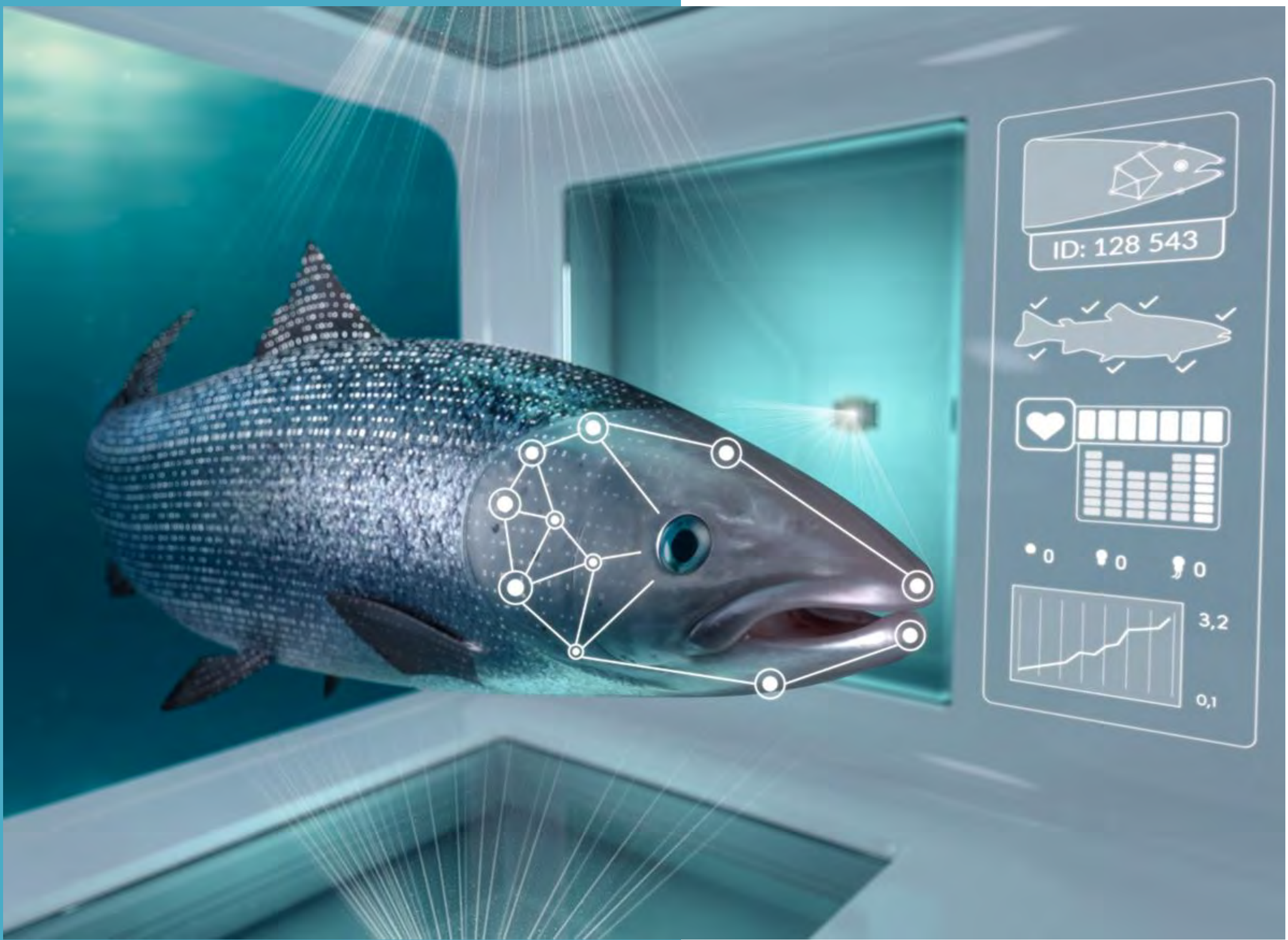
CERMAQ

iFarm: Final report documenting the biological and technological results at midway Phase 4 – Cermaq Norway AS avd Langøyhovden



Cermaq Norway

03.06.2024

Table of contents

Summary

The iFarm aquaculture concept, being developed by BioSort AS in partnership with Cermaq Norway AS was granted four development licences by the Norwegian Directorate of Fisheries in June 2019. The objective of the project is to develop an advanced prototype of iFarm to evaluate the feasibility of future commercial product development. This has been successfully done in phase 1-3 in the project where prototype A and B was developed, while the first production version 0 development was initiated in phase 4. The iFarm concept 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 emaciation status or lethargy status, their wound prevalence/severity and also their morbidity status.

The iFarm development licences in Phase 4 consisted of 5 cages. Four phases of the iFarm project are underway from 2020-2024. This report addresses Phase 4 from when the first cages were stocked on the 25th April 2023 until 31st January 2024. Spring 1-year smolts were stocked in two periods: a) 25th April 2023 (M9 – M10) and b) 4th May 2023 (M6 – M8). Fish in all cages were from a pooled hatchery AquaGen QTL-Innova SHIELD stock from Cermaq Norway AS hatchery 1. Cages M7 and M8 were stocked into cages with iFarm equipment, and M6, M9 and M10 were placed in open cages from the start. A large net docking was installed in cages M9 and M10 on 3rd November 2023.

This report 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, 2022).

The drivers for this stagnation are wide-ranging and multi-factorial, and also manifest themselves in other Atlantic salmon production regions around the world (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, the potential genetic and ecological impacts of escaped farmed fish upon wild stocks amongst others (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 its 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 innovation 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 being 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 prototype B production system consists of an adapted snorkel cage that holds fish 12 m 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 6 meters. Atlantic salmon must access the water surface to refill their swim bladder with air and have the opportunity to do so by swimming up through the snorkel to the surface (see Stien et al., 2016a). The aim is that each time the fish swims to the surface it must pass through the iFarm sensor which will then identify it and measure various performance, welfare and health parameters.

The iFarm development licence Phases 1-4

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 health and welfare monitoring was carried out to initiate the first full-scale "proof of concept" for the iFarm system. This testing was 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 snorkel cage at the same farming site. Phase 2 involved full scale testing of eight adapted iFarm cages and one associate cage from the first stocking of fish in May 2021 until the slaughtering of the last cage in February 2023. All cages in Phase 2 were fed using adapted underwater feeding systems. Phase 3 involved full scale testing of nine iFarm and associate cages, from the first stocking of fish in June 2022 until the slaughtering of the last cage in January 2024. All cages in Phase 3 were fed using adapted underwater feeding systems. Findings on the testing of Phase 1, Phase 2 and Phase 3 of the system have been outlined in the Phase 1, 2 and 3 final reports, submitted to the Norwegian Directorate of Fisheries on 25th July 2022, 28th September 2023 and 16th May 2023, respectively.

This current report addresses the extended project activity progressing to midway Phase 4 reporting period of the iFarm development licence where development of production version 0 was initiated as outlined below.

Technical design and cage set-up Phase 4

Geographical location

This development concession was carried out at the Cermaq Norway AS Langøyhovden production site 68.48236^{o} N, 14.51975^{o} E (see Figure 1).

