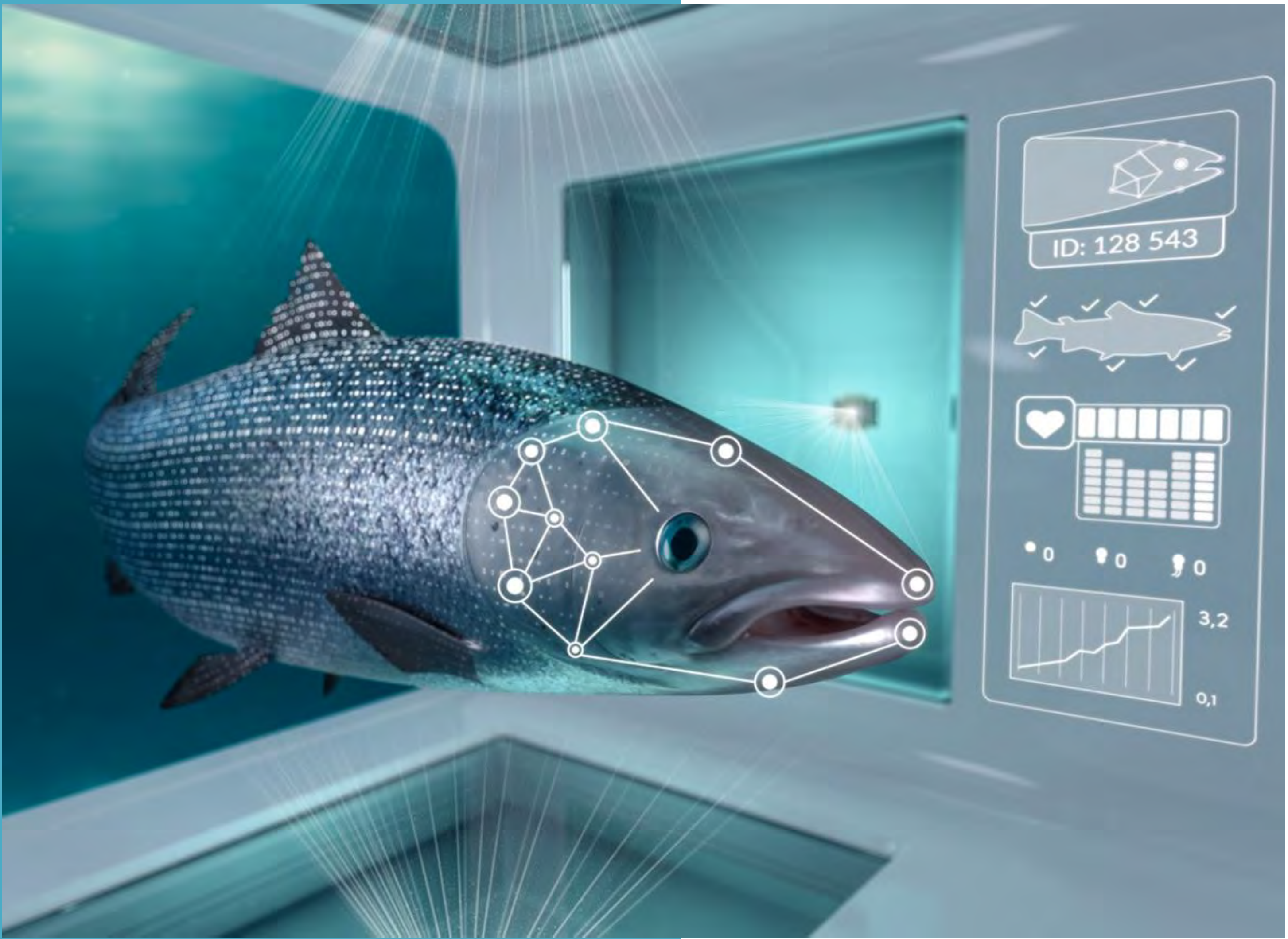
iFarm

Final report for the iFarm development license project



Cermaq Norway

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Summary

The iFarm project, aimed at introducing precision fish farming by focusing on tackling health challenges in aquaculture, received four development licenses to develop new production technologies to support sustainable growth in aquaculture. Implemented within standard cages, iFarm utilizes a submerged net roof and a snorkel passage to the surface where the iFarm unit is mounted. This system employs sophisticated computer camera vision technology for tracking and storing fish data in individual health records and facilitates subsea sorting of fish.

Three development phases, within three complete commercial salmon production cycles, have been carried out and documented successfully. With this, the established mandatory criteria from the Directory of Fisheries for the project is fulfilled when submitting this final report in June 2024. A supplementary fourth phase is however initiated aiming to take the product further than described in the original application.

The project has progressed combining expert collaboration in areas such as salmon farming, fish health, mechanics, and software together with iterative product development to meet established criteria. Cermaq has fulfilled the role as project owner and leader, while natural responsibilities dedicated to operational farming and technology development were distributed between Cermaq and BioSort. In addition, ScaleAQ has contributed as equipment supplier and partner in cage design activities, Nofima has served as a documentation partner, and DNV was engaged to provide third-party verification and approval of the iFarm concept.

The primary insights and enhancements implemented in the global iFarm cage design primarily revolve around the aim of optimizing the salmon's rearing environment in terms of behavior and fish performance. Examinations of snorkel opening size and sensor opening characteristics has resulted in an iFarm design featuring three wide sensor openings for bidirectional swimming - horizontally oriented, but slightly tilted, with dimensions of 2x1x1 m. The net roof is gradually conical, and the snorkel is equipped with anchors so snorkel depth can be varied. Feeding, with water borne feed distribution, primarily occurred beneath the net roof at an approximate depth corresponding to the snorkel, typically ranging between 10-15 meters.

Operational enhancements and functional innovations have been decisive in project execution. Furthermore, successful solutions such as zipper systems for connecting the net roof to the existing net and net roof openings for facilitating the placement of in-pen equipment like lights or lift-up systems, have been embraced by the industry.

The iFarm project has developed a sensor chamber with recognition technology (computer vision) for identification of individual fish, for counting lice on fish and for registering other parameters such as various welfare indicators and growth metrics. To achieve this, sensor set ups including length, lighting options and camera configuration have been incrementally developed and the project has successfully collected data through all life-stages of a marine production cycle. Each iFarm sensor chamber currently has 10 cameras with custom-designed lenses to see the fish from various angles and six illumination units giving excellent conditions for computer vision. The project has established software infrastructure collecting and displaying data via live dashboards covering weight, lice, and welfare indicators on a population level. In addition, individual fish recognition has been demonstrated over time, which is used for individual health records.

Throughout the project, a gentle fish sorting mechanism has been developed to facilitate sorting of individuals with pre-defined traits, in addition to a solution for infrastructure post-sorting. Two sorter iterations have been tested at commercial sites, while the third iteration has been developed and will be installed during 2024. The current iteration of the sorter chamber is integrated in the 2x1x1 m sensor chamber and has three enclosing walls designed as roller curtains to gently capture the fish. The project has demonstrated solutions for transport after sorting such as guiding the fish to a smaller net volume and the current set-up includes a vacuum suction system which transports individual fish to a surface holding entity.

Biological performance has been followed closely with well-established routines including production performance, operational welfare indicators and laboratory-based welfare indicators with key focus areas on project specific parameters such as behavioral monitoring. Production results have indicated higher feed conversion ratios in iFarm pens compared to a Cermaq benchmark and control cages and while fish health has generally been evaluated as good from phases 1-4, some risk factors have been identified and followed up closely. Targeted mitigating actions were initiated which resulted in improvement in FCR and a reduction in some welfare risks that are associated with snorkel type production. The survival rate was above 90% for the majority of cages from phases 1 to 3 and with high superior share at harvest, on average 89% and 90,5% for phase 1 and phase 3, respectively.

The development license project has shown that iFarm has the potential to be realized as a commercial product. Beyond the development license project, iFarm will be further piloted to document value creation by aiming to remove the need for group-based lice treatments, improve fish welfare and health, and provide insights into population growth and health through individual health records.

The iFarm project is a unique project that aims to improve farming in traditional, already existing salmon farming production systems. Understanding salmon behavior and adapting technology accordingly have been essential for successful project execution. This final project report presents key achievements and evaluations with the aim of sharing relevant knowledge with the industry and contribute to innovation and sustainable growth.

