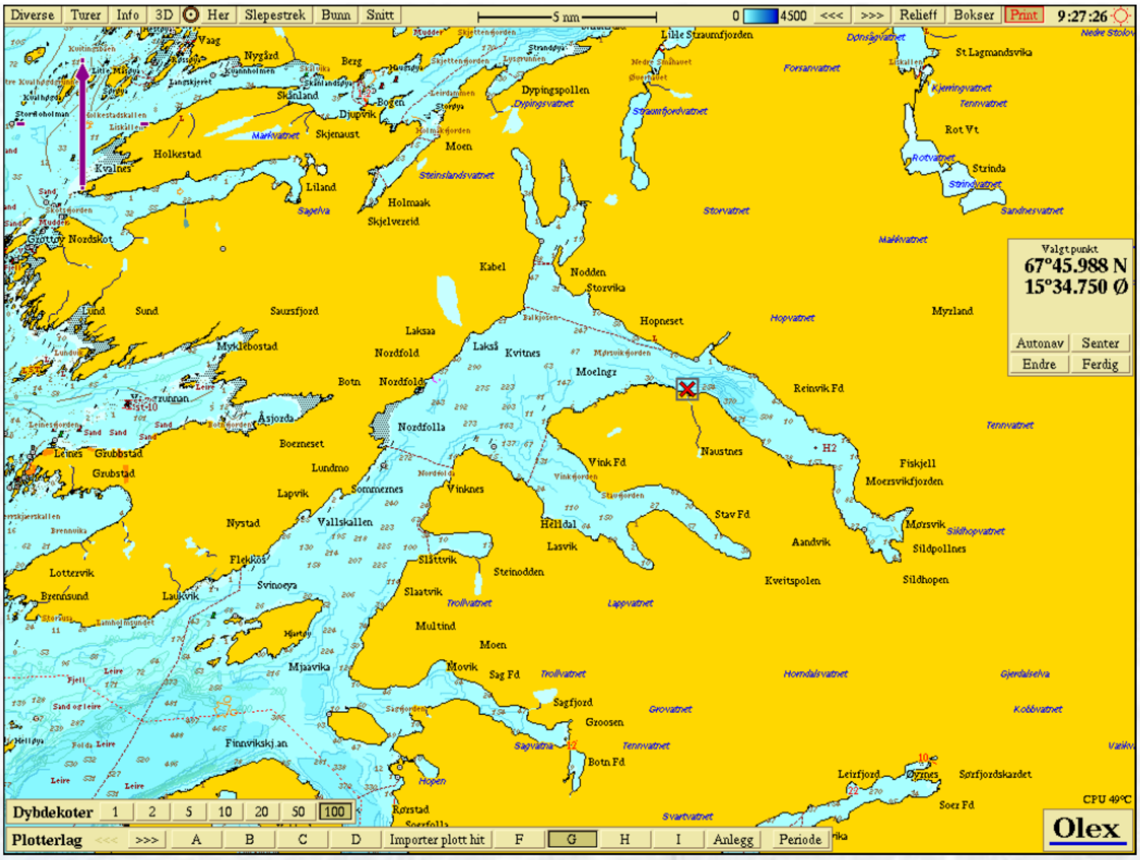


Figure 1 Map showing the Cermaq Utvikling AS facility Martnesvika, where the iFarm cages are located (farm location highlighted with a red boxed x). Map courtesy of Olex AS and reproduced from the Martnesvika site report by Akvaplan-niva.

Phase 1 timeline and set up

Phase 1 of the project began when the fish were transferred to seawater on the 14th and 16th September 2020. Phase 1 used autumn 0+ smolts stocked in three production cages at Martnesvika, including 1 associate adapted snorkel cage (cage M9) and two iFarm cages, (cages M10 and M11), hereafter termed the associate cage/M9, iFarm 1/M10 and iFarm 2/M11, respectively. Placement of the cages within the cage group at the Martnesvika site is shown in Figure 2 below.

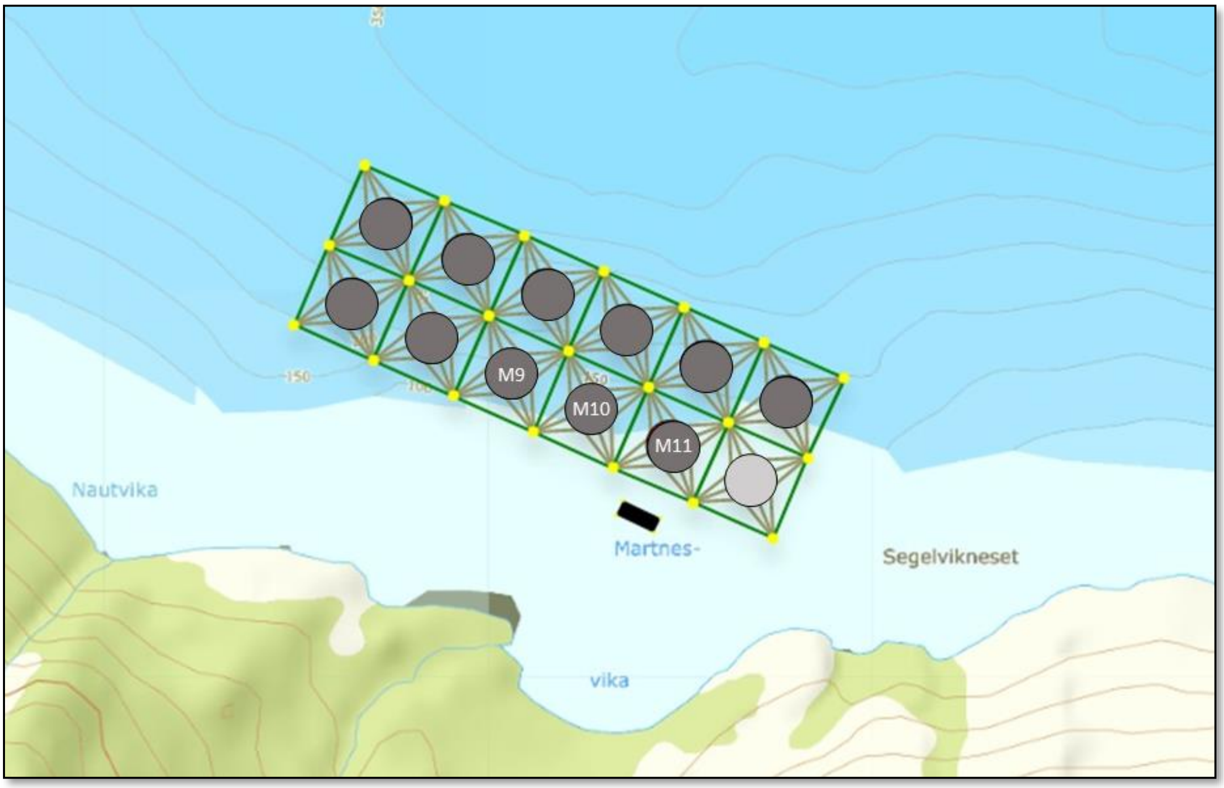


Figure 2 Figure showing the placement of the Phase 1 cages within the Cermaq Utvikling AS facility Martnesvika. Specifically, the associate cage (M9) and the two iFarm cages, (cages M10 and M11, respectively)