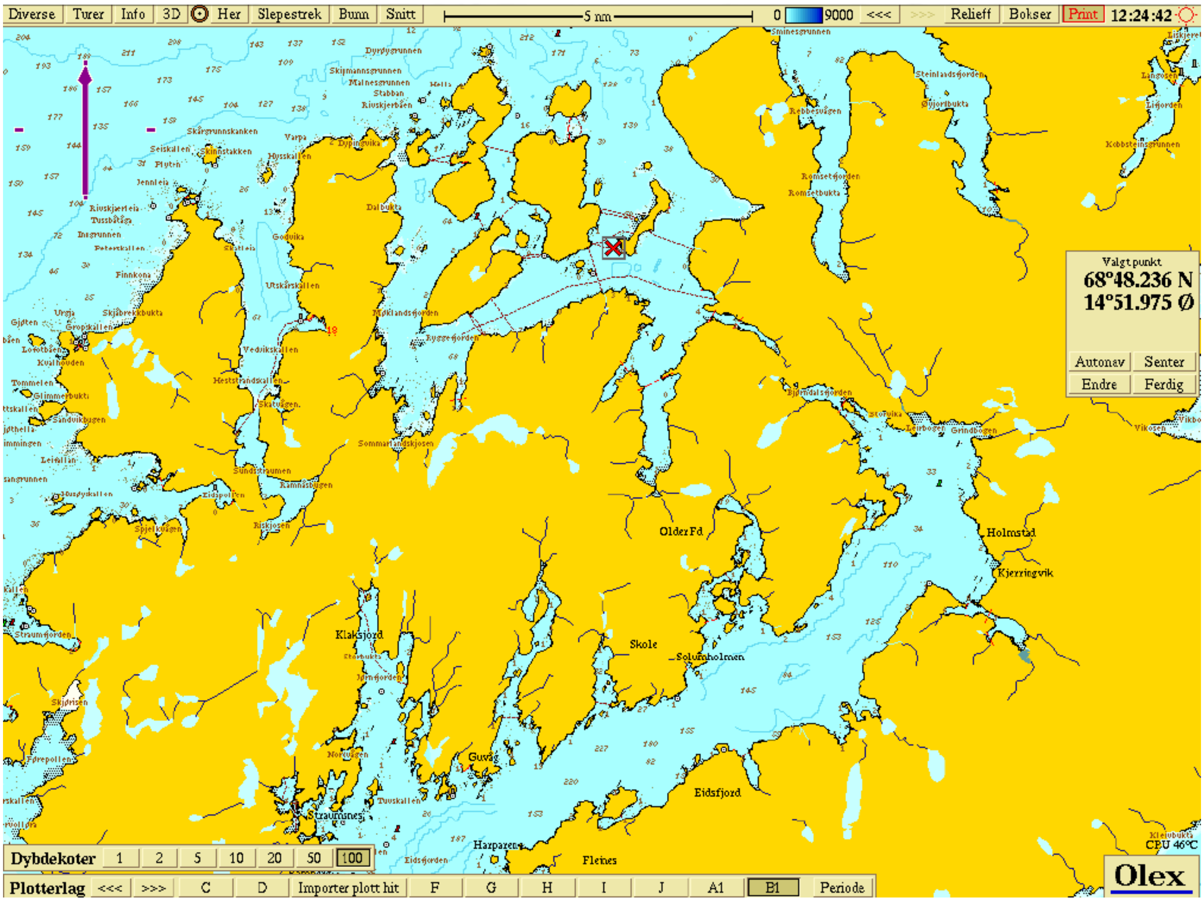


Figure 1 Map showing the Cermaq Norway AS facility Langøyhovden, where the iFarm cages are located (map location highlighted with a red boxed x). Map courtesy of Olex AS and reproduced from the Langøyhovden site report by Akvaplan-niva.

Phase 4 timeline and set up

Phase 4 of the project is currently underway and began when the fish were transferred to seawater on the 25th April 2023. Phase 4 used spring 1-year fish stocked in five iFarm and associate production cages at Langøyhovden, cages (M6-M10, see table 1).

Spring 1-year smolts were stocked in two periods: a) 25th April 2023 (M9 – M10) and b) 4th May 2023 (M6 – M8). Fish in all cages were from a pooled hatchery AquaGen QTL-Innova SHIELD stock from Hatchery 1. Cages M7 and M8 were stocked into cages with iFarm equipment, and M6, M9 and M10 were placed in open cages from the start. A large net docking was installed in cages M9 and M10 on 3rd November 2023. This approach aimed to investigate whether the duration of acclimatization to the sea environment prior to introducing the snorkel and net roof affected fish adaptation to the iFarm system.

Table 1 outlining the source hatchery, wellboat, date of stocking and cage destination of fish for iFarm Phase 4 at the Cermaq Norway AS facility Langøyhovden 11238. Also shown are water temperatures at time of transfer and fish size and stocking number.

Hatchery	Wellboat	Date of stocking	Cage	Mean water temp. at seawater transfer	Mean weight	Number stocked
Hatchery 1	BB Steigen	04.05.23	M6	5.2	88 g	160 651
Hatchery 1	BB Steigen	04.05.23	M7	5.2	102 g	139 267
Hatchery 1	BB Steigen	04.05.23	M8	5.2	77 g	143 578
Hatchery 1	M/S Dønnland	25.04.23	M9	4.6	115 g	168 257
Hatchery 1	M/S Dønnland	25.04.23	M10	4.6	119 g	174 995

Placement of the cages within the cage group at the Langøyhovden site is shown in Figure 2 below.

Figure 2 Figure showing the placement of the Phase 4 cages within the Cermaq Norway AS facility Langøyhovden 11238.

Daily operations and husbandry

iFarm follow the standard procedures for daily operations at the Langøyhovden site. Dead fish are removed from the cages daily using LiftUp. Moribund fish at the surface are removed from the cage every day and they are euthanised by an overdose of Benzoak vet. (30-40 ml/100l water). Lice are counted weekly by the farm personnel.

Net cleaning

Net cleaning followed the Langøyhovden 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 five times from stocking until 1st September (see Table 2) and the cleaning procedure included the cleaning of the main net, snorkel net and roof for iFarm cages, and the main net for the associate cages.

Table 2 showing the time of cage cleaning and service boat used.

Cleaning week	Service boat
2023 – 31	M/S Breidsund
2023 – 39	M/S Breidsund
2023 – 45	M/S Breidsund
2024 – 17	M/S Breidsund

Net changes

At Langøyhovden, Midtgard smolt nets (ScaleAQ) were used in all cages from the time of stocking. Cages M6, M7, M9 and M10 underwent a net change, where the smolt nets was changed to larger Midtgard post-smolt nets (ScaleAQ) in December 2023. The smolt net in M8 was not changed to post-smolt net in December because of bad weather and decreasing water temperatures. It is planned to change the net in M8 in May 2024.

Project plan

The iFarm project goals and objectives will be addressed over three phases, and with an additional fourth phase to supplement project data which will run until 2025 (see Figure 3 below). This final report addresses the first half of Phase 4.