1. Introduction

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 associated with 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 aquaculture concept being developed by BioSort AS in partnership with Cermaq, applied for ten development licences from the Norwegian Directorate of Fisheries, and was ultimately granted four licences in 2019 (Norwegian Directorate of Fisheries, n.d.). Concurrently with the reduction to four development licenses, the agreement with Directory of Fisheries was to evaluate the potential of iFarm by developing and testing an advanced prototype (Prototype A and B). Whereas future development of Product versions 0 and 1, which represents further development stages before a commercial product, are beyond this project. Throughout the development period, iFarm has evolved from a pilot concept (Figure 1 and Concept video) to an advanced prototype of the technology (Prototype video), towards commercialization.

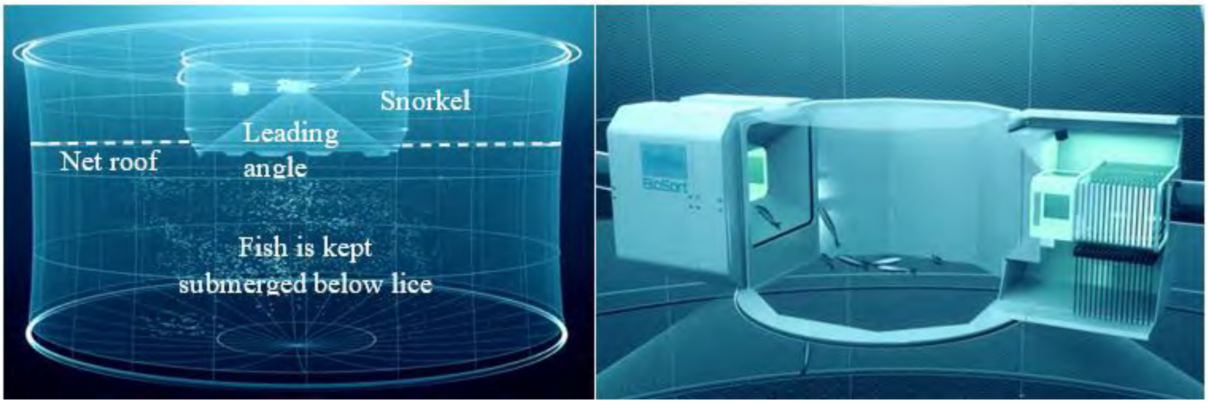

Figure 1: Original drawings of the iFarm system. System designed with a net roof to keep the fish deep and a snorkel to access the surface (to the left). The net roof has a leading angle and the iFarm unit itself is placed in the snorkel with a pre-chamber, sensor chamber and sorting chamber (to the right).

The iFarm development project with a budget-frame of NOK 586 million has been carried out according to plans in the period between January 2020 and June 2024. All public reports are published on Cermaq's homepage (www.cermaq.no/iFarm).

This document is the last of several deliveries to meet eight specific target criteria set by the Directorate of Fisheries as the basis for awarding the four developmental licenses. All target criteria must be met in order to apply for conversion of the development licenses to ordinary licenses. The purpose of this report is to provide an evaluation of the whole project in accordance with target criterion 8.1 and at the same time to present key results and learnings from the project that may be relevant to the industry. The report will also highlight key knowledge gaps and risks that should be addressed in the future. The work in the project has been based on a principle of openness, and only sensitive information related to the companies involved and for competition-purposes has been kept confidential.

2. The iFarm Concept

The iFarm aquaculture concept is a novel production technology that aims to introduce individual-based precision farming to Atlantic salmon aquaculture. Recognition of individual salmon and generating individual health records is a unique part of the iFarm technology (Figure 3). BioSort utilizes software to recognize a biometric fingerprint of head features similar to state-of-the-art facial recognition software. The distinctive head geometry and spot pattern of individual fish is used to create an ID database. Individual health information is stored in their respective health journals each time the fish passes the sensor.

iFarm systems were integrated within commercial circular open cages, deployed with 6.5 meters deep lice skirts. iFarm cages consist of an adapted snorkel cage with a submerged net roof, which keeps the fish population deep, and a snorkel passage which the fish must swim through to reach the surface to fill air in their swim bladders. The snorkel is 44 m in circumference at the surface and has a conical base where the iFarm sensor arrangement is mounted to enable complete population surveillance (Figure 3).

The iFarm docking is both the structural connection between the upper part of the snorkel and the net roof, and at the same time the mounting platform for the iFarm house unit. iFarm has evolved during the project to find optimal design settings to fulfil functional requirements, but the core functionality remains the same as described in the project application. Fish are directed to the iFarm house using a gradually inclining net roof before they continue through the iFarm house openings equipped with advanced illumination and camera technology. Sophisticated computer vision models run continuously to collect information about every fish passing through the system, including lice detection and other parameters related to health, welfare and growth. The sorting mechanism operates in the same sensor opening and is connected to a simple system for transporting sorted fish to a surface entity. Non-sorted fish return via the same openings to the main net volume below the roof to feed.

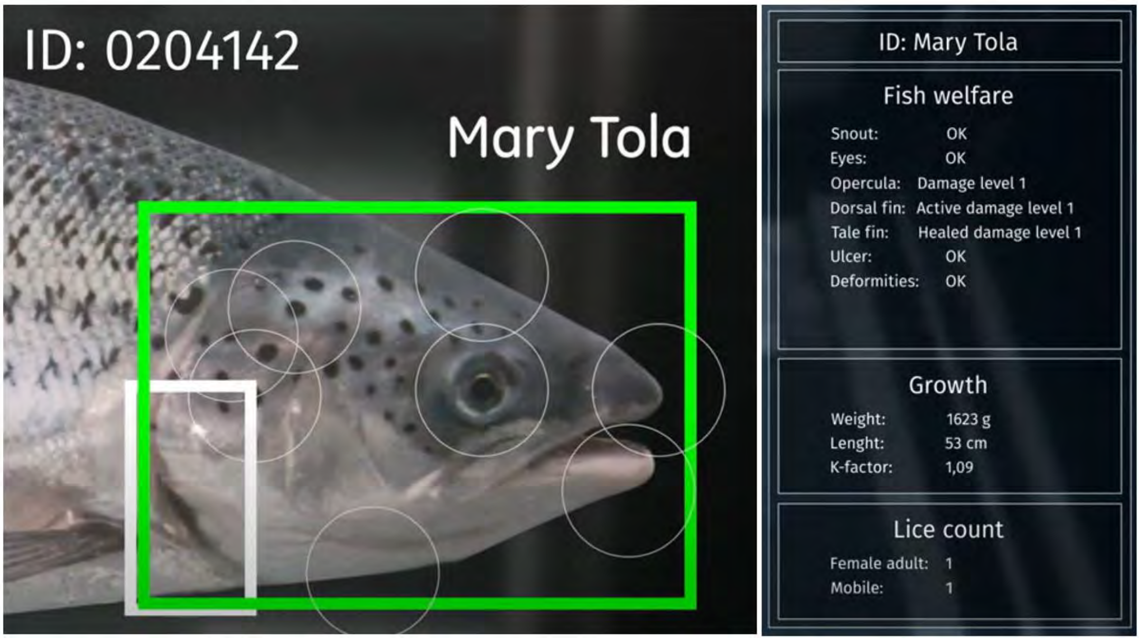

Figure 2: Illustration of fish recognition and individual health records. The distinctive head geometry and spot pattern of individual fish is used to create an ID database. Individual health information is stored in their respective health journals each time the fish passes the sensor.