Fish were from a pooled hatchery AquaGen QTL-Innova SHIELD stock from the Lødingen fisk AS hatchery. One group of fish were transferred from the hatchery via the Langsund wellboat on the 13th September 2020 and deployed into the associate cage M9 on the 14th September 2020. Further fish transfers were undertaken using the Viknatrans wellboat from the same hatchery on the 15th September 2020, and fish were transferred into iFarm 1, M10 and iFarm 2, M11 on the 16th September 2020. Average seawater temperatures at the time of transfer on the 14th and 16th September 2020 at 3 m depth were 11.9 °C and 12.3 °C, respectively. Lice skirts were not initially deployed on these cages until mid-November (Permaskjørt, Botngaard, 5m depth). Numbers of fish in each cage at the time of transfer were: 157 430 (mean weight ca. 80 g) for the associate cage (M9); 144 927 (mean weight ca. 98 g) for iFarm 1 (M10), and 165 405 (mean weight ca. 109 g) for iFarm 2 (M11).

Feeding systems

Fish were remotely fed to appetite from the Nordfold feeding center, Steigen, using existing Cermaq Norway AS feeding regimes for the Martnesvika locality. Fish in the associate cage (M9) and iFarm cages (M10 and M11) were fed via two different feeding systems. The associate cage (M9) used the existing surface feeding system that is utilised at the Martnesvika site, consisting of a centralised rotator spreader (VARD, 8001) that distributed feed at the surface within the snorkel with a feed spread of ca. 5-20 m diameter. iFarm 1 (M10) and iFarm 2 (M11) were fed by a recently developed underwater feeding system (ScaleAQ) that distributed feed via two feeding points below the snorkel at a depth of 10 or 15 m for iFarm 1 (M10) and iFarm 2 (M11), respectively (see Figure 3). Water based feed delivery was driven by the differential pressure between the water level created inside the feeding unit and the sea surface. The feed exited an underwater pipe outlet and had limited horizontal feed distribution at the feed point of ca. 0.5 m. Fish were fed a commercial diet from seawater transfer.

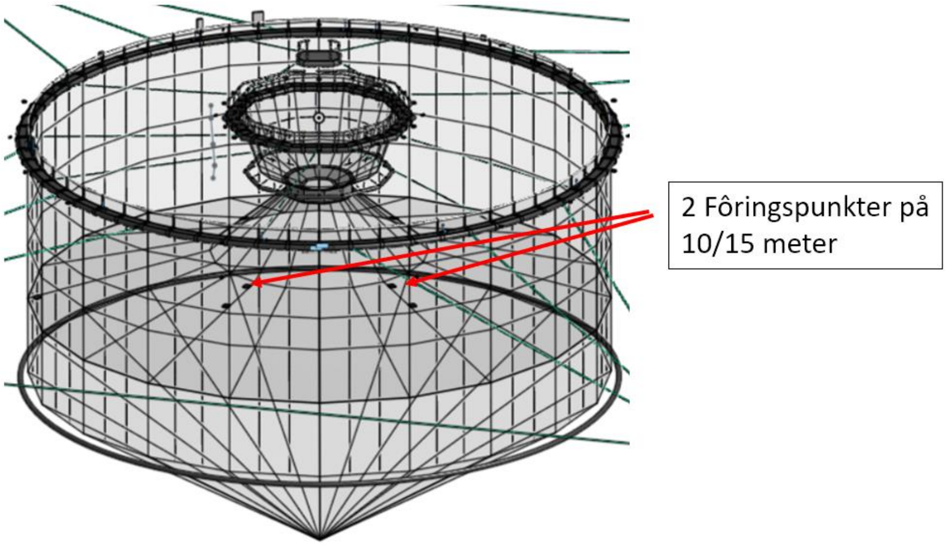


Figure 3 Technical information regarding feeder placement for each of the iFarm cages utilised in Phase 1 of the iFarm project at the Cermaq Utvikling AS facility, Martnesvika. iFarm 1 (M10) had two feeding points at 10 m deep and iFarm 2 (M11) had two feeding points at 15 m deep

Artificial lighting systems

Fish in each of the associate and iFarm cages were subjected to artificial underwater lighting throughout the natural diurnal and nocturnal period from time of stocking in September 2020. Underwater lighting was provided via four underwater lights (AkvaGroup, Akva Aurora SubLED Combi) which were placed in the feeding zone, under the net roof at a depth of 10 m (iFarm 1, M10) or 15 m (iFarm 2, M11).

Daily operations and husbandry

The iFarm and associate cages followed the standard procedures for daily operations at the Martnesvika site. Where possible, dead fish were removed from the cages daily using LiftUp. Moribund fish at the surface were removed from the cage every day and they were euthanised by an overdose of Benzoak vet. (30-40 ml/ 100l water). Lice were counted once a week.

Net cleaning followed the Martnesvika site's cleaning plan, and any extra cleaning was carried out when needed. Cleaning was carried out by a service boat using net cleaning robot rigs. The iFarm and associate cages were cleaned a total of eight times during the production cycle and the cleaning procedure included the cleaning of the main net, snorkel net and roof. No nets were changed on either the iFarm or associate cages during the production cycle.

Regular operational routines, such as manual lice counting, manual fish health monitoring and net cleaning operations are currently working well in each of the iFarm cages. However, bringing the iFarm docking and sensor housing to the surface for cleaning has proven difficult and potential solutions were explored in the latter stages of Phase 1 and this work will continue in Phase 2. Numerous handling processes and operations have been performed throughout the Phase 1 production cycle. The fish in the iFarm and associate cages have been transferred to a well boat a total of three times during the production cycle, two during de-licing and one for harvesting. During these operations, the net roof was partially or completely removed to assist in the process.

Project plan

The iFarm project goals and objectives will be addressed over three phases (see Figure 4 below). This report addresses Phase 1 from time of stocking until slaughter.