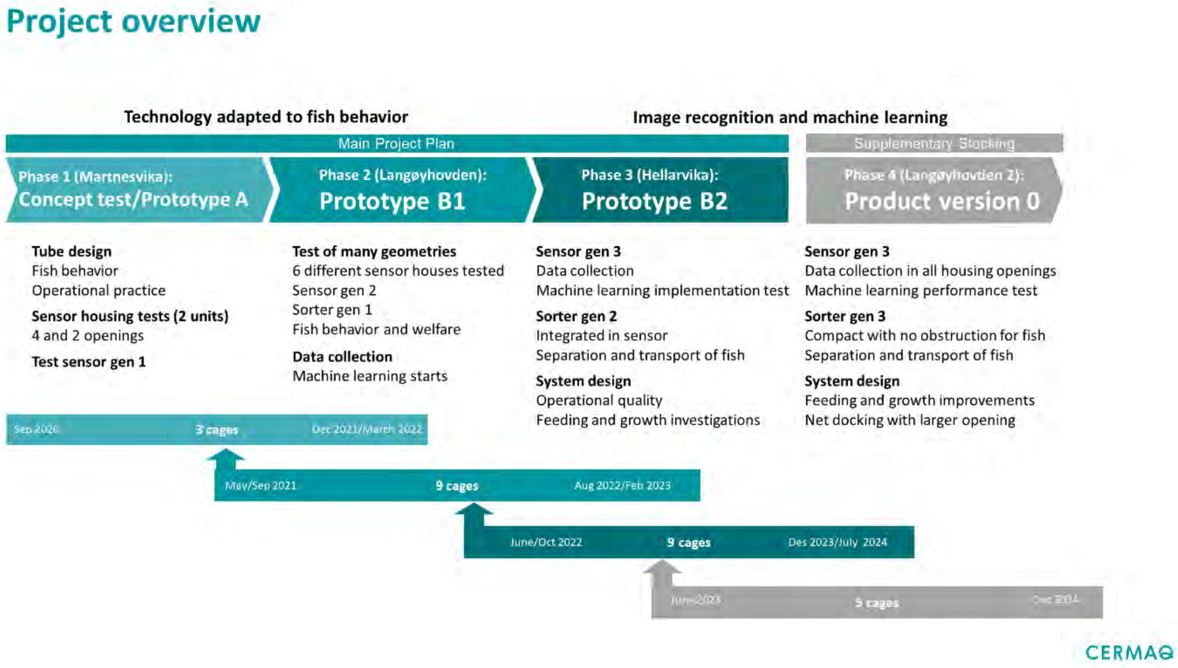


Figure 3 Overview of the iFarm project and Phase 1-3 timeline from 2020-2024, including the additional Phase 4 from 2023-2025. This report addresses the midway Phase 4 period from 25th April 2023 until 31st January 2024.

Cage design and rearing system characteristics

The iFarm production systems in Phase 4 were in principle equal to the previous generations with modifications of the net roof and snorkel depth. The snorkel depth is 12 meters below the water surface to limit fish interactions with potentially lice-rich surface waters. Unlike other snorkel cages, the snorkels themselves are not skirted and a commercial lice skirt (Permaskjørt, Botngaard) was therefore fitted around the edge of each iFarm cage structure to a depth of 6 m. The iFarm snorkel itself can have a variable depth between 3 and 7 meters and the docking station and iFarm unit is mounted at the narrowest point. The circumference of the snorkel at the water surface is 44m (see Figure 4a and 4b). Two cages, M7 and M8, were equipped with net dockings before stocking, while three cages M6, M9 and M10 remained open for the first months in sea before equipping them with net dockings during the autumn of 2023. The net dockings were tested in Phae 3 and continued in Phase 4 due to positive results in behaviour measurements. An important operational milestone in the project is the installation of net dockings in open cages M9 and M10 whilst fish were in the cage. Due to an error in the Midgard cage zipper in M10 the net docking was removed during delousing in December 2023 when nets were changed from smolt to post-smolt nets. Net dockings were also temporarily removed from pens M7 and M8 in January 2024 due to a jellyfish / fish health situation and have not been returned to the cages at the time of reporting. M7 had a net docking installed from

04.05.2023 to 14.01.2024, M8 from 04.05.2023 to 12.01.2024, M9 from 03.11.2023 to the time of writing, and M10 from 03.11.2023 to 01.12.2023.

The snorkels were placed 10m off center within the outer collar of the 160m circumference nets, which is the same placement as in Phase 2 and Phase 3. This placement facilitated boat-crane access and improved staff access to the iFarm collar. Each snorkel was equipped with anchors to allow for adjustable snorkel depth. The iFarm docking and house could easily be mounted and removed using six rope shackles. The docking was simplified compared to Phase 3 to a design without large pouches below the docking to house sorter elements and without structural pipes in the fish traffic area. M8 had a docking installed from 03.07.2023 to 02.11.2023.

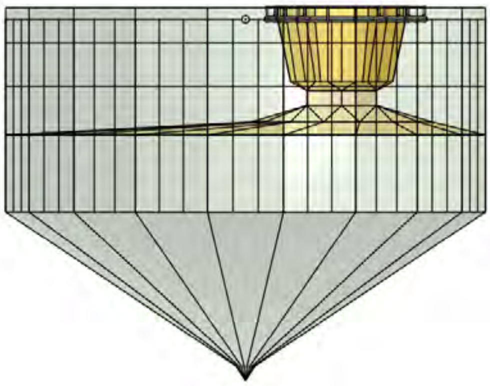


Figure 4a, side view of iFarm snorkel cage, named net docking.

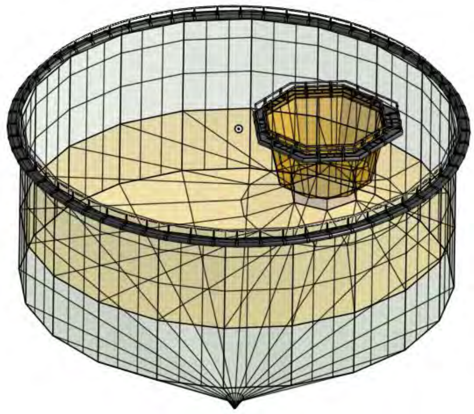


Figure 4b, ISO view of the net docking.

iFarm docking

The iFarm docking station is the structural connection between the net docking and the sensor house. The docking reduces the opening area from 45 to 15m² and its diameter from 7 to 4m. A new feature in iFarm version 4 is that nets are not sewn to the docking. Thus, the net docking can be installed alone and make up the net roof and snorkel structure while dockings for iFarm house installation can be mounted in the field using 6 heavy duty rope shackles. This significantly improves logistics, operations and HMS conditions compared to old iFarm designs (see Figures 5a-e, outlining technical specifications of the iFarm floater, net docking, bottom ring and docking stations).

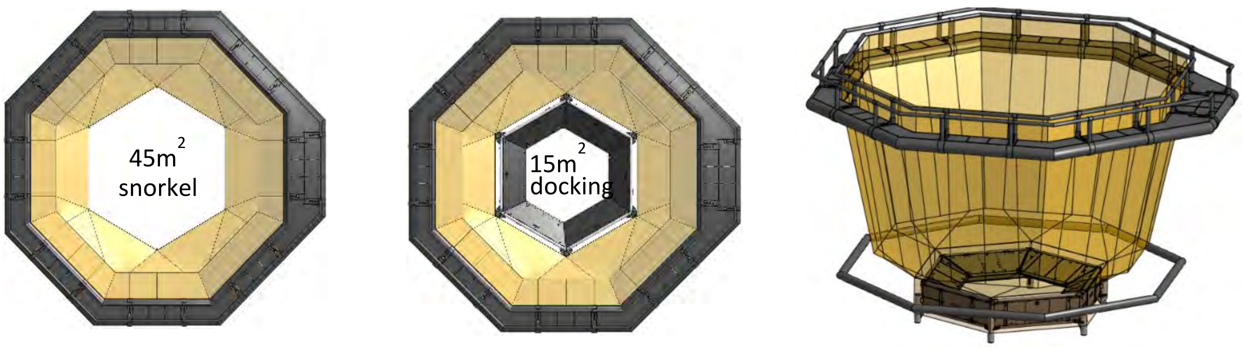


Figure 5a-c, iFarm floater and net docking opening, Docking mounted reducing the opening from 7 to 4m, iFarm floater, bottom ring, and upper part of net docking (net roof missing).

Figure 5d, Docking being lifted in the cage by a farm boat.

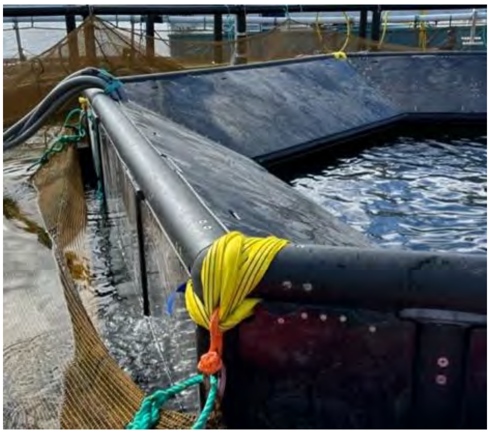


Figure 5e, Docking mounted with 6x 9T rope shackles.