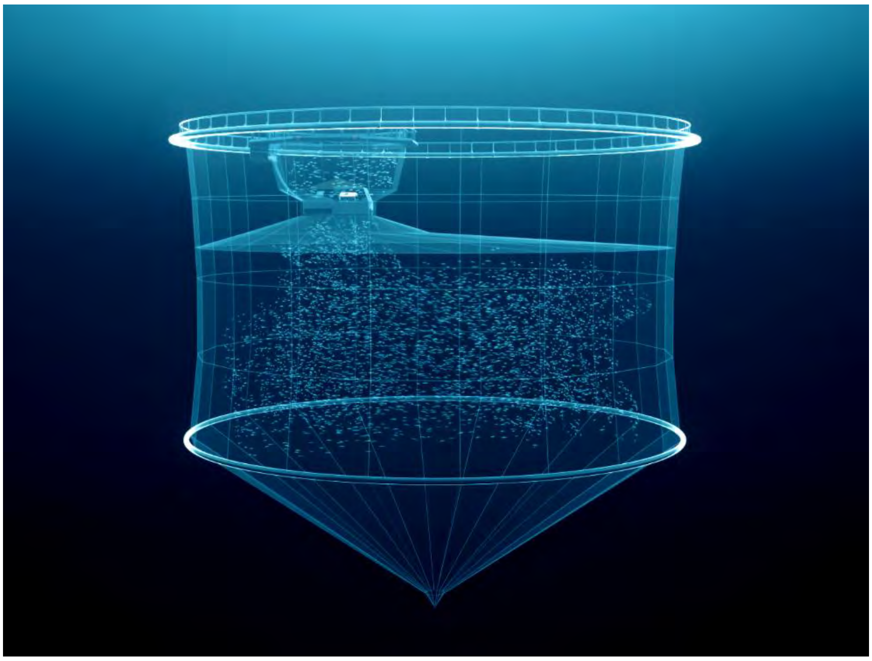

Figure 3: Illustration of the iFarm cage structure including snorkel, net roof, docking, iFarm house, and feeding system.

3. Project Goals

The main goal of the project has been to develop and test iFarm, for the purpose of evaluating if this production technology has the potential to be realized as a commercial product. This has involved development and testing of:

- Different cage and iFarm geometries for evaluating their effects upon fish behavior in and around the snorkel and sensor house.
- A sensor and sorting system, enabling individual health records and the ability to sort out and transport fish to holding volumes.
- A cage system that is efficient to install and operate.

Each project phase had specific aims and objectives to enhance focus and guide the direction of the project.

4. Project Plan and Reporting

The iFarm project goals and objectives have been addressed over three phases originally planned from 2020-2024, and an additional fourth phase to supplement project data which is running in 2024. The different phases in the iFarm project are described in figure 4. This report gives a final overview of all phases in the iFarm project.

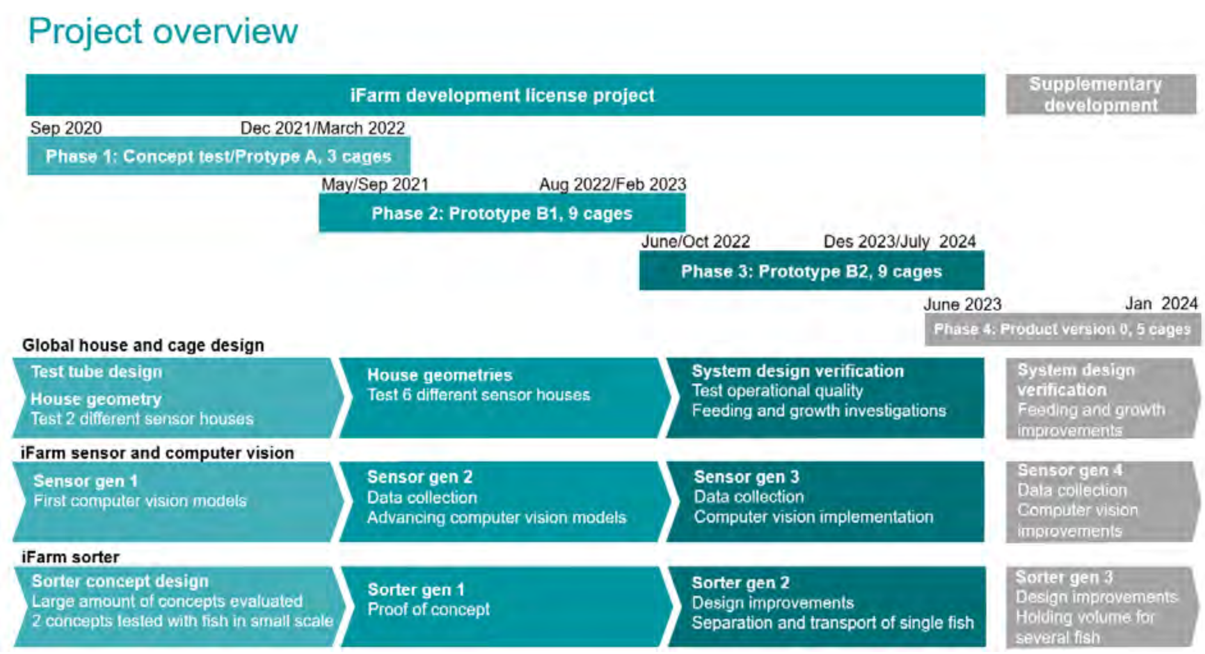

Figure 3: Project overview of the iFarm project describing the main elements of each development phase.

Phase 1 (September 2020 –January 2022):

- Full-scale testing of two iFarm Prototype A systems with focus on operations, technology introduction and fish health.
- Continuous welfare monitoring was carried out to validate the first full-scale "proof of concept" for the iFarm system.
- Midterm report delivered: 1st September 2021
- Final report delivered: 25th July 2022

Phase 2 (May 2021 – February 2023):

- Full scale testing of eight adapted iFarm Prototype B cages and one associate cage to test and improve Prototype B design.
- First versions of software infrastructure and computer vision models.
- The first sorter test in commercial cage
- Midterm report delivered: 22nd April 2022
- Final report delivered: 28th September 2023

Phase 3 (June 2022 – January 2024):

- Design verification of Prototype B. This involved six adapted iFarm cages and three associate cages with an extra focus on improving underwater feeding.
- Software algorithms were matured to producing daily numbers and trends.
- New sorter test including transport to surface.
- Midterm report delivered: 30th April 2023
- Final report delivered: 16th May 2024

Phase 4 (May 2023 – January 2024):

- Initiated Product version 0 tests consisting of four adapted iFarm cages and one associate cage aiming to take the product further than described in the original application.
- Midterm report delivered: 3rd June 2024

5. Project Organization and Execution

The unique nature and complexity of the iFarm-project has required an iterative approach where the iFarm and associated technologies have been progressively developed, verified and tested on-site in large scale farming operational environments. This set some clear demands when framing the project in terms of organizational and executional structure. The main responsibility was divided between Cermaq and BioSort, where Cermaq was project-owner and overall project-leader, while BioSort was responsible for the development of iFarm- and associated technologies. Overall project progress was governed by a joint Steering Group constituted of members from Cermaq- and BioSort Management, while an Innovation Strategy Team made up of selected personnel in Cermaq and BioSort Management ensured priorities and strategic direction to the developmental work. Project Management with good support functions from procurement and economy, communication, IT, OHS and Quality ensured proper progress and execution of the Product Development part and iFarm Farming trials. To ensure optimal overall iFarm-project execution, relevant internal and external professionals and competence were involved (BioSort, Cermaq, ScaleAQ, Nofima, DNV) covering a wide area of expertise, serving specific purposes, responsibilities and activities to account for the varying levels of requirements and complexity within different areas of focus ranging from operations, product development to documentation. Overall iFarm project organization is outlined in figure 5.

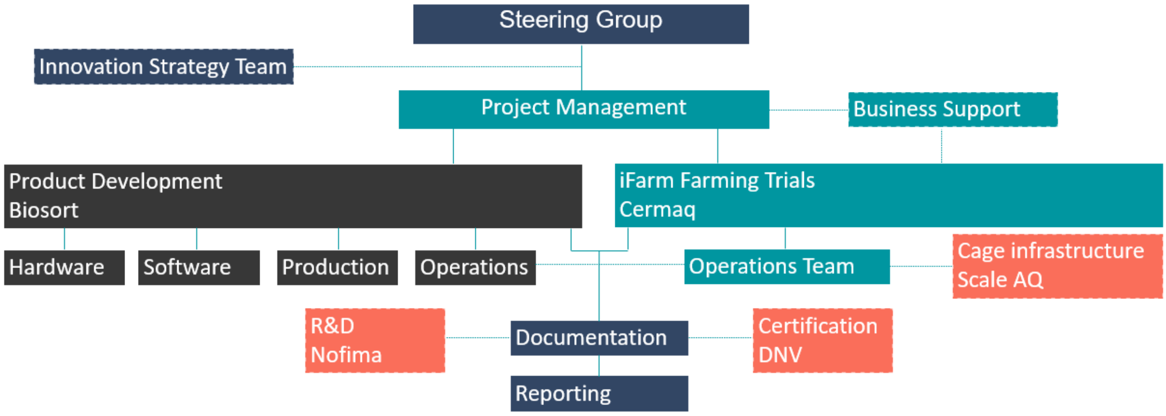

Figure 4: Organization and executional structure of the iFarm-project. In addition to a range of Cermaq and BioSort personal, numerous personal from ScaleAQ, Nofima and DNV contributed to the iFarm development project.