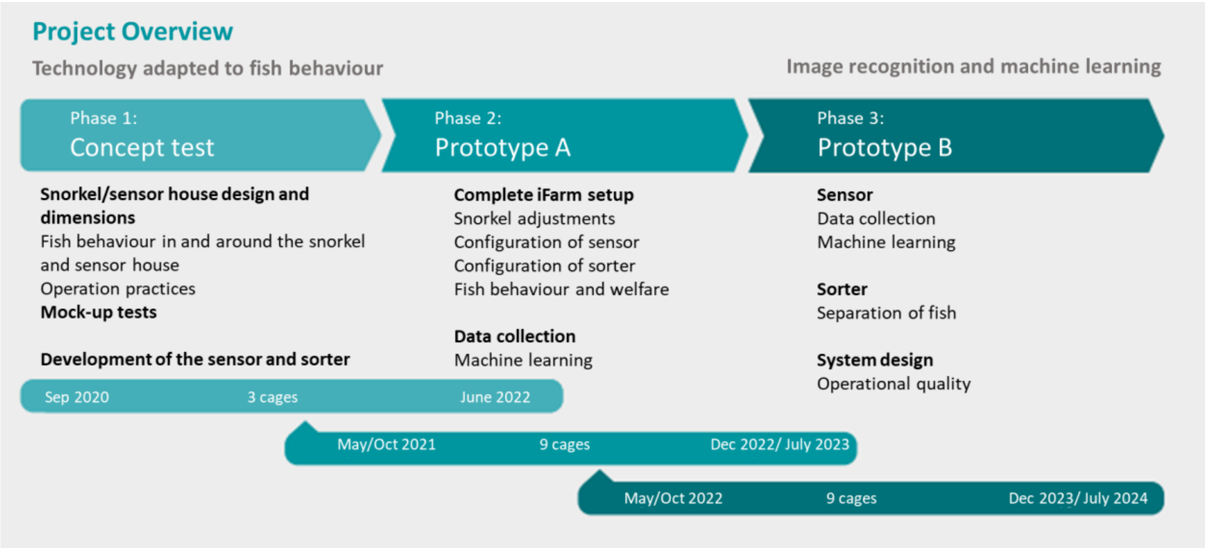


Figure 4 Overview of the iFarm project and Phase 1-3 timeline from 2020-2024. This report addresses the entire Phase 1 period from September 2020 until March 2022.

Technical development

The phase 1 testing commenced in September 2020 and utilised three cages including: 2 iFarm units, termed iFarm 1 and 2, that were generally similar but had different net roof configurations and different sensor housings; and a third associate cage that was an adapted snorkel cage (see Figure 5). As stated in the introduction, the iFarm production systems in Phase 1 are adapted snorkel cages that hold the fish either 10 m (iFarm 1, M10) or 15 m (iFarm 2, M11) below the water surface to limit the salmon's contact with potential lice reach surface waters. Unlike other snorkel cages, the snorkels themselves were not skirted and a commercial lice skirt (Permaskjørt, Botngaard) was therefore fitted around the edge of each iFarm and associate cage to a depth of 5 m. Within each iFarm snorkel at a depth of 6 m was the iFarm docking station with a circumference of ca. 19 m, a diameter of ca. 6 m and an opening with a diameter of 3 m. The circumference of the snorkel at the water surface was ca. 44 m. A third adapted snorkel cage (associate cage, M9) was monitored in Phase 1 and consisted of an open snorkel to the surface starting at 11 m deep that culminated in a 90 m circumference snorkel at the water surface. Detailed descriptions of the system design can be found in the user handbook and the "Erfaringslogg etter installasjon av iFarm 2020" (attachment 1, non-public).

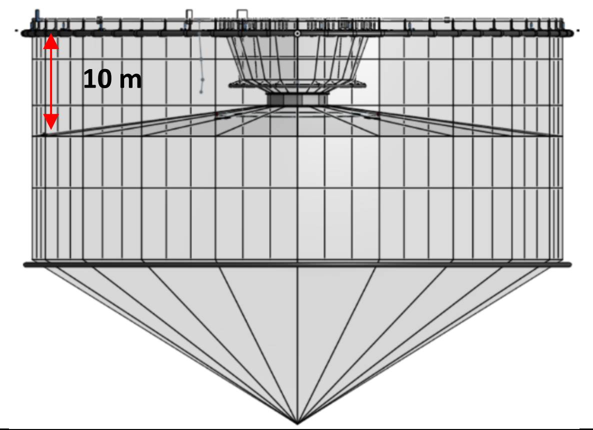
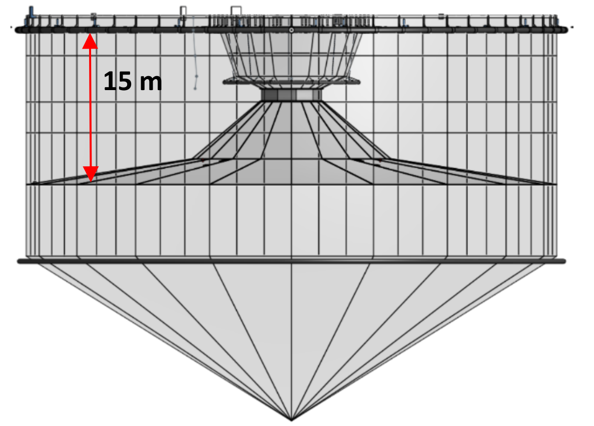
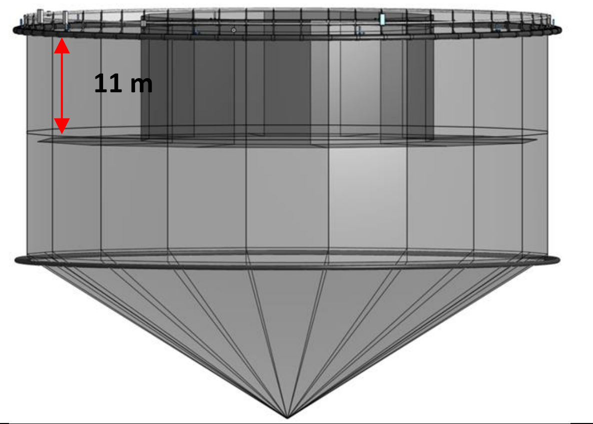
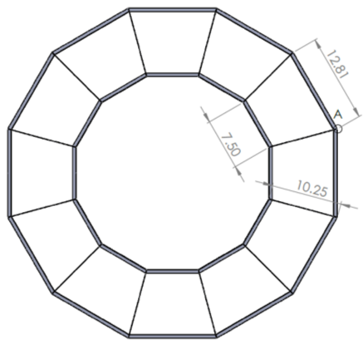
	
iFarm 1 with the roof net starting at 10 m deep	*iFarm 2 with the roof net starting at 15 m deep*
	
Associate cage with roof net starting at 11 m deep	*Overview of the snorkel dimensions for the associate cage*

Figure 5 Technical specifications and information for each of the iFarm and associate cages utilised in Phase 1 of the iFarm project at the Cermaq Utvikling AS facility, Martnesvika.