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

To be able to monitor fish behaviour in and around each iFarm net docking, docking station and sensor house, especially in relation to system design choices, the iFarm units are equipped with 3 (in periods 6) surveillance cameras. These cameras are used to e.g., monitor fish traffic through the iFarm docking station, the number of fish in the snorkel above the docking station and the behavior of the fish immediately below the snorkel. The footage from these cameras was also supplemented with footage from the feeding cameras installed in each cage and with overhead cameras mounted on the inner snorkel ring and outer cage ring for e.g., monitoring fish surfacing activity (see Figures 6a-c). Video streams can be seen live by users through the BioSort product Argus.

IP cameras:
1 camera looking up into upper volume
1 camera looking down
1 camera looking across docking opening
1-3 cameras observing the housing openings
2 surface cameras
1 feed camera

Figure 6a IP camera box mounted on the net docking, which is later moved to docking when this is installed.

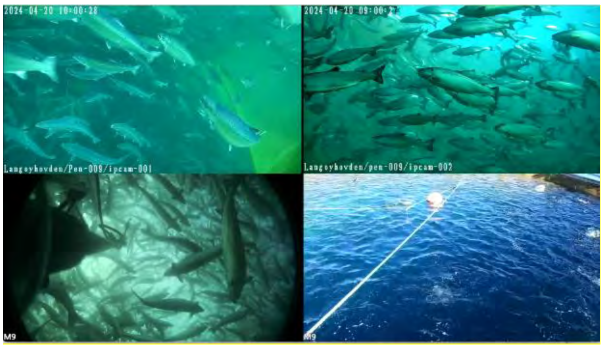


Figure 6b IP camera view with net docking.

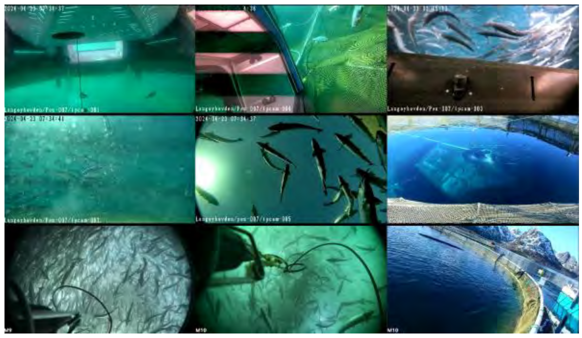
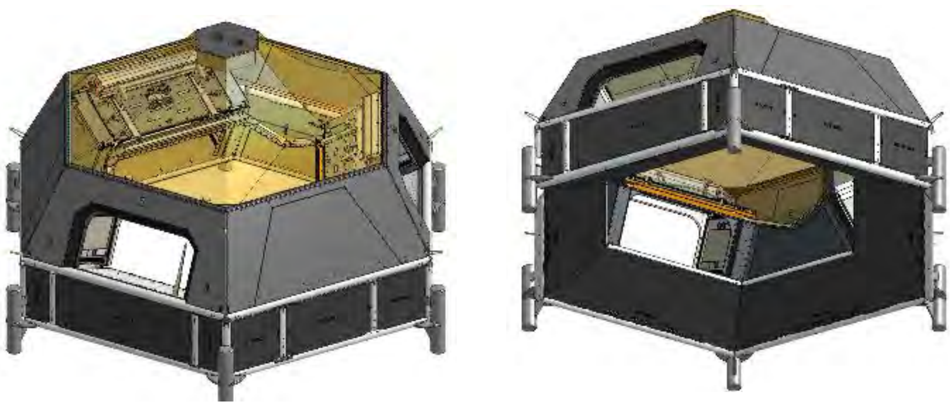


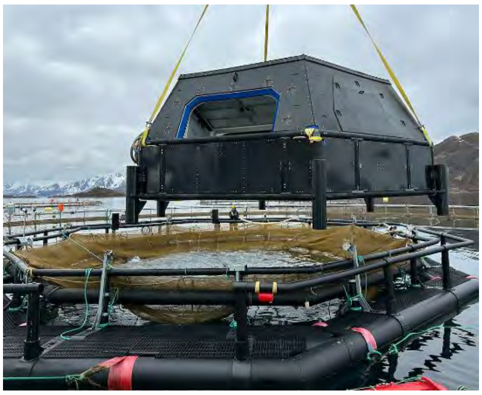
Figure 6c IP camera, feed and surface camera view with sensor house mounted.

iFarm sensor house

The sensor and housing prototypes A and B tested in Phases 1, 2 and 3 and the experiences with camera and light placement and settings in these designs was the foundation for the Product version 0 sensor and housing design in Phase 4. The house design used in Phase 4 resembles the design from Phase 3 but the diameter of the house was increased to 4m, compared to 3m in Phase 3, to make more space for the fish to move in and through the house. Sensors were mounted in all three house openings (dimensions 2x1x1m as in Phase 3) and facilitated complete population surveillance. In addition to the three openings with sensor arrangements, this house was designed with the option of opening three additional openings without sensors (“dummy” openings). Dimensions of these openings were 1.5x1x1m (see Figure 7 and Figure 8). Furthermore, feeding infrastructure became an integrated part of the iFarm house and feed was distributed through six pipes in each of the six edges (see Figure 9 c and d). To facilitate feeding surveillance, a channel for a feeding camera was designed in the middle of the iFarm house.



Figures 7 Sensor house and docking from side and bottom with sides with optional openings.



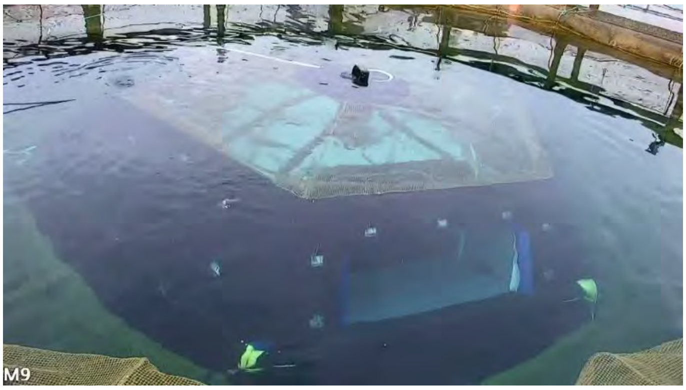


Figure 8 iFarm installed and submerged.

Mechanical structures and hardware of the camera system, lightning units and electronics are similar to the Phase 3 Hellarvika sensor but were improved in terms of reliability and serviceability. The updated sensor also featured custom-designed optics ensuring exceptional image quality across the entire field of view.

Feeding systems

Fish are remotely fed from the Sandset feeding center using existing Cermaq Norway AS feeding regimes for the Langøyhovden locality. All five cages at the site were fed by an underwater feeding system (AkvaGroup) that distributed water-borne feed via six feeding points. The feed distributer was either integrated in the iFarm house or, when the iFarm house was not mounted, is a customized version of AkvaGroup`s "Sjøstjerna" of two sizes, where the feeding points are distributed in a circle with 3m and 5m in diameter. The feeding arrangements used are shown in figure 9a-d. In the open cages M6, M9 and M10, the feeding arrangement was placed in the centre of the cage, while cages M7 and M8 with snorkels and which periodically had the iFarm house installed, they were placed 7-8 meter off centre due to the off centre placement of the snorkel. To secure good start feeding, the snorkel was mounted shallow and all feeding points were placed at 5 m where it was expected that the fish would find the feeding point more easily after stocking. The feeding arrangements were descended twice as the production progressed, first to 7.5m and secondly to 10m. Having the feeding point next to the entry point to the surface had a specific aim to stimulate traffic both up and down.

Fish were fed a commercial diet from seawater transfer utilising: i) Intro 100 HH 50mg Q, 4 mm ii) Intro 100 HH 50mg Q, 4 mm, iii) Power 200 F1 50mg, 4 mm iv) Power 500 HO3 50mg, 6 mm, v) Eco CQ N3 1200 50A, 7mm and vi) Eco CQ N3 1200 50A, 9 mm.