The experience shows that the relative dynamic and iterative approach with close interactions and collaboration between the operations, suppliers of technology and equipment (BioSort, Scale AQ), and documentation providers (Nofima, DNV) was one of the biggest success factors for timely execution and progress of the iFarm project.

5.1 Project tools

A number of tools were used in the iFarm-project in the planning, execution and follow-up of the progress, both general available tools such as the Microsoft 365 platform, with Teams as the Common Data Environment (CDE), to more tailored solutions according to specific demands. Dashboards with intuitive overviews and graphics were created in PowerBI with data from numerous sources and systems (APIs) for easy access and availability internally to project-members for a number of purposes, ranging from surveillance and control of environmental parameters, fish welfare, behavior and performance in the iFarm Farming Trials to reporting and documentation at an administrative level. The video tool Argus, developed by BioSort, was employed for behavioral monitoring. This tool provides all project partners with access to live and stored video streams from IP cameras and feeding cameras installed in each cage. Argus has also served as an important tool in daily operations for fish monitoring during installations, maintenance, decommissioning, and feeding.

6. Handling of Risks

The risk associated with the iFarm project included a number of internal and external factors that could potentially affect the project at different levels, ranging from those with high level administrative and executional consequences to factors relevant for more everyday operations at the farm level. Hence, the risks associated with the iFarm project were categorized into three main levels based on the nature and complexity of the risks for the purpose of handling each risk at their appropriate level:

1. Overall Project risk; Associated with the execution of the iFarm development project - the project's progress, goal achievement, results, and technology development. Reserved for the project owner (Cermaq), the Steering Group, the Innovation Strategy Team and the Directorate of Fisheries in cases where it was relevant.
2. HAZID; Risks associated with the design and production of system components, individually and in combination (total) reserved for validation and certification of components in relation to regulatory requirements.
3. Risks in the Operations; Associated with general operation and production of salmon in the iFarm Farming Trials – biological risks (fish health, welfare, growth and performance), external environment and Occupational Health and Safety (OHS).

6.1 Overall Project Risks

One factor that potentially could have had a huge impact on the project was the COVID-19 Pandemic with the onset of restrictions barely three months into 2020: with both local, national and global effects and constraints on international shipping, production of components abroad together with restrictions on personal interactions. However, the iFarm project could be executed according to plan with only the need for smaller adjustments, highlighting that active and continuous handling of risks during planning and execution were crucial for the overall success of the project.

6.2 Occupational Health and Safety in the iFarm

One of the mantras in Cermaq is «People first», hence OHS has had an important role in the iFarm Farming Trials. Operational personnel have been involved in the choice of components and infrastructure, but also included in the design and verification work of iFarm specific equipment. The result being utilization of particular infrastructures, such as the Midtgard concept for effective and safe handling of nets, but also more specific adaptions to equipment and procedures for safe and practical everyday operations;

1) The wide and practical working platform on the iFarm floaters; allowing for space and access to work safely and effectively with different types of equipment, tools and daily tasks looking after the fish, counting sea-lice etc.
2) Specific handrail stairs for safe access to the iFarm floater working platform from the main floater.
3) Strategic placement of winches for different purposes; i.e safely pulling the iFarm floater towards the main floater, hand-winches on the iFarm-floater handrails for controlled and gentle reduction of the volume of the tube-net and lifting the iFarm-dockings to the surface for daily tasks, maintenance, placing of sensor-houses and other operations.

Weekly follow up of the operations in the iFarm Farming Trials focused on near misses and risks of incidents to reduce the frequency of unwanted events. In summary the frequency and number of near-misses and reported incidents at the iFarm-sites were comparable to that in the ordinary sites, and there have been no serious OHS-events reported in the iFarm-project.

6.3 Fish Health, Welfare and Performance Risks

The iFarm development project is in essence about monitoring and responding to changes in the health, welfare, behavior and performance of fish, and all risk-aspects has been thoroughly dealt with in the measuring programs in each phase of the project and is covered in other parts of this report.

6.4 External Environmentally Risks

The iFarm Farming Trials sites, like any other of Cermaq's farming sites, have followed internal procedures and risk assessment related to external environmental risks. Accordingly, regular reporting of incidents or events in the trials if such occurred. There have been two serious incidents reported in the iFarm-project related to the external environment.

The first was an incident at Cermaq site Langøyhovden registered 3rd of June 2022 where a small hole was observed below the net-roof in one of the pens during net-cleaning. The hole was immediately fixed, and re-catching nets were launched around the whole site, followed by immediate reporting of the incident to the Directorate of Fisheries, all according to Cermaq's Contingency Plan. Since no fish were caught in the re-catching nets on the day of and the following days after the incident, and there were no observations of escapees in the area, the incident was classified as a suspicion of escape incident rather than an escapee event. A committee was appointed to investigate the incident further where both internal and external professionals contributed and were able to identify the root cause of the incident. The root cause being an issue with only the specific net and located at an isolated area that easily could be improved. The report revealed new risk elements to be aware of going forward and was implemented in the project, i.e. in the design, verification and production processes of the nets and in association with operations and handling such as in the regular inspection and monitoring activities of the nets during the production.

The second incident occurred at Cermaq site Hellervika 24th of October 2022 after stocking of S0 smolts. During the daily routine check of the pens after stocking, undersized smolts were found in the LiftUp in two of the pens with the newly stocked smolts. This triggered notification to the Directorate of Fisheries of a suspicion of escape incident followed by a range of corrective actions according to Cermaq's Contingency Plan; i.e. immediate and frequent inspection of the net-pens with respect to undersized fish swimming out of or stuck in the nets, or other evidences of deviation using ROV and cameras. No fish were observed in the nets and no deviations were found during the inspections of the pens using ROV, hence in dialogue with the Directorate of Fisheries certain actions were initiated to document the extent of undersized individuals and correct the situation. These were weighting and measuring length of all deceased fish in combination with active removal and humane culling of undersized individuals in the respective pens until such individuals no longer could be detected. The root causes of the incident were determined to be undersized individuals at the smolt-supplier, in combination with insufficient documentation and control of the size-distribution of the smolts prior to sea-launch. Although this incidence occurred during the iFarm-project, the risk elements revealed were not in any way caused by or related to the iFarm and iFarm Farming Trials per se, but it was included in this report due to the relevance for the industry in a more general context, highlighting the importance for implementing practices and actions to avoid and prevent incidences like this from happening again.

7. Technical Design Development

A functional iFarm technology has been developed in the project. In this chapter the incremental development of the key components and report on functionality of the iFarm cage system is described. Results from both small-scale trials and commercial stockings have iteratively narrowed down design alternatives and guided the project priorities and product development focus. Adaptations to the original application are described exhaustively in the project's "Change register".

A range of global cage setups were tested during the project, together with eleven iFarm houses with different properties. To optimize fish data collection, the sensor chamber layout and computer vision models have gradually matured, and two successful sorter tests have been carried out in commercial cages. iFarm has evolved to an advanced prototype combining hardware that supports biology and operational routines (Figure 6) with software technology for individual fish recognition and data collection (Figure 7).

It is important to emphasize that the unique specifications of the technology have necessitated a significant degree of custom-made solutions. This encompasses global cage solutions as well as sensor and sorter technology. BioSort has developed and produced in-house solutions for components such as cameras, illumination, sub-sea motors and robotics, and computer vision algorithms. An overview of the product development is given in the sections below.