From fish stocking in mid-September 2020, until the iFarm sensor houses were mounted on the docking stations in February 2021, iFarm 1 (M10) and iFarm 2 (M11) were identical, except for the geometries of the net roofs. Based on daily observations for 5 months, the project concluded that there was not a large difference between the two cages in terms of fish behaviour and that both geometries would serve the purpose. Given that the 15 meter net roof reduced cage volume below the net roof substantially, cage geometries based upon the 10 meter net roof were chosen for Phase 2 of the project. However, to improve the potential lice protecting effect of the snorkel (see Oppedal et al., 2017), it was decided to use a 12 meter net roof depth for Phase 2 but keeping the net roof shape the same as for M10.

With regard to the horizontal placement of the snorkel collar ring, the two iFarm cages at Martnesvika both have the snorkel placed 5 meters off centre in each of the cages and a separate work platform is used to allow people to move from the outer cage collar to the inner snorkel collar. Both in terms of boat-crane access and staff access to the iFarm collar, this has not been ideal. Based on this, the project decided that the snorkel will be placed 10 meters off centre within the outer collar of the 160 m circumference net in Phase 2. This will improve crane access and also allow the separate working platform to be replaced with a working platform that is integrated with the iFarm collar.

iFarm docking station housed within the snorkel

The iFarm docking station is both the structural connection between the upper part of the snorkel and the snorkel floor, and at the same time the docking station for the iFarm sensor unit (see Figures 6). The docking stations are also fitted with 'zodiac-boat' type air tubes around the dockings, designed to keep the docking in a floating position at the time of installation or service.

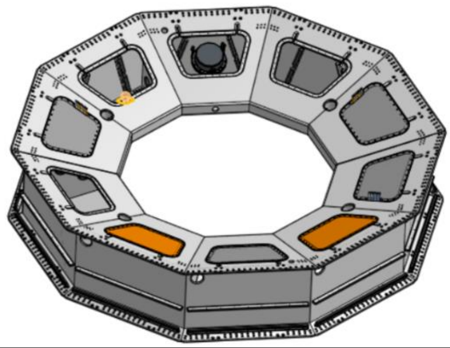
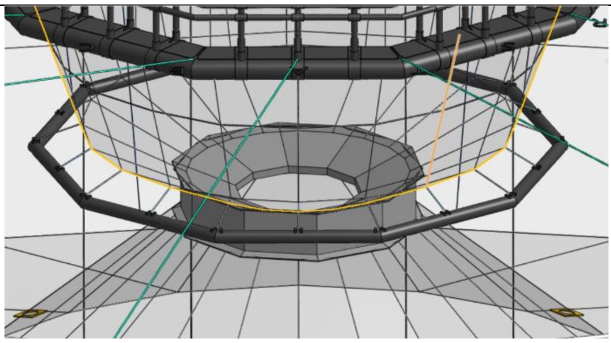
	
The iFarm docking station	*The iFarm docking station in relation to the snorkel tube and snorkel floor*

Figure 6 Technical specifications and information for each of the iFarm docking stations utilised in Phase 1 of the iFarm project at the Cermaq Utvikling AS facility, Martnesvika.

Camera set-up for fish monitoring in and around the iFarm sensor housing

To be able to monitor fish behavioural OWIs in and around each iFarm system, especially in relation to system design choices, the iFarm docking units were equipped with 5 (in periods 6) surveillance cameras. These cameras were used to e.g., monitor fish traffic thought the iFarm docking station, the number of fish in the snorkel above the docking station and also the behaviour of the fish immediately below the docking station. The footage from these camera's was also supplemented with footage from the feeding camera's installed in each cage and also with two overhead cameras mounted on the inner snorkel ring and outer cage ring for e.g., monitoring fish surfacing activity (see Figure 7 for an example of the camera output from each iFarm cage).

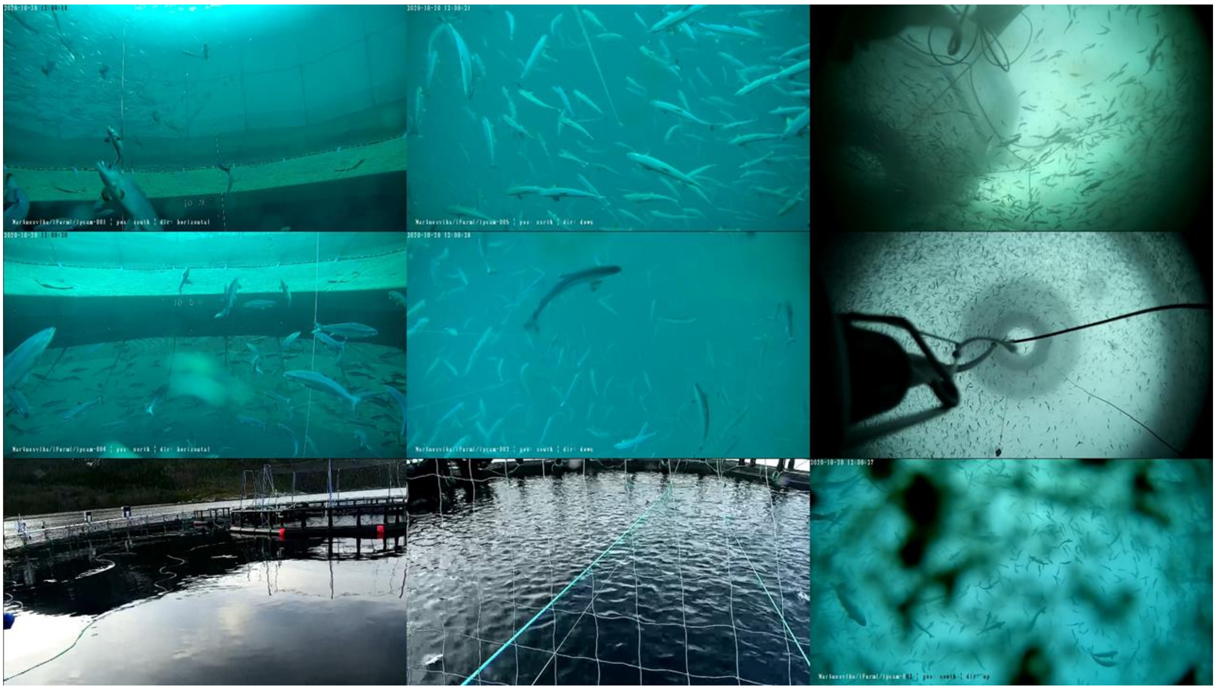


Figure 7 Photo collage showing relevant fields of view for each camera from iFarm 1 (M10) before the sensor housing was mounted upon the docking stations. Video feed included footage from the feeding camera and also overhead cameras for monitoring e.g., fish surfacing activity within the snorkels.

iFarm sensor housings

Two different iFarm sensor housings were installed in each of the iFarm cages on the 9th February and 26th February 2021 (iFarm 1 and iFarm 2 respectively).

The purpose of the two different sensor housings is to study what works best to establish the desired quality of sensor images from a technical point of view and also how to manage fish traffic through the sensors (from a biological point of view).