Figure 9a, iFarm feeding system in air.

Figure 9b, iFarm feeding system when mounted in a snorkel without iFarm house.

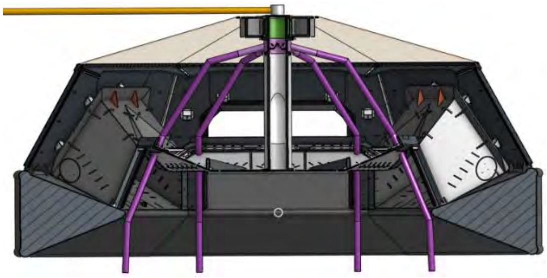


Figure 9c, iFarm feeding system implemented in the iFarm house.

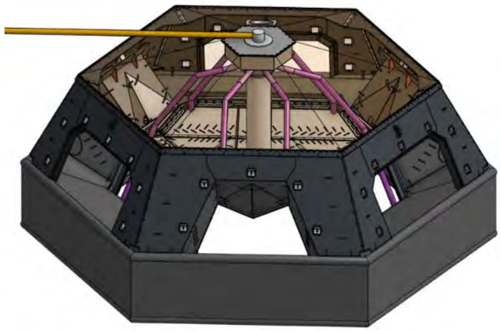


Figure 9d, iFarm feeding system implemented in the iFarm house.

Artificial lighting systems

Fish in each cage have been subjected to artificial underwater lighting using existing plans for Cermaq Norway. Under this plan, fish stocked before the 1st August have underwater lights from 1st November until 2nd May, and fish stocked after the 1st August have underwater lights on from stocking until the 1st May. Underwater lighting is provided via four underwater lights (AkvaGroup, Akva Aurora SubLED Combi) placed in the feeding zone, under the net roof at a depth of approximately 15 m (see Figure 10).

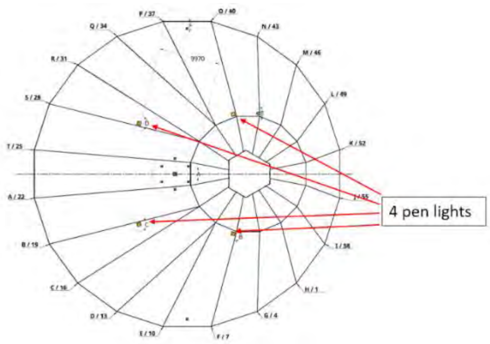


Figure 10, showing the position of lights within each cage.

iFarm sorter

The third-generation sorter has been successfully developed and built (Figure 11).

Based on experiences from Phase 3 was the third-generation sorter in Product version 0 updated with the following improvements:

- The five rigid walls from the second-generation sorter have been replaced with roller-curtain-like walls. Side walls enter from their resting position in the sensor sides and move in x-direction, while the centre wall is lifted in y-direction with grasshopper leg shaped mechanical arms on each side. This eliminates the need for extra space below the docking, resulting in a cleaner docking design.
- To avoid leaving a small opening at the top of the mid wall where fish can escape, but at the same time eliminate risk of damaging the lights with a potential wall collision, a soft rubber ledge is placed on the top of the mid-wall.
- The sub-optimal solution with shutter doors covering the suction channel during passive stage is replaced with a tract made of canvas material. This makes the guiding to the suction channel gentler with minimum mechanical impact.
- All surfaces are made smooth and gentle for the fish.

Sorter functionality has been tested and validated in air and seawater.

Comprehensive testing and tuning were carried out in air to ensure stable and smooth action for all moving parts, as well as stable and predictable sorting action, both activated manually and by computer vision control. Further, the sorter underwent so-called strain testing, meaning that the mechanical movements were repeated numerous times to ensure robustness and document potential wear and tear. The sorter was also submerged to ensure adequate stability and speed of all movements in the sea water environment.

Figure 11 3rd generation sorter opening with smooth opening for guiding fish into the transportation channel.

The 3rd generation sorter will be tested in a Cermaq commercial cage in June 2024 and an important goal of the test is to carry out data-driven autonomous sorting.

Developing of software infrastructure architecture and computer vision

From the initial computer vision algorithms in Phase 1 with basic image capturing, early versions of machine learning algorithms for simple fish detection and simple data handling frameworks to manage image storage and retrieval, the project has taken major leaps. Through Phases 1, 2 and 3, software infrastructure and computer vision models has greatly evolved and the focus in Phase 4 was to make infrastructure and computer vision models more robust, with improved accuracy and prepare for commercial deployment. The following list summarizes achieved functional requirements for the sensor:

- Image Capture and Real-Time Processing Pipeline: Optimized to run on the latest Nvidia GPUs. BioSort's edge pipeline supports multiple camera captures and simultaneously runs various computer vision algorithms, to make sorting decisions, and send health reports of individual fish to the data pipelines.
- Real-time Computer Vision Algorithms: Developed for the detection, segmentation, and 3D localization of fish; detection of lice and other welfare indicators; identification of individual fish; estimation of biomass, size, and growth rates.
- Large Data Handling: Implemented cloud storage solutions and data retrieval pipelines optimized for scalability and efficiency.
- Salmon Identification Service (SID): Utilizes an online clustering algorithm for identifying individual fish based on their unique dot patterns.

- Control Algorithms: Developed for sorter actions using custom actuator controls and automated subsea antifouling.
- Embedded Software: Manages all electronics, environmental sensors, power distribution, motors, lamps, and camera triggering.

The framework for all machine learning models was built in previous Phases of the project and the focus in Phase 4 was further improvements. The models can be summarized as follows (for more detailed description, see Phase 3 end report) and is visualized in Figure 12:

- Multi-camera image capture: groups images from different cameras captured at the same time together
- Fish head and bounding boxes: detects when and where a fish is in the image
- Fish instance segmentation: identifies the precise shape of the fish
- Fish tracker/multi view association: associate the same fish across several cameras
- Fish key points/stereo/biomass: detection of specific key points on the fish
- 3D positioning and tracking: triangulate the 3D position of key point location
- Biomass: estimate length and weight of the fish
- Aggregation: aggregate health information from different viewpoints
- Lice detection: detect lice of different stages; adult female lice, mobile lice and Caligus
- Welfare indicators: detect welfare indicators according to the Laksvel protocol
- Fish localization and tracking in 3D: uses key points and multi view to triangulate the 3D position of fish in the sensor
- Fish ID and the Salmon Identification service: identifies individual fish by the unique spot pattern and consolidates it with other detections (e.g lice, welfare, weight). This record goes into the so called “Salmon Identification Service” (SID), where it is related to previous records from the same fish. The complete health history of this individual is stored in the “Health Record Database”.