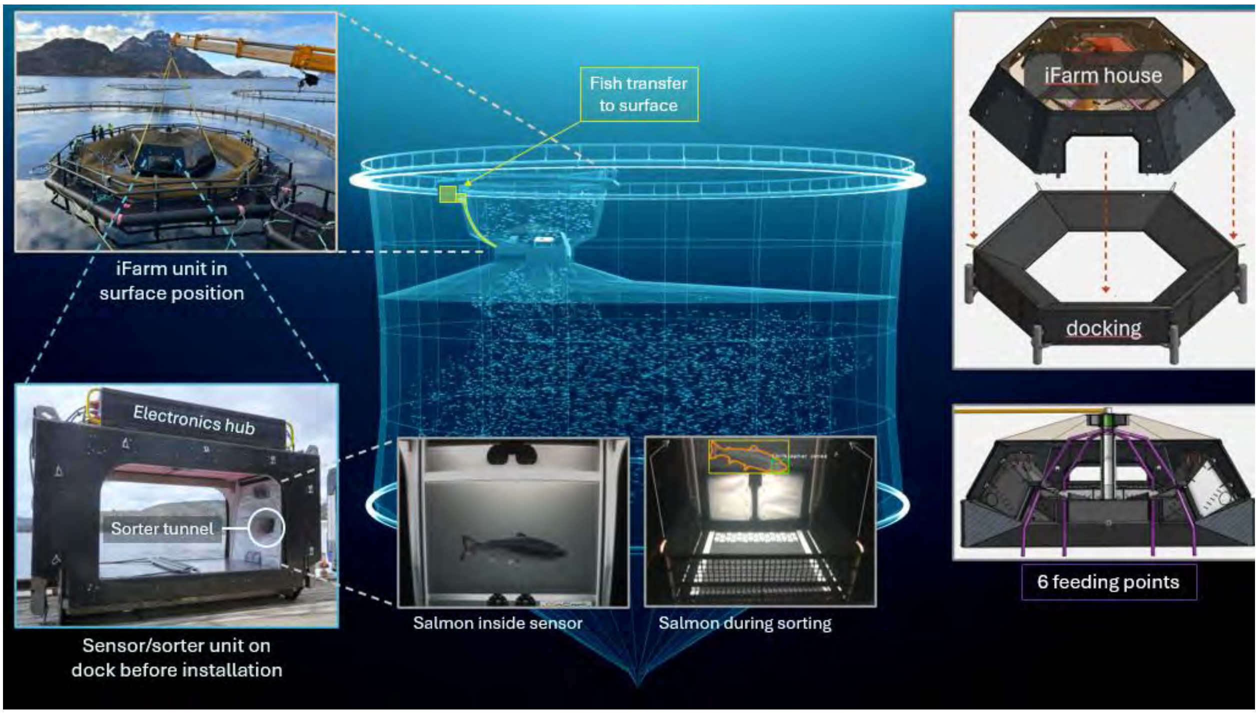

Figure 5: The complete iFarm system including snorkel, net roof, docking, iFarm house, feeding system, sensor units, sorter unit and transportation system to the surface.

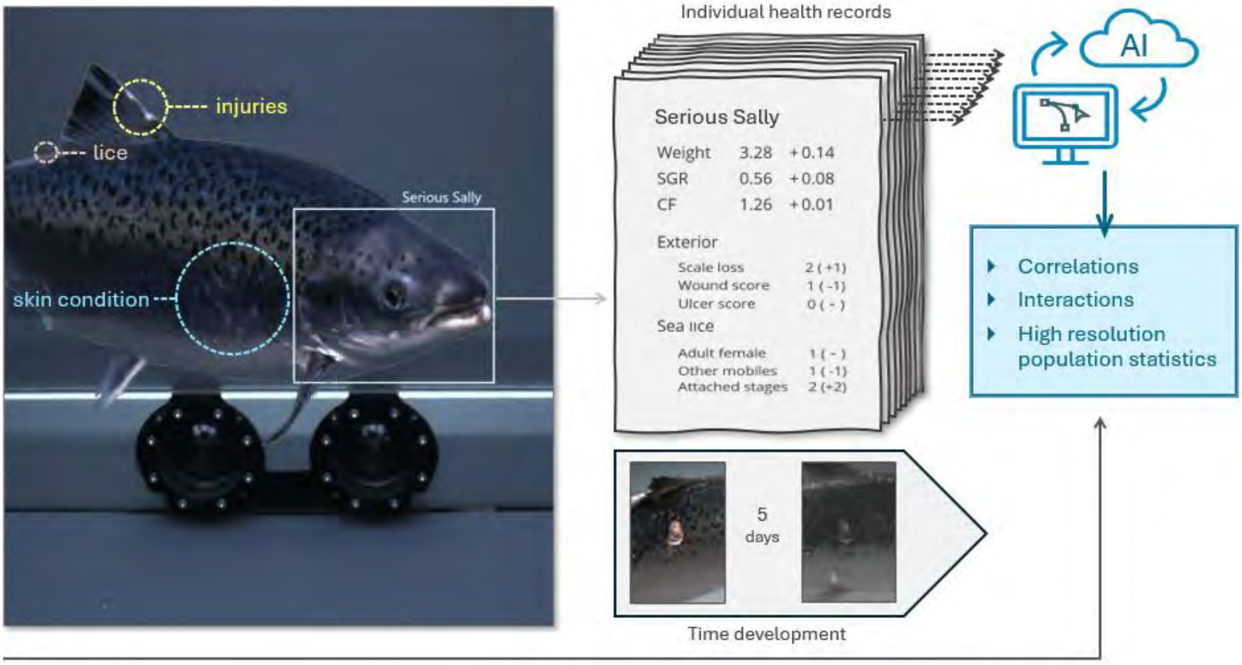

Figure 6: The iFarm computer vision system identifies single individuals, collect individual data and generate individual health records. This can be used to find correlations, unknown interactions between parameters and generate high resolution population statistics.

7.1 Global Cage and House Design

The project has iteratively developed a cage and housing design that utilizes adapted snorkel cages, suited for daily operations and fish husbandry with a focus on fish behavior. Each iteration incorporated feedback and improvements, which progressively enhanced the product. The main decisive steps for achieving the optimal global cage and iFarm house design are presented in the ladder in Figure 8. The monitoring program related to fish behavior, health, and performance, has been actively utilized and considered to refine and shape decisions. In addition, functional enhancements to meet operational requirements was conducted.

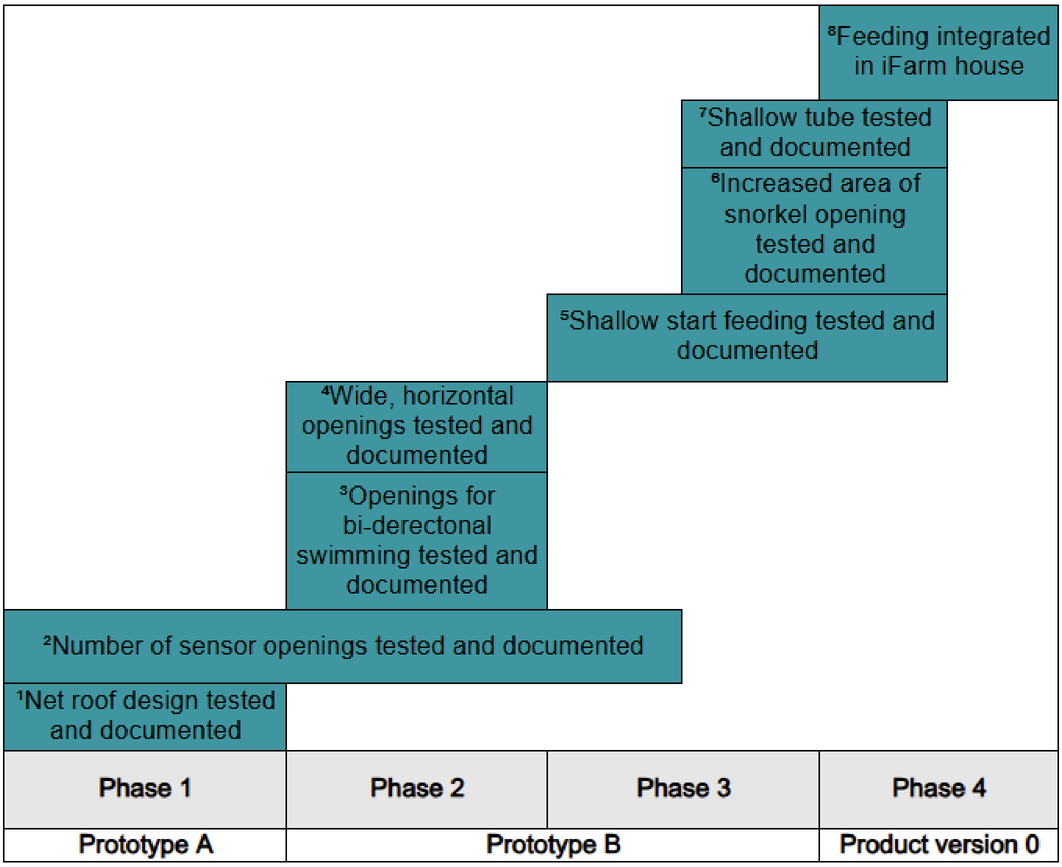

Figure 7: Iterative improvement of iFarm cage and house elements. Superscript numbers before the textboxes give guidance to the main text in the chapter.