The variations in sensor house design will affect both upward and downward traffic and it is so far not possible to conclude on the optimal sensor house design. Cermaq Utvikling AS and BioSort AS will continue to explore different geometrical designs of sensor housings in Phase 2 and 3, as well as exploring the number of openings in each sensor house. The net roof and snorkel are both sewn into the docking station, which is very labour-intensive both at initial installation and also during net change operations. Due to this, Phase 2 will utilize a less labour-intensive method than sewing to connect the net to the docking stations.

To install the iFarm sensor housings, the zodiac-boat type air tubes around the dockings were inflated as outlined in Figures 8-9 below.

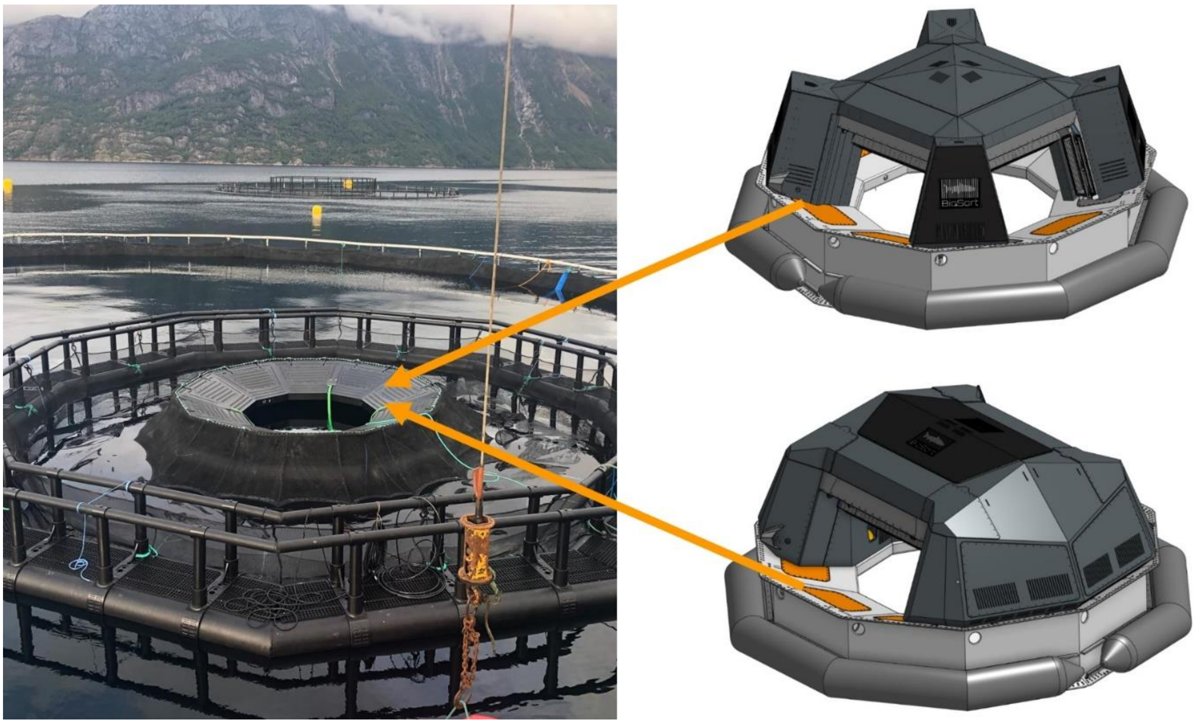


Figure 8 Figure consisting of a photo showing the docking station at the water surface within the cage and a digital model of the two types of sensor houses.

Figure 9 Photo of the installation of the Dome sensor housing to iFarm 1 (M10).

iFarm machine vision sensor arrangement and testing protocol

The two iFarm sensor housings were equipped with the following sensor arrangements. One of the four openings in the Dome housing was equipped with a sensor arrangement that include 11 high resolution machine vision cameras and 10 illumination units, all designed for iFarm by BioSort AS. Light wavelength was fully controllable. The sensor housing also incorporated submersible machine vision computing and control electronics (see Figure 10).

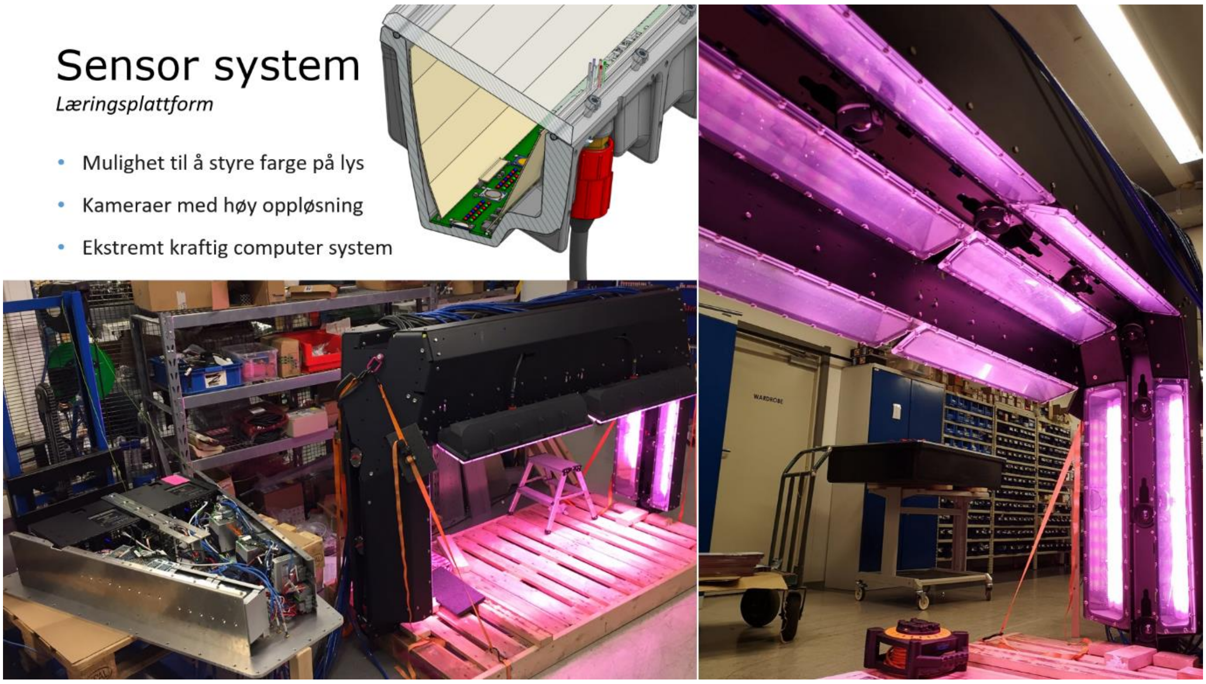


Figure 10 The sensor opening is designed as a learning platform to experiment with illumination and camera combinations. The sensor opening can also be seen in the photo from the installation of the Dome housing, shown earlier (Figure 8).