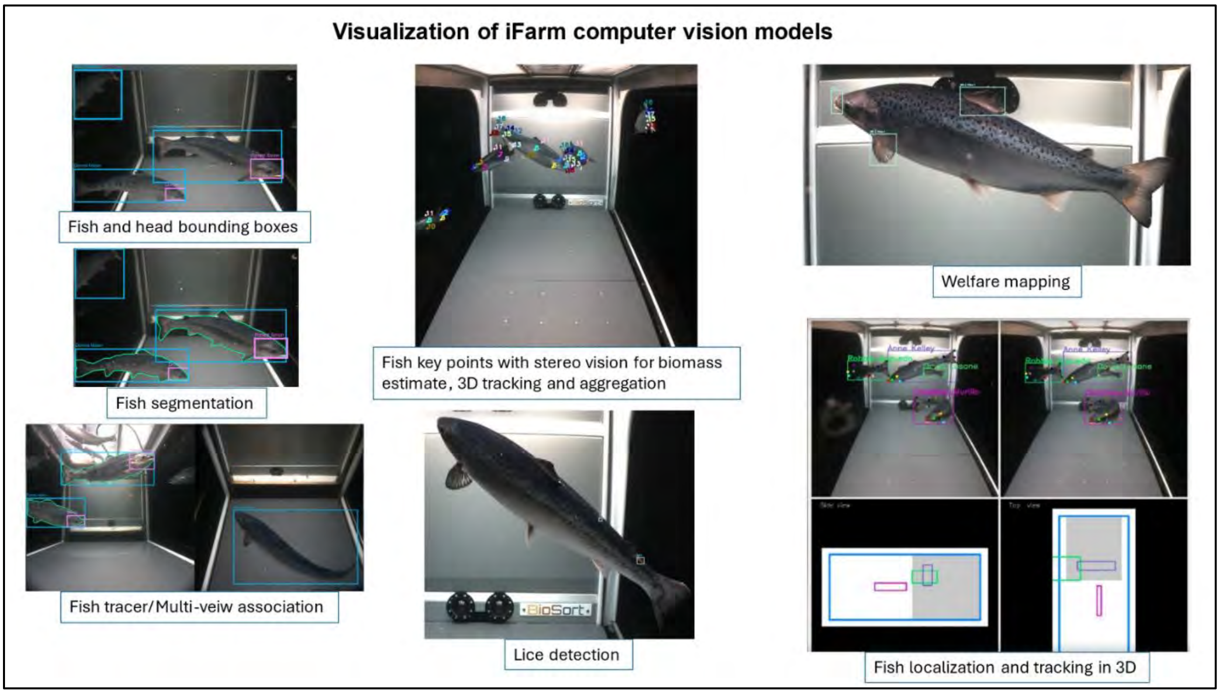


Figure 12 visualization of iFarm computer vision models.

The sophisticated software infrastructure developed in Phase 3 was enhanced in Phase 4 with the addition of a new element: a pipeline built to direct sensor data to a database, from which population statistics could be displayed for end users. The current dashboard displays average weight, weight distribution, lice number, prevalence of welfare parameters, and traffic through the sensors.

Fish health and welfare

Fish health monitoring plan

Cermaq Norway's fish health monitoring plan was applied throughout Phase 4 for the Cermaq Norway AS Langøyhovden farming site. Compared to regular farming cages, the fish in the iFarm system have reduced/smaller openings to the surface. The purpose of fish health monitoring is therefore to assess the extent to which this affects the fish in the iFarm system.

The health of the fish is monitored in two ways:

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

The welfare monitoring program utilises a suite of OWIs (Operational Welfare Indicators) and LABWIs (Laboratory-based Welfare Indicators) based upon the environment the fish are subjected to (input-based OWIs) or the fish themselves (individual or group level outcome-based OWIs and LABWIs).

Fish health and welfare monitoring

The fish health situation at Langøyhovden has generally been classified as good by fish health personnel, with low mortality and a low incidence of moribund fish throughout the reporting period. At the start of production there was increased stocking related mortality in the fish from cages M9 and M10. A few weeks after stocking, a Tenacibaculosis outbreak developed in M6 which lasted for three weeks. Over the winter, there was an increase in ulcers in all cages, and this was, in addition to treatment and handling, the main reason for mortality during the reporting period in these cages. Ulcer development may also have increased due to high levels of stinging jellyfish (*Apolemia uvaria)* at the site throughout winter. An increase in ulcers over the winter was also observed in Phase 1, Phase 2 and Phase 3. Ulcer developments are set as an important risk factor in the iFarm project. Screening and histology taken throughout this reporting period has shown Piscine Orthoreovirus 1 (PRV-1) and *Moritella viscosa* (winter ulcers).

Input-based OWIs

Dissolved oxygen saturation levels were generally over 80 % across the four reported depths of 5, 10, 15 and 25 m 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). This data is also comparable to that reported in Phases 1-3 of the development project. Fish were subjected to water temperatures ranging from a peak during summer 2023 at ca. 12 - 14°C. The lowest temperatures were recorded in January 2024 at ca. 2 - 4°C depending upon depth. It has been suggested that temperatures outside 6 – 17 ° C can present potential welfare challenges e.g., temperatures below 6 - 7 °C increase the risk of winter ulcers (Noble et al., 2018 and references therein). Whilst fish were subjected to temperatures below 7 ° C during winter, this is a challenge all fish faced in Phase 4, irrespective of the rearing system they were farmed in. It has previously been suggested that water quality in the snorkel can be compromised if there is e.g., a buildup of fish in the snorkel or restricted water flow into the snorkel. This was not the case in the iFarm cages.

Group-based OWI and LABWIs – Behaviour

Fish surfacing activity

In Cage M8, surface activity showed a general increase from July 2023 as summer and autumn progressed, reaching a peak in October 2023. It began decreasing before the standard docking was replaced with a net docking at the start of November 2023, and this decreasing trend continued for the rest of the monitoring period. In Phase 3 surface activity for the majority of cages increased as winter and spring progressed and summer approached. In phases 1 to 3 there was a trend for reduced surface activity during sensor house deployment.

Fish aggregating in the snorkel

It has been reported that fish can aggregate in the snorkel when held in snorkel cages and this may lead to reduced oxygen saturations in the snorkel (Kolarevic, Stien et al., 2018). Aggregation of fish in the iFarm cage snorkel did not seem to have a detrimental effect upon oxygen saturation levels at 5 m deep, which were generally above 80 %. This was also noted in Phases 1-3. There were some differences in the number of fish observed in the snorkel between the iFarm cages. In cage M7 there were slightly more fish in the snorkel when the sensor house was mounted than when it wasn't. However, these numbers were also similar to the numbers of fish recorded in the snorkel during the same time period in cage M8 that had only a net docking at that time. In general for cage M8, there appeared to be an low increase in the number of fish in the snorkel with. For cage M9, fish numbers in the snorkel were relatively stable during the deployment of the net docking from November 2023 until the end of the reporting period. As with other Phases of the project, increased winter aggregation of fish in the snorkel is considered a potential risk factor for ulcer/sore driven mortalities. A key lesson learned from the earlier Phase 2 was to act early on wound/sore developments, even if they are related to winter ulcer outbreaks, as increased fish number/density in the snorkel may be a risk factor for driving or exacerbating the problem. This monitoring approach continues to be adopted in Phase 4.

Fish traffic

The amount of fish traffic heading to the surface through the docking station/sensor house for the iFarm cages was somewhat similar that reflected in the surface activity data, increasing as summer and autumn progressed before decreasing from October/November 2023. As data was lacking in some time periods due to technical problems, the opportunities for inter-cage comparisons regarding the timing of sensor house deployment upon fish traffic are limited, but the limited data available suggests that the deployment of the sensor house on cage M7 led to somewhat decreased and less variable traffic in comparison to cage M9. In Phase 2, the reduced surface activity of the fish after sensor mounting was not always reflected in the traffic data through the docking station/sensor house, unlike in both Phase 1 and 3.

Swimming speed and cohesion

If fish are exhibiting problems with buoyancy, they can increase their swimming speeds to generate lift (Sievers et al., 2021). The swimming speed of cages M7 and M8 were generally either i) low/slow or ii) medium/cruising speed during summer and mostly stable medium/cruising speed for the rest of the reporting period, irrespective of cage configuration. The deployment of the sensor house in cage M7 did not have a marked impact upon swimming speeds, aside from a short term drop from medium/cruising to low/slow after deployment. Swimming speeds in Cage M9 were mostly stable medium/cruising swimming speeds during net docking deployment. This data was generally similar to other Phases of the iFarm project. Cohesion in cages M7 and M8 generally varied between mixed behaviours for the majority of the reporting period and uniform schooling over some observation periods in mid-winter. Cage configuration appeared to have no effect on this data. Cage M9 had a mix of mostly uniform schooling after initial net docking deployment, followed by a combination of loose schooling or mixed behaviours for the remainder of the reporting period. In Phase 3, some erratic swimming was observed when the sensor house was deployed in one cage but not the other. In Phase 2, swimming cohesion below the snorkel generally increased over time towards uniform circular schooling for the majority of iFarm cages, both for feeding and non-feeding periods, irrespective of whether the sensor house was deployed or not, with some minor exceptions. In Phase 1, different iFarm set-ups affected group cohesion in different ways. Group cohesion was generally lower in the iFarm cage with the 10 m snorkel compared to the 15 m snorkel cage, especially at night and during non-feeding periods. Cohesion during feeding in Phase 1 was similar for both iFarm cages irrespective of whether the sensor house was mounted or not.