Cage design development was initiated before the first stocking in commercial cages, with a pre-project at IMR's research station at Matre in the period between 2017-2019. This enabled the project to narrow down design alternatives and accelerate development during the project. While a range of variants were evaluated at a commercial scale, the core of iFarm has resembled the successful mock-up prototypes from the pre-project.

In addition to the pre-project, over 50 concepts were analysed with Aquasim before finalizing the two Prototype A concepts tested in phase 1. One test in phase 1 included evaluations of net roof design and depth, where one roof design featured a steeper net cone below the snorkel, and the other featured a constant angled net roof. Additionally, net roof depth was at either 10 m or 15 m in cages that were 40 m deep at their deepest point (Figure 9). There were no significant differences in fish traffic to the surface nor number of fish in the snorkel between the two different geometries. There was a small but significant difference in surface activity between the geometries, with fish surfacing marginally more in the coned net roof that began at 15 m depth. However, as this difference was minimal (0.35 ± 0.26 vs 0.43 ± 0.23 jumps per fish per hour) and there were no differences in other behavioral parameters (Figure 10), the net roof was standardized to be at a constant angle and set at 12 m for the following project phases[1].

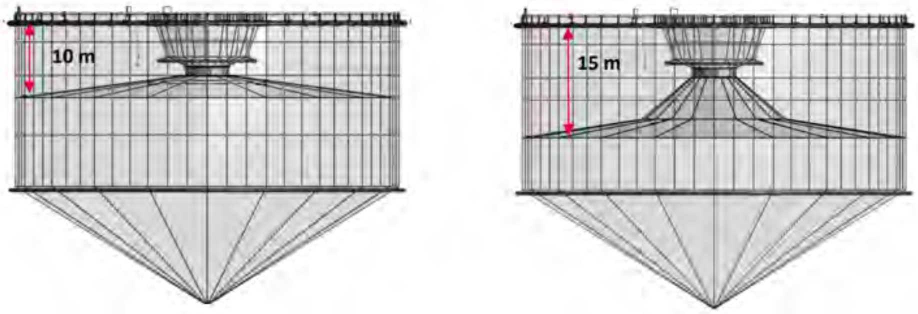

Figure 8: iFarm cage geometry in phase 1: 10 m deep net roof with a constant angle to the left and 15 m deep net roof with a coned entrance to the snorkel to the right.

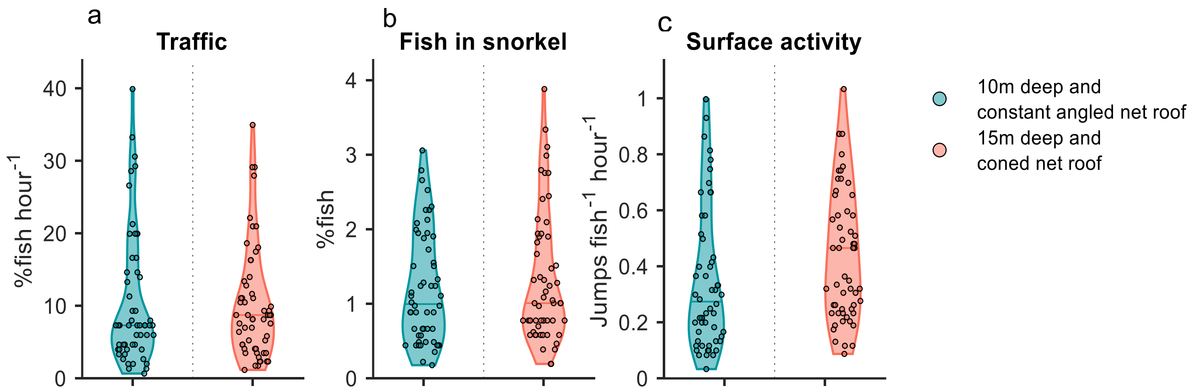

Figure 9: Violin plots outlining the effect of differing net roof angles and snorkel depths upon a) fish traffic to the surface, b) fish in the snorkel and c) surfacing activity of the fish during phase 1 of the development project.

iFarm house variants examined in the project encompassed diverse geometrical designs aimed at optimizing the passage of fish to and from the surface. Comparison of the house with two 2.5x1 m openings (Saddle house) and the house with four 2x1 m openings (Dome house) in phase 1 (Figure 11), showed that there was a small, but significant difference in traffic with higher traffic in the Dome house (0.7 ± 0.3 vs 0.6 ± 0.3 fish hour^{-1}), and similar numbers of fish in the snorkel and surfacing activity (see Figure 12). This supported the Dome house as the favorable design[2].

Figure 10: Illustration of the phase 1 Dome house with four openings to the left and the phase 1 Saddle house with two openings to the right.

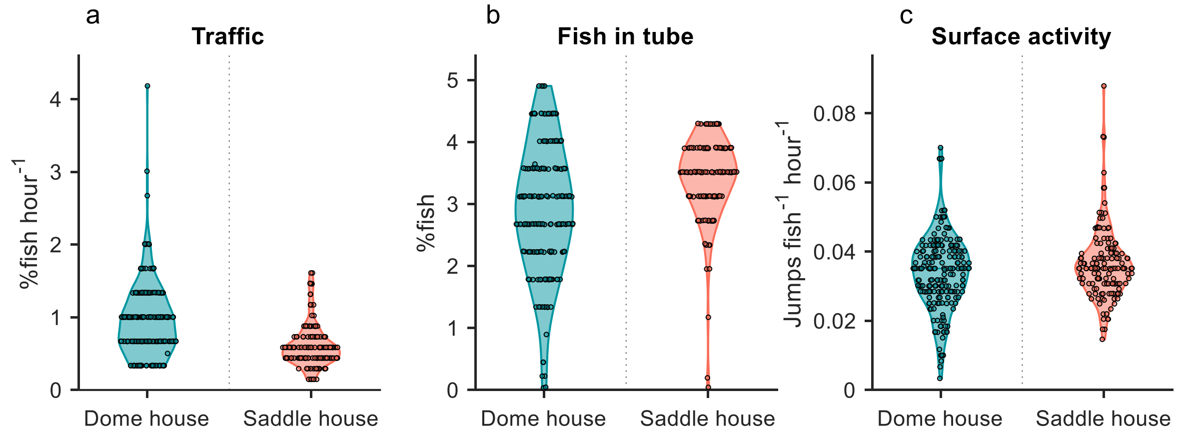

Figure 11: Violin plots outlining the effect of snorkel depths and house designs upon a) fish traffic to the surface, b) fish in the snorkel and c) surfacing activity of the fish during phase 1 of the development project.

Six different house designs were tested in phase 2, with the Dome design proving to be the best performing. One learning outcome was that the house design with openings for swimming in both directions gave more favorable behavior than the house with dedicated return openings. When comparing the Dome house with openings for swimming both to and from the surface to the main cage volume and the Two-way house with dedicated return openings (see figure 13) there were some differences in results. The deployment of the dome house slightly reduced the levels and variability of fish traffic to the surface, whilst the Two-way house slightly increased traffic and traffic variability. Both house designs increased the number of fish in the snorkel, whilst surface activity was either reduced in the Dome house or increased in the Two-way house (see Figure 14). In addition, there was a more variable, and unwanted, increase in number of fish in snorkel in the Two-way house, which also can be related to the higher number of surface activity events observed after Two-way house installation. Having house openings for swimming both ways was evaluated as the most favorable and was considered to introduce lowest welfare risks[3]. This design was also favorable in terms of sorter functionality, since a combined sensor and sorter opening allowed for sorting fish swimming both up and down.