The remaining 3 openings in the Dome housing and 2 openings in the Saddle housing were equipped with the same type of sensors, but with illumination and cameras units only from above. The technical driver for this camera and illumination configuration was to provide BioSort AS with the capability to capture images of fish from above. Whilst there are numerous drivers for this, a primary driver is the ability to read fish tags that can help with the identification of individual fish later in Phase 1 testing and development. The valuable experiences gained during Phase 1 with regard to camera settings, illumination type, the depth of sensor as well as the camera arrangement and tests of the next iteration sensor will be applied in Phase 2.

Biological documentation Phase 1

Fish health monitoring

The purpose of Cermaq Norway's fish health monitoring plan is to ensure good fish health. This plan was applied throughout Phase 1 for the associate cage and the corresponding iFarm systems. Via close monitoring, Cermaq and BioSort AS wanted to detect possible situations that may reduce fish health and/or welfare at an early stage. Compared to regular farming cages, the fish in the iFarm system have reduced/smaller openings to the surface. The purpose of fish health monitoring was therefore to assess the extent to which this affected the fish in the iFarm system.

The health of the fish was monitored in two ways:

1) As a part of daily operations all relevant production parameters were registered daily. This included environmental parameters, feed consumption, mortality, growth (and sea lice weekly). There was also daily camera surveillance and recording of fish behaviour at multiple depths within the systems (iFarm 1, M10 and iFarm 2, M11).
2) The fish health situation at the farm was followed up with monthly fish health visits by authorized fish health personnel. For a detailed description on the fish health situation in the iFarm units, see the fish health report (attachment 3, not public).

Fish health, from a production perspective, was generally good in both the associate and iFarm cages. Over the winter during early 2021 there was an increase of wounds, most likely winter ulcers in all cages at Martnesvika, and ulcers were the main driver for mortalities in late winter/early spring 2021, especially in the iFarm cages. Piscine orthoreovirus 1 (PRV-1), the causative agent behind HSMI was also detected in 6/20 samples on April 22nd, 2021. HSMI was also detected in 5/5 samples in July 2021. Macroscopic scoring of gill status reported no fish with moderate/severe gill problems in the iFarm cages for the majority of the sampling OWI scoring events but it was observed in ca. 25% of fish in the associate cage in August 2021 and < 10 % of fish (all cages) in November 2021. Histopathological examination of the gills from the May, September and November 2021 and November 2021 -January 2022 sampling points are outlined below.

Fish welfare monitoring

The purpose of fish welfare monitoring was to document the welfare of the fish in the iFarm systems (M10 and M11) and the corresponding associate cage (M9). Following on from the health monitoring program outlined above, with the use of detailed and on-hand monitoring of fish welfare, Cermaq Utvikling AS and BioSort AS wished to detect possible situations that may reduce welfare at an early stage. The welfare monitoring program utilised a suite of OWIs (Operational Welfare Indicators) and LABWIs (Laboratory-based Welfare Indicators) based upon the environment the fish were subjected to (input-based OWIs) or the fish themselves (individual or group level outcome-based OWIs and LABWIs).

Environmental Operational Welfare Indicators

Input based environmental Operational Welfare Indicators, OWIs (Dissolved oxygen, DO and water temperature) were monitored at three depths in both iFarm cages and the associate cage. DO saturations were generally over 80 % for the entire reporting period and did not drop to levels that are sub-optimal in relation to water temperatures the fish were exposed to during the reporting period (Remen et al., 2016). Water temperatures at all depths in all cages dropped from a ca. 13 ° C peak in mid-September 2020 to a ca. 2 °C low in mid-March 2021. From Spring 2021 temperature then increased steadily to 14 °C by July/August 2021 before decreasing again steadily to ca. 5 °C in February 2022.

Morphological Operational Welfare Indicators

Morphological OWIs were followed closely throughout Phase 1 using the Cermaq Welfare Scoring protocol for scoring 11 external parameters according to a 0-3 scale. Particular attention was paid to OWIs that are especially applicable to snorkel cages (snout damage, skin damage and fin damage, after Stien et al., 2016a and Oppedal et al., 2019). In general, no major differences were found between the range of OWIs measured in each cage for the duration of the reporting period. Snout damage levels exhibited seasonal trends and were generally comparable between cages. For example snout damage i) increased during autumn and winter 2020/2021, ii) decreased during the summer 2021, before iii) increasing again during autumn and winter 2021/2022. It was generally the case that no fish had severe snout damage in either of the iFarm or associate cages and when they did it was a minor percentage of fish and no clear cage trend was apparent. Levels of scale loss and fin damage were generally similar between the iFarm and the associate cages. In general, no fish had severe scale loss in either of the iFarm or associate cages for the majority of Phase 1 and when they did it was a minor percentage of fish with no clear link to a particular cage. Only minor percentages of fish exhibited severe fin damage until late summer 2021 and these low levels increased in all cages during November 2021 following two (mechanical and bathing) de-licing events in autumn 2021. The prevalence of moderate skin haemorrhaging increased in all cages as Phase 1 progressed and a small number of fish exhibited severe skin haemorrhaging at the end of the May 2021 in both the associate and iFarm cages. Moderate skin haemorrhaging then markedly decreased for the rest of Phase 1 and no further fish were observed with severe levels of skin haemorrhaging. Opercular damage was generally low from September 2020 until February 2022, irrespectively of cage and in several sampling events there were no fish with opercular damage for the entire Phase 1 period. The only exception to this was the associated cage in August 2021, where the incidence of opercular damage increased. Interestingly this opercular damage also coincided with severe gill damage at the same time. By November 2021 the incidence of opercular damage decreased in the associate cage and also appeared in the other cages at this time. The rare incidences of cataracts were generally mild and not linked to a specific cage throughout the Phase 1 period. Incidences of other types of eye damage were generally very low from September 2020 until March 2021, peaked in May 2021 where the incidence of mild eye damage increased in all cages, especially in the associate cage compared to the iFarm cages. By July 2021, no fish exhibited eye damage, but in August 2021 damage frequencies increased in all cages.