Tilt angle

No tilted swimming behaviour > 25 ° was observed during daily observations by Cermaq feed staff. However, it should be noted that tilt angle was only documented from a limited viewpoint from feed cameras and was not documented at night.

Group-based OWI and LABWIs – Appetite

Daily Feed delivery

Fish were remotely fed to apparent satiation using existing Cermaq Norway AS feeding regimes for the Langøyhovden locality using mobile underwater feed cameras. No marked differences in daily feed delivery were observed between the associate open or iFarm cages for the majority of the reporting period. There also appeared to be no short-term drop in feed delivery (appetite) during the weeks immediately after the sensor house being deployed in cage M7 in comparison to either the open cage (M6) or the fish held with the net dockings (M8 and M9). Daily feed delivery for the 1+ smolts in Cages M9 and M10 that were transferred at a slightly higher smolt weight, was generally slightly higher than that of cages M6-M8 but showed a similar seasonal trend irrespective of whether a net docking was mounted or not. When comparing the effect of feeding depth upon perceived appetite: i) no inter-cage differences in daily feed delivery were apparent when fish were fed at 5m depth when cages M7 and M8 had a net docking, or ii) when the feeders were at 7.5m and cage M7 still had a net docking but cage M8 had its net docking changed to a standard one. After feeding depths were lowered to 10m, feed delivery was somewhat higher in cage M7 (net docking) compared to the period that cage M8 still had its standard docking.

eFCR

Estimated production results from Phase 4 suggest fish in all cages have a good and comparable appetite and similar economic FCR (eFCR). Estimated eFCR values for the fish at the midway point were within an acceptable range for all cages. Feeding is as expected with the new submerged feeding system.

Group-based OWI and LABWIs - Growth

TGC

Growth is also as expected with the new submerged feeding system. TGC values at the end of the Phase 1-3 production cycles were slightly lower in the iFarm cages compared to the associate cages. The difference in TGC between the iFarm cages and the associate cages has decreased throughout the Phases. In Phase 4, it was tested to place the feeding arrangement just below the narrowest part of the snorkel and hence 7-8 meter off center whenever a net docking was mounted in the cage (meaning 04.05.2023 to 14.01.2024 in M7, 04.05.2023 to 12.01.2024 in M8, 03.11.2023 to the time of reporting for M9, and 03.11.2023 to 01.12.2023 in M10). This was tested to evaluate whether it has an impact on traffic through the docking and to ensure good start feeding after smolt transfer. As well as placing the feeding arrangement off centre, feeding points were initially placed at 5 m where it was expected that the fish would find the feeding point more easily after stocking. The feeding arrangements were then descended twice as the production progressed, first to 7.5 m and secondly to 10 m. From Phase 3, this start feeding procedure seemed to have a positive effect and the same positive tendencies have been observed in Phase 4.

Group-based OWI and LABWIs – Mortality

Cumulative mortalities

Cumulative mortalities were generally low but a little variable during the Phase 4 reporting period. This is similar to Phase 3 and a marked improvement upon Phase 2, where the health situation in Phase 2 was often challenging, contributing markedly to mortalities in Phase 2, as did isolated delousing events. Cumulative mortalities in the Phase 4 reporting period are low. Cumulative mortalities in Phase 3 were also low for the iFarm and associate cages. In general, mortality levels in Phase 4 were similar to Phase 1 and 3, where cumulative mortality was generally low for both the associate and iFarm cages and was < 6% and less than in Phase 2 for the most part.

Cause specific mortalities

Mortalities in the open cage were primarily due to an outbreak of Tenacibaculosis in early summer 2023. Mortalities in the cage that had the iFarm sensor house mounted were primarily driven by wounds, especially after a handling incident associated with delousing in December 2023, the acute presence of stinging jellyfish (*Apolemia uvaria*) around the cages and also in relation to sensor house deployment. Mortalities in the cage where the net docking was replaced by a standard docking for a period of 4 months were primarily driven by HSMI and wound related mortalities. The drivers for the cages that were open until November 2023 before having a net docking mounted were primarily wounds, handling and transfer related. Fish in the cage that had the sensor house mounted (cage M7) had the highest percentage of mortalities attributed to wounds in Phase 4, both related to common winter ulcers and also sores potentially due to contact/mechanical injuries. The highest number of wound related mortalities were registered in the iFarm cage following a delousing incident and when the sensor house was deployed. In Phases 1 - 3, there were also more wound/ulcer related mortalities in the iFarm cages than in the associate cages. It appears 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 may be a driver for developing ulcers. Snorkel cleaning routines have also been updated in relation to potential mechanical trauma risks from biofouling organisms.

Individual based OWIs and LABWIs

Snout damage

No fish with severe snout damage were sampled from the open cage, M6 and small numbers were sampled in M7 when the net docking was mounted. In cage M8 the prevalence of severe snout damage slightly increased when the net docking was replaced with a docking and worsened again even after the docking was removed. In M9 and M10, severe snout damage was absent until January 2024 and affected between 5-10% of sampled fish. In Phase 3, severe snout damage was generally absent at all time points irrespective of cage type or time of year, with the exception of a low number of sampled fish at various timepoints. In Phases 1 and 2, 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.

Scale loss

Severe scale loss was generally most prevalent in cages M6 and M7 just after smolt transfer and decreased as time progressed. In cage M8, it was highest in the sampling just after snorkel removal in January 2024, and the same pattern was apparent for cage M10. In Phase 3, severe scale loss was often low at many time points irrespective of cage type or time of year. However, there was sometimes increased prevalence in some cages soon after smolt transfer or following mechanical delousing. In Phase 1, it was generally the case that 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. In Phase 2, there were sometimes cases of severe scale loss at various timepoints, especially in late winter/early spring.

Skin haemorrhaging

Skin hemorrhaging during the Phase 4 reporting period was generally absent or mild for each cage, irrespective of cage configuration or time point. This was also the case for Phases 2 and 3.

Fin damage

The number of fish with severe fin damage in cage M7 was most prevalent in the months after smolt transfer and in cage M8 it was highest when the standard docking was mounted. Otherwise, there were no clear trends in relation to cage configuration or time point. In Phase 3, severe fin damage was also often low at many time points irrespective of cage type or time of year. In Phase 2, the frequency was mixed and generally more severe than Phase 4. In Phase 1 only a minor percentage of fish exhibited severe fin damage until fish were subjected to mechanical delousing events.

Wound status

The numbers of fish sampled with active wounds was also generally absent or mild for most cages throughout the reporting period, irrespective of cage configuration or time of year. However, after the handling incident associated with delousing in December 2023 and when the sensor house was mounted in cage M7, the number of fish sampled with severe active wounds increased. There was no clear trend in the numbers of fish sampled with severe healed wounds throughout the reporting period, for most cage configurations or time point. However, it appears that in cage M8 the prevalence of severe healed wounds slightly increased when a docking was introduced into the net docking, and improved after this was removed. When considering wound status in relation to wound-linked mortalities in Phase 4 (see group-based OWI section above), wound related mortalities were highest in cage M8 following an incident related to delousing and when the sensor house was mounted for 1 month during winter in M7. In Phases 1 – 3 the least number of wound related mortalities were registered in the open cages. Adapted snorkel/iFarm production is a clear risk for wound development during late winter/early spring. It appears that potential mechanical trauma e.g., the fish coming into contact with the sensor house, or any incidences of increased fish aggregations in the snorkel in late winter/early spring (as seen in Phase 2) may be a driver for developing ulcers.