Figure 12: Illustration of the phase 2 Dome house with openings for swimming in both directions to the left and the phase 2 Two-way house with dedicated return openings to the right.

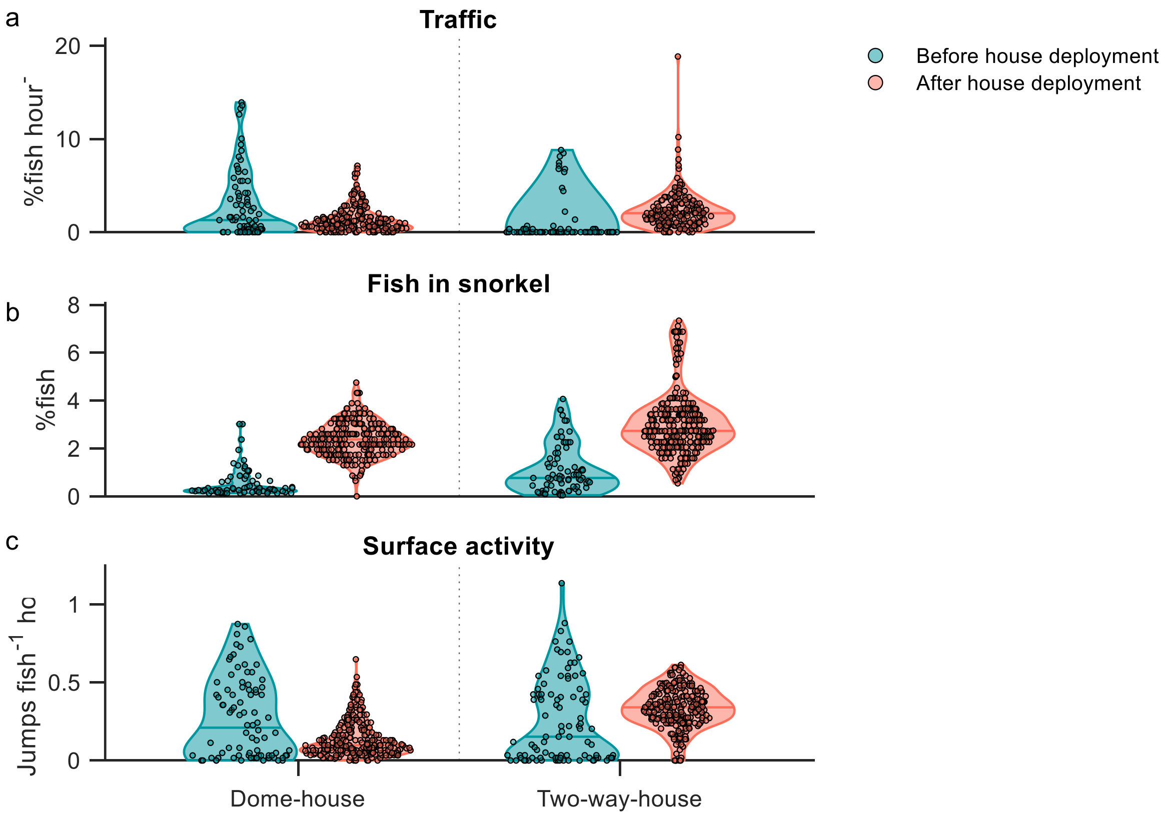

Figure 13: Violin plots outlining the effect of sensor house designs and house deployment upon a) fish traffic to the surface, b) fish in the snorkel and c) surfacing activity of the fish during phase 2 of the development project.

Another important finding from phase 2 was that fish did not return to the main cage volume from the snorkel at the desired levels when house openings were narrow[4]. This can be illustrated by comparing the behavioral effects of introducing the Dome house, which had 2x1 m wide openings, with the Pyramid house, which had 1.5x2 m narrow and tall openings (see figure 15). Fish traffic levels were similar for both house designs before and after deployment, but traffic variability decreased during house deployment. The number of fish in the snorkel increased after deployment of both houses, but the effect was more pronounced with the

Pyramid house. Surface activity was either reduced in the Dome house or increased in the Pyramid house and there was less variation in surface activity in both cages following house deployment. However, the higher surface activity in the Pyramid house coincided with a high fish density in the snorkel (see figure 16). The Dome house was evaluated as the most favorable.

Figure 14: Illustration of the phase 2 Dome house with wide openings to the left and the phase 2 Pyramid house with narrow vertically oriented openings to the right.

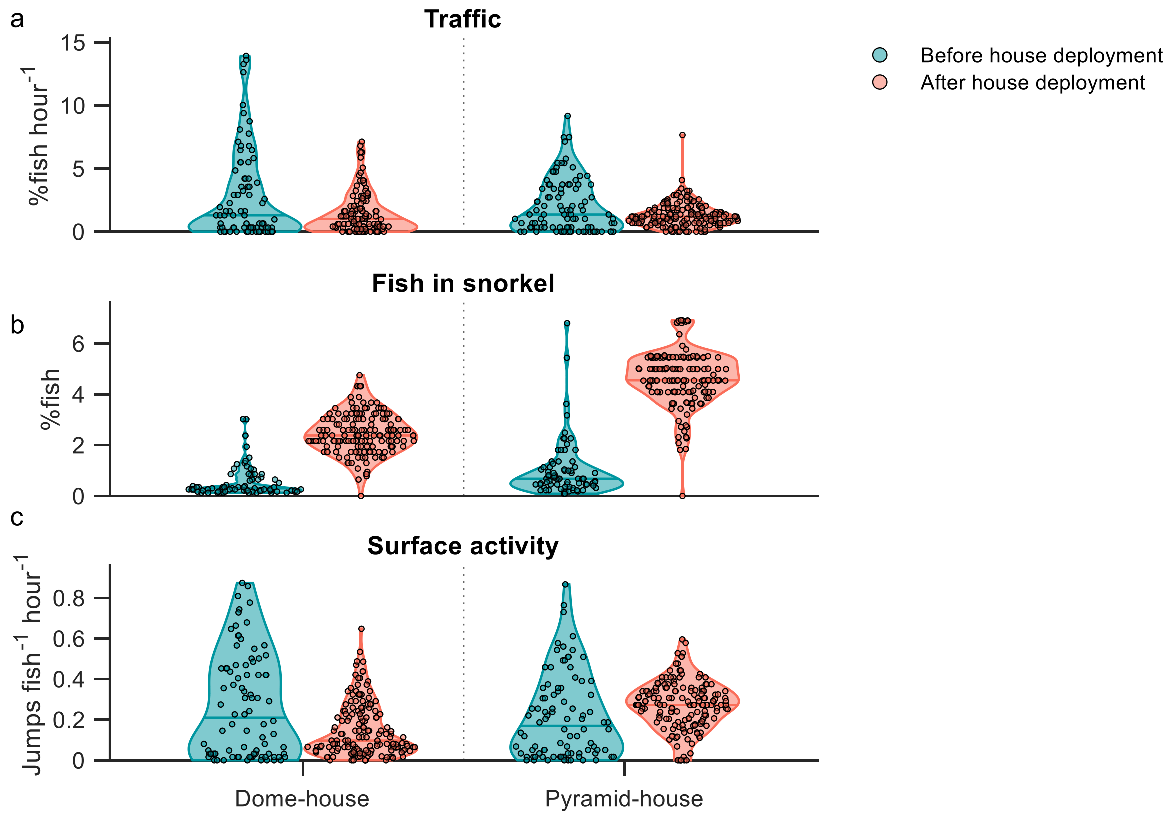

Figure 15: Violin plots outlining the effect of sensor house designs and house deployment upon a) fish traffic to the surface, b) fish in the snorkel and c) surfacing activity of the fish during phase 2 of the development project.

Experiences from phases 1 and 2 suggested that whilst deployment of the Dome house featuring wide openings, slightly tilted yet horizontally oriented, with dimensions of 2x1 m did impact fish behavior, this house featured the most favorable design[2,3,4]. Thus, the Dome house was continued in phase 3 and 4.