Fish Behaviour

Fish behaviour is a valuable indicator for assessing fish welfare and was closely followed in Phase 1 using a suite of behavioural OWIs and LABWIs (Laboratory-based Welfare Indicators). There was a marked decrease in fish surface activity when the sensor houses were mounted in the iFarm cages, revealing a reluctance for the fish to utilise the snorkel after this event. Whilst fish in the iFarm cages may require some time to get used to the new sensor house structures on top of the docking station and may either not know how to swim though it or be reluctant to do so, the drop in surface activity was consistent for a prolonged period and also differed between cages. Removal of the sensor house from iFarm cage 2 in May 2021 did not have a marked impact upon fish surfacing activity. However, in the period July – mid-August 2021 where water temperatures were at their greatest, surface activity increased dramatically in both cages (to pre-sensor house deployment levels) but again was higher in iFarm 2 in comparison to iFarm 1 and remained high until mid-September 2021, irrespective of whether the sensor house was deployed (iFarm 1) or not (iFarm 2). After this point, surface activity decreased in both iFarm cages. During the period the sensor houses were mounted in both the iFarm 1 and iFarm 2 cages until May 2021, jumping activity did not appear to vary markedly between the iFarm cages or different iterations of iFarm development within each cage. However, some modifications of the dome sensor house in iFarm 1 when it was first mounted increased surface activity to levels similar to that seen in iFarm 2. When comparing surface activity in the iFarm cages to other studies on standard and snorkel cages, surface activity frequencies the iFarm cages are somewhat similar (see Dempster et al., 2008; Dempster et al., 2009; Wright et al., 2018; Oppedal et al., 2019).

There was an increased aggregation of fish in the snorkel of the iFarm cages until ca. mid-April 2021 in both iFarm cages. The rate of increase in fish number within the snorkel was slower in iFarm 1 than the iFarm 2 cage. The drivers for this are unclear, especially as fish were fed below the snorkels at either 10 or 15 m deep (for iFarm 1 and 2, respectively). These aggregation levels remained relatively stable in iFarm 1 until June, before gradually to the start of July 2021. Numbers again increased in July, before abruptly dropping for the remainder of Phase 1 monitoring. In iFarm 2, fish numbers in the snorkel had already began slowly decreasing in May 2021 and continued to do so for the remainder of the monitoring period. Fish aggregations did not seem to have a detrimental effect upon oxygen saturation levels at 3 m deep which were generally above 80 %. Higher numbers of fish in the snorkel during the late winter months may have contributed to the increased frequency of ulcers/wounds in the iFarm cages during this time. Further investigation of this is required.

No tilt angle swimming behaviour was observed that could be indicative of buoyancy problems in the fish. Swimming speeds below the snorkel were generally lower in the iFarm 1 cage (M10) compared to iFarm 2 (M11) before the sensor was mounted. Swimming speeds were mostly matched between iFarm cages after sensor mounting and dropped at all time points in both cages from mid-May onwards until the end of the reporting period. Fish swimming below the snorkel depth in iFarm 2 had both a steeper net roof and a reduced cage volume at the observation depth than fish iFarm 1 and this may have affected how their swimming dynamics at the start of Phase 1. Oppedal et al., (2017) reported no effect of differing snorkel depth on swimming speeds. Another study has reported no clear and consistent differences in swimming speeds between fish held in snorkel and control cages (Stien et al., 2016) whereas a further study by Oppedal et al., (2019) reported that fish can swim 1.14 times faster in snorkel cages than controls. However, if changes in swimming speed are minor, our operationalised scheme may be a little too crude to pick up these differences when compared to other methods (such as swimming speed expressed as body lengths per second). Group cohesion below the snorkel were generally lower in the iFarm 1 cage (M10) compared to iFarm 2 (M11) before and after the sensor was mounted. This trend may again have been related to net geometry - fish swimming below the snorkel in iFarm 2 were swimming in a cage with a steeper net roof and a reduced cage volume at the observation depth than fish iFarm 1 and this may have meant fish schooled more tightly than the other iFarm cage.

No marked differences in daily feed delivery were observed between the associate, iFarm 1 or iFarm 2 cages for the majority of the reporting period and daily activity scoring of fish at the start and end of feeding was generally scored as normal by the Cermaq feed staff.

Mortalities

When mortality data is benchmarked against historical data from all farms in Martnesvika's corresponding farming region (P09) (Grefsrud et al., 2021) overall mortalities could be classified as low. When mortalities were also benchmarked against mortality levels in the Cermaq Welfare Scoring protocol, weekly mortalities remained consistently within Level 0 from the beginning of Phase 1 until the mechanical and bathing de-licing events in Autumn 2021. Weekly mortality levels then remained in Level 0 until the fish were slaughtered. However, cumulative mortalities were higher in the iFarm cages (even though they were within Level 0), especially in iFarm 1 from April 2021 onwards until and following de-licing. Whilst a distinct number of mortalities in each cage could not be attributed to a specific cause, handling associated with de-licing was the primary identified driver for mortalities in all cages, especially in the associate cage and iFarm 1. Wounds were the second highest known driver for mortalities, both related to common winter ulcers and also sores potentially due to contact/mechanical injuries. There were more wound/ulcer related mortalities in both iFarm cages than in the associate cage. Ulcerative disease disorders are problematic in salmon farming especially when water temperatures are low (< 7 °C, MarinHelse, 2018). They can be drivers for mortality and causative agents are suggested to be multifactorial, including pathogens (*Moritella viscosa, Tenacibaculum* spp. and *Aliivibrio (Vibrio) wodanis*) and mechanical trauma (e.g., MarinHelse, 2018; Nilsson, Stien, Iversen et al., 2018; Sommerset et al., 2021). Whilst the increased mortalities due to winter ulcer in the iFarm cages may simply be due to unfortunate infection dynamics in and around the iFarm cages, it cannot be discounted that potential mechanical trauma e.g., the fish coming into contact with the sensor house, or the increased fish aggregations in the snorkel in late winter/early spring 2021 may be a driver for developing ulcers. Mortalities attributed to HSMI/CMS also increased during late spring 2021 reporting period and Piscine orthoreovirus 1 (PRV-1), the causative agent behind HSMI was detected in 6/20 samples on April 22nd, 2021. In autumn 2021, mortalities attributed to HSMI/CMS also increased during the month following the de-licing events in iFarm 1.

Gill and Heart Histopathology

Gills and hearts were histopathologically examined from May 2021 until slaughter to investigate if the elevated mortalities observed during the late winter/early spring period in the iFarm cages could be related to deviating fish health. As evaluated from the histological gill score, fish in iFarm 1 had a higher gill score than fish from the other two cages in May 2021, and more so compared to the associate cage. The gill score of iFarm 1 was lying on the borderline between mild and moderate changes, and the changes observed can be expected to have mild to moderate effect upon gill function. From the qualitative evaluation, it appears various particles in the water and zooplankton and non-planktonic stages of sea lice could have contributed to the higher score in iFarm 1. During the period up to September 2021 all cages showed no to minor pathological changes, which is an improvement for the iFarm cages. iFarm 2 showed a slight increase at the terminal sampling point prior to slaughter in November 2021 with no to moderate changes. At the terminal sampling points prior to slaughter of iFarm 1 and the associate cage in January and February 2022 respectively, the gill score continued to remain at no to minor changes.