Condition factor

Condition factor at the end of October 2023 was comparable between all cages and are higher than the threshold considered to indicate emaciation in Atlantic salmon post-smolts (> 0.9, Stien et al., 2013). In Phase 3, cages with the large net docking mounted had a higher condition factor than open cages and cages with the iFarm sensor housing or just the iFarm docking installed. Condition factor levels of the fish in Phase 4 are also similar to the condition factors from Phase 2 and Phase 1.

Gill and heart status

Gill and heart pathologies from the sampling during periods where the sensor houses and snorkels were mounted were mainly absent or mild. Recent work has reported that fish farmed in snorkel cages can have more pronounced gill problems than fish produced in open cages (Oldham, 2023), we did not see the same trend in this Phase. However, gill health is followed closely in Phase 4.

Internal OWIs

Scoring of internal OWIs (digesta score, liver score, visceral fat score, nephrocalcinosis score) were carried out from July 2023 (T0) until January 2024 (T2). The digesta score revealed some fish with diarrhoea, cast and empty gut and the highest levels of these findings were seen in cage M8 just prior to the sensor house being mounted at T0 and also cages M9 and M10 at T0, which were open cages at the time of sampling. The situation improved as time progressed. Liver colour is a multifactorial iceberg indicator and its exact drivers need further scientific evaluation. Liver colour, especially a pale liver is associated with high fat accumulation (Mørkøre et al. 2020, Lutfi et al., 2023) and therefore nutritional disorders. A dark liver may be a sign of disease (MarinHelse, 2018). An orange liver (score 3) is here viewed as a sign of normal liver. Overall, liver colour scores were mainly normal, score 2 (light orange) and 3 (orange) in sampled fish during the first period of Phase 4 (from T0 to T2), with some exceptions at T0 across all cages where a small portion of fish had darker livers. Visceral fat levels were generally low (lean) at T0 and there was a minor increase from T1 to T2 across all cages, irrespective of cage configuration. Signs of mild calcification in the kidney (nephrocalcinosis score 1) were seen in all fish sampled at T0 (June 2023) and this is often an artifact from the hatchery phase. After this timepoint the levels of mild calcification dropped markedly by the next sampling period and decreased further by the last sampling in January 2024.

References

Føre, M., Frank, K., Norton, T., Svendsen, E., Alfredsen, J. A., Dempster, T., Eguiraun, H., Watson, W., Stahl, A., Sunde, L. M., & Schellewald, C. (2018). Precision fish farming: a new framework to improve production in aquaculture. biosystems engineering, 173, 176-193.

Hersoug, B. (2021). Why and how to regulate Norwegian salmon production? –The history of Maximum Allowable Biomass (MAB). Aquaculture, 545, 737144.

Hersoug, B., Olsen, M. S., Gauteplass, A. Å., Osmundsen, T. C., & Asche, F. (2021). Serving the industry or undermining the regulatory system? The use of special purpose licenses in Norwegian salmon aquaculture. Aquaculture, 543, 736918.

Iversen, A., Asche, F., Hermansen, Ø., & Nystøyl, R. (2020). Production cost and competitiveness in major salmon farming countries 2003–2018. Aquaculture, 522, 735089.

Kolarevic, J., Stien, L. H., Espmark, Å. M., Izquierdo-Gomez, D., Sæther, B. –S., Nilsson, J., Oppedal, F., Wright, D. W., Nielsen, K. V., Gismervik, K., Iversen, M. H., & Noble, C. (2018). Welfare Indicators for farmed Atlantic salmon: Part B–Fit for Purpose OWIs for different production systems. 2018). Welfare Indicators for farmed Atlantic salmon: tools for assessing fish welfare. 351pp, 146-237.

Lutfi, E., Berge, G. M., Bæverfjord, G., Sigholt, T., Bou, M., Larsson, T., Mørkøre, T., Evensen, Ø., Sissener, N.H., Rosenlund, G., Sveen, L., & Ruyter, B. (2023). Increasing dietary levels of the n-3 long-chain PUFA, EPA and DHA, improves the growth, welfare, robustness and fillet quality of Atlantic salmon in sea cages. British Journal of Nutrition, 129(1), 10-28.

MarinHelse (2018). Veileder i Dødfiskkategorisering. 101pp. Developed by MarinHelse AS, Tromsø. https://www.marinhelse.no/produkter/veilederdodfiskkategorisering/

Mørkøre, Turid & Moreno, Helena & Borderías, A.J. & Larsson, Thomas & Hellberg, Hege & Hatlen, Bjarne & Romarheim, Odd & Ruyter, Bente & Lazado, Carlo & Jiménez-Guerrero, Raúl & Bjerke, Målfrid & Benítez-Santana, Tibiábin & Krasnov, Aleksei. (2020). Dietary inclusion of Antarctic krill meal during the finishing feed period improves health and fillet quality of Atlantic salmon (*Salmo salar* L.). British Journal of Nutrition. 124. 1-40. 10.1017/S0007114520001282.

Noble, C., Gismervik, K., Iversen, M. H., Kolarevic, J., Nilsson, J., Stien, L. H. & Turnbull, J. F. (Eds.) (2018). Welfare Indicators for farmed Atlantic salmon: tools for assessing fish welfare 351pp.

Norwegian Directorate of Fisheries (2022). Statistics on Atlantic salmon and rainbow trout production accessed on 04.04.2022. https://www.fiskeridir.no/English/Aquaculture/Statistics/Atlantic-salmon-and-rainbow-trout

Oldham, T. (2023). Salinity and temperature alter the efficacy of salmon louse prevention. Aquaculture, 575, 739673.

Oldham, T., Simensen, B., Trengereid, H., & Oppedal, F. (2023). Environmentally responsive parasite prevention halves salmon louse burden in commercial marine cages. Aquaculture, 563, 738902.

Remen, M., Sievers, M., Torgersen, T., & Oppedal, F. (2016). The oxygen threshold for maximal feed intake of Atlantic salmon post-smolts is highly temperature-dependent. Aquaculture, 464, 582-592.

Sievers, M., Korsøen, Ø., Warren-Myers, F., Oppedal, F., Macaulay, G., Folkedal, O., & Dempster, T. (2021). Submerged cage aquaculture of marine fish: A review of the biological challenges and opportunities. Reviews in Aquaculture.

Stien, L. H., Bracke, M., Folkedal, O., Nilsson, J., Oppedal, F., Torgersen, T., Kittilsen, S., Midtlyng, P. J., Vindas, M. A., Øverli, Ø., & Kristiansen, T. S. (2013). Salmon Welfare Index Model (SWIM 1.0): a semantic model for overall welfare assessment of caged Atlantic salmon: review of the selected welfare indicators and model presentation. Reviews in Aquaculture, 5, 33-57.

Stien, L. H., Dempster, T., Bui, S., Glaropoulos, A., Fosseidengen, J. E., Wright, D. W., & Oppedal, F. (2016a). 'Snorkel' sea lice barrier technology reduces sea lice loads on harvest-sized Atlantic salmon with minimal welfare impacts. Aquaculture, 458, 29-37.

Young, N., Brattland, C., Digiovanni, C., Hersoug, B., Johnsen, J.P., Karlsen, K. M., Kvalvik, I., Olofsson, E., Simonsen, K., Solås, A. M., & Thorarensen, H. (2019). Limitations to growth: social-ecological challenges to aquaculture development in five wealthy nations. Marine Policy, 104, 216-224.

Collaborators

BioSort

Nofima