For the histological heart score in May 2021, the same score distribution was seen with the highest level in the hearts of fish from iFarm 1, followed by iFarm 2 and the associate cage. By September 2021, iFarm 1 was still scoring highest, followed by equal scores in the associate cage and iFarm 2. All cages improved in heart score by their end points prior to slaughter. Observed histological changes in the heart in terms of general heart inflammation appeared typical for HSMI, which coincides with the diagnosis reported in the fish health report. Cardiovascular performance is important for fish health, and it seems likely that lesions observed in the gills and in particular the hearts can at least in part have contributed to increased mortalities. This was reflected in the elevated mortalities at certain periods of the production cycle that were attributed to HSMI/CMS especially in the period July-September 2021 (all cages) and also in November 2021 (iFarm 1).

Vertebral deformities

Vertebral deformities were monitored from x-ray images from May 2021 until slaughter. Deformities were observed in all three cages at both sampling points. The recorded lesions were comparable to the common types of pathology which are typical for farmed salmon in recent years. There were no apparent differences in type and prevalence of deformities between cages, except for a higher prevalence of cross-stitch pathology in the associate cage. Fusions are the most common type of lesions in farmed salmon and may be found in variable numbers and sizes in most harvest groups of salmon. In this material, the prevalence of fusions was between 7.5 % and 17.5 % in May 2021, and between 10 % and 20 % at termination. Most fusions were small, and probably without consequence, either for fish welfare or product quality. Cross-stitch vertebrae were found at termination, but not in the earlier sampling in May 2021. This corresponds well with current knowledge about this condition, which is that cross-stitch pathology gradually becomes visible on X-ray only as fish grow past 1 – 3 kg in size. The seemingly higher prevalence of cross-stitch pathology in the associate cage may result from the fact that these fish were more than 6 kg at the time of slaughter, compared to ca. 3.9 kg and 3.3 kg in iFarm 1 and 2, respectively. A third type of pathology which is not uncommon in farmed salmon is signs of reduced mineralization, in the form of compressed vertebrae, platyspondylia (Kvellestad et al., 2000). This appeared not to be a problem in the fish groups in Phase 1. In summary, the findings from Phase 1 do not indicate any relation between the different cage environments and vertebral deformities.

Sea Lice Monitoring

After smolt transfer in 2020 there were generally low sea lice levels in the fjord system. Sea lice infestation levels were generally low throughout the first half of Phase 1 for the associate and iFarm cages and required two Slice interventions for two weeks from 8th November 2020 and 2nd June 2021. Lice were observed in the iFarm systems earlier than anticipated in October 2020, which is most likely because the lice skirts weren't installed from the start. There was an increase in lice pressure between week 30 and 42 in 2021, and the associate and iFarm cages were treated with a mechanical de-licing treatment (12-17th September 2021) and a bathing treatment (11-13th October 2021). In comparison, the remainder of the cages at Martnesvika had a total of two slice treatments (November 2020 and June 2021), three mechanical de-licing events (August, September, and November 2021) and one bathing treatment (October 2021). All cages were subjected to continuous submerged artificial lighting and the fish in the iFarm cages were fed via submerged feeding systems at either 10 m (iFarm 1, M10), or 15 m (iFarm 2, M11) depth; a previous study has suggested both of these strategies are beneficial for preventing sea lice infestations (Frentzl et al., 2014). Differing snorkel depths in this study did not affect the number of de-licing treatments. Whilst a previous study has shown that snorkel depth alone can affect lice infestation levels, with deeper snorkels decreasing infestation pressure (Oppedal et al., 2017), the data reported in Phase 1 cannot be compared to this study as the cages are a combination of lice skirts and snorkel.

Production Performance Monitoring

Overall growth performance, condition factor and feeding efficiency at the end of Phase 1 were lower than desired in the iFarm 1 and iFarm 2 cages. There may be numerous drivers for this poorer performance and it is difficult to differentiate between them as both the cage design and feeding systems differed between the associate and iFarm cages. Firstly, with regard to cage design, the associate cage had a 11 m deep snorkel with a circumference of 90 m at the surface, whereas the iFarm cages had snorkels starting at either 10 m or 15 m deep and each snorkel had a circumference of 44 m at the surface. Secondly, the associate cage was fed at the surface and only the iFarm cages were fed using submerged feeders. Thirdly, this is the first time submerged feeding has been used in Cermaq and whilst feeding was initially better than expected in the first half of production with the submerged feeding system, one of the biggest challenges when the fish grew bigger was to find a way to distribute the feed better. A solution to this was not found in Phase 1, and the desired growth was not reached in the second half of production. As a result of this experience, the feeding system has been changed before Phase 2 and 3 of the project, where all cages will be fed using underwater feeding systems. Whilst fish were slaughtered at differing time points, meaning direct comparisons between cages in terms of slaughter weight is difficult, growth performance was poorer in the iFarm cages than the associate cage and accumulated TGC values at slaughter were higher in the associate cage, than either of the iFarm cages. This trend was also reflected in condition factor and eFCR. Condition factor at the end of the Phase 1 reporting period was higher in the associate cage, than for iFarm 1 and iFarm 2. Whilst condition factor was lower in the iFarm cages than the associate cage, mean condition factor values in all cages were higher than the threshold considered to indicate emaciation in Atlantic salmon post-smolts (> 0.9, Stien et al., 2013). Condition factor in this study was also similar or higher than that reported in other studies on snorkel cages. For example, Wright et al., (2018) reported a condition factor of ca. 1.15 in both snorkel and control cages. Oppedal et al., (2019) also reported that condition factor was ca. 1.25 in snorkel cages and this did not significantly differ from standard control cages in their study. Average eFCR values at the end of the Phase 1 production cycle were lower in the associate cage compared to the iFarm cages. As stated earlier, whilst the poorer production performance observed in the iFarm cages may have been linked to the comparatively poor feed management and distribution performance of the underwater feeding system, the effect of cage design/rearing system cannot be discounted.

Product quality control at slaughter found percentages of Superior fish to be generally similar across all cages in Phase 1, and were 86 %, 87 % and 94 % in the associate cage, iFarm 1 and iFarm 2, respectively. The remaining fish were downgraded to Production grade and the dominant proximate driver for downgrading was ulcers. The prevalence of ulcers is generally higher during winter, and the different cages being slaughtered during different weeks between December and March, and at different water temperatures, may explain the variation between them. Melanin sports found were within the reported average in Norway, except for iFarm 2 which was slightly above. The reported levels for the iFarm and associate cages were somewhat higher than the average for Cermaq Nordland. The proportion of fillets with melanin spots in Norway in 2014 was reported to be 19 % on average (Mørkøre et al., 2015).. Whilst the aetiology of melanin spots is difficult to determine and can be linked to handling and/or smolt robustness, both Bjørgen et al., (2019) and Malik et al., (2021) have reported that Piscine orthoreovirus 1 (PRV-1), the causative agent behind HSMI, has been related to their occurrence. The fish in iFarm 2 were markedly more affected by mortalities related to HSMI prior to slaughter and this may explain the variation and the higher occurrence in this cage both in terms of spot frequency and severity.

Samarbeidspartnere

BioSort

Nofima