In phase 3, tests were dedicated to evaluating the Dome house over time to further identify product improvements[2]. Following the deployment of the Dome house in a cage containing fish weighing approximately 1.2 kg in May 2023, there was an overall reduction in traffic and surface activity compared to an associate cage equipped with a snorkel and open docking solution. In May and June, the number of fish in the snorkel was higher in the cage with an open docking solution, but cages were comparable for the remainder of the evaluation period. Swim speed analysis of fish directly below the snorkel revealed no significant difference between the cages (example data, Figure 19), suggesting that the fish were not experiencing severe buoyancy challenges during observation periods even though sensor deployment reduced fish traffic and surface activity. The phase 4 house was designed with three additional openings without sensors, providing a total of six openings, for an even more open solution[8].

Figure 16: Illustration of the phase 3 docking to the left and the phase 3 Dome house to the right.

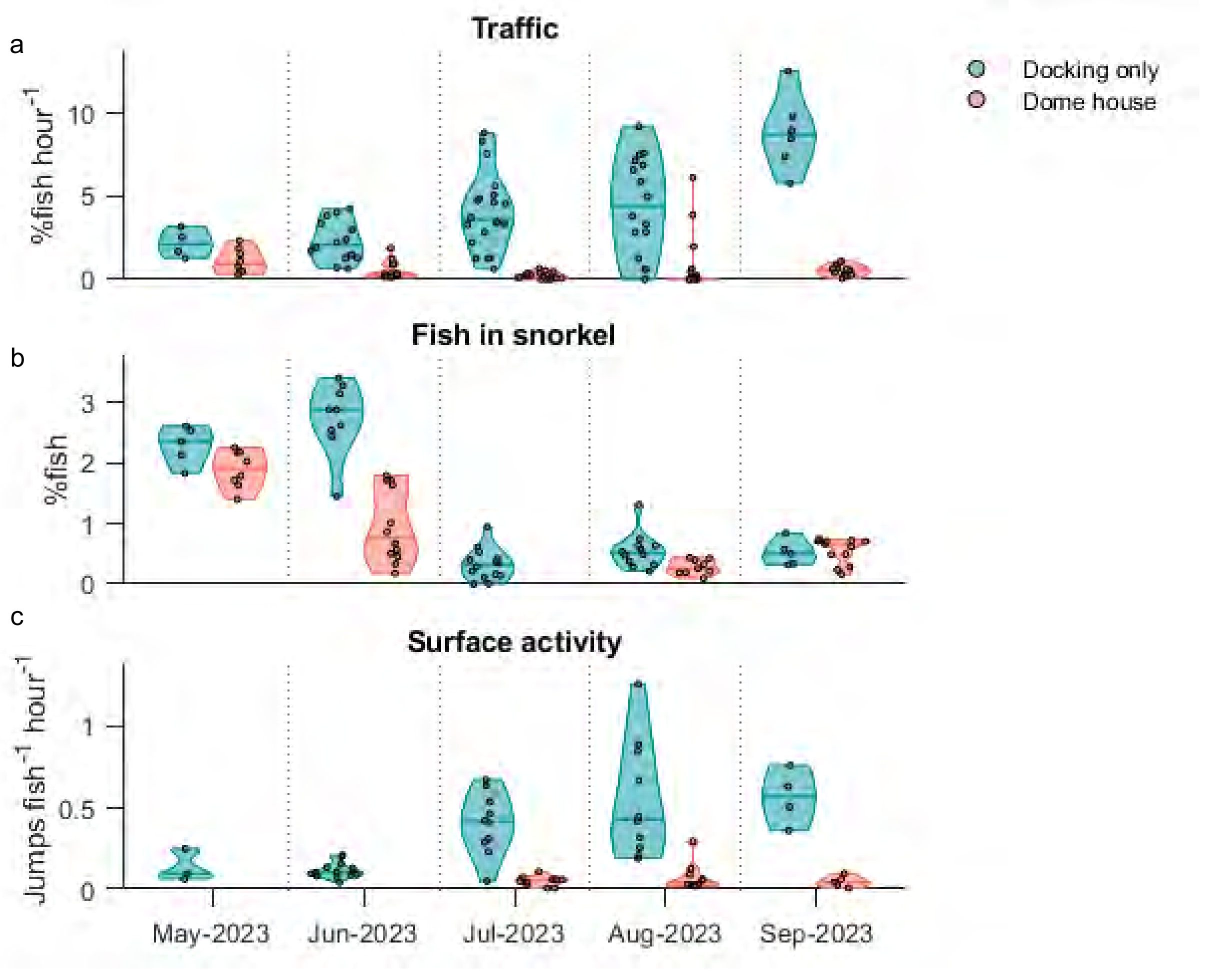

Figure 17: Violin plots outlining the effect of dome house deployment upon a) fish traffic to the surface, b) fish in the snorkel and c) surfacing activity of the fish during house deployment from May to September 2023 of phase 3 of the development project. The above behavioral parameters are also plotted for an iFarm cage with docking only. NB: there are some months with missing data for the dome house due to issues with data collection.

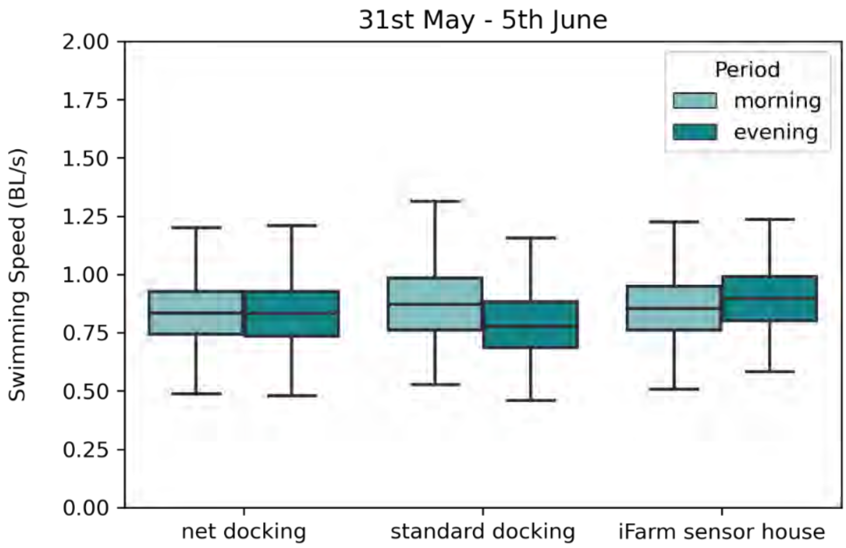

Figure 18: Box plots showing the effect of snorkel type (net docking vs standard docking) and dome house deployment upon fish swimming speeds (body lengths per second) below the snorkel for a one-week case study in May-June 2023. Swimming speeds were audited in the morning and evening of each monitoring day.

In comparison to a standard snorkel cage, the surface opening area in the iFarm cage is markedly smaller. Through the initial phases of the project, it was clear that the standard docking with a smaller opening (ca. 7 m^2) influenced fish surfacing activity and fish utilization of the snorkel volume. Whilst a reduction in surface activity did not lead to the detection of tilted swimming behaviors, increased swimming speeds or vertebral deformities that can be indicative of long-term problems with buoyancy, growth and feeding efficiency were impacted. In phase 3, a 'net docking' with a larger snorkel opening (ca. 45 m^2) was introduced, constructed without the need for a rigid docking to be the structural connection between the net roof and snorkel, to make operational routines easier. Swim speed analysis from this cage showed similar results as in cages with smaller docking and house in the observation period (Figure 19), but the introduction led to a slightly higher and more variable fish traffic and less fish accumulating within the snorkel volume during the winter months[6] (see figure 20). This observed effect was less pronounced during the summer. Levels of surface activity and the variability in this activity was generally matched between cages in both winter and summer and there was a slight increase in surface activity during summer when fish are known to increase their surfacing activity, possibly due to factors such as season and temperature (e.g., Furevik et al., 1993).Tests with a shallow snorkel by introducing anchor points to adjust snorkel depth were introduced in phase 3 and continued in phase 4, with the objective of creating a shallower snorkel volume above the docking to inhibit the build-up of fish in the snorkel [7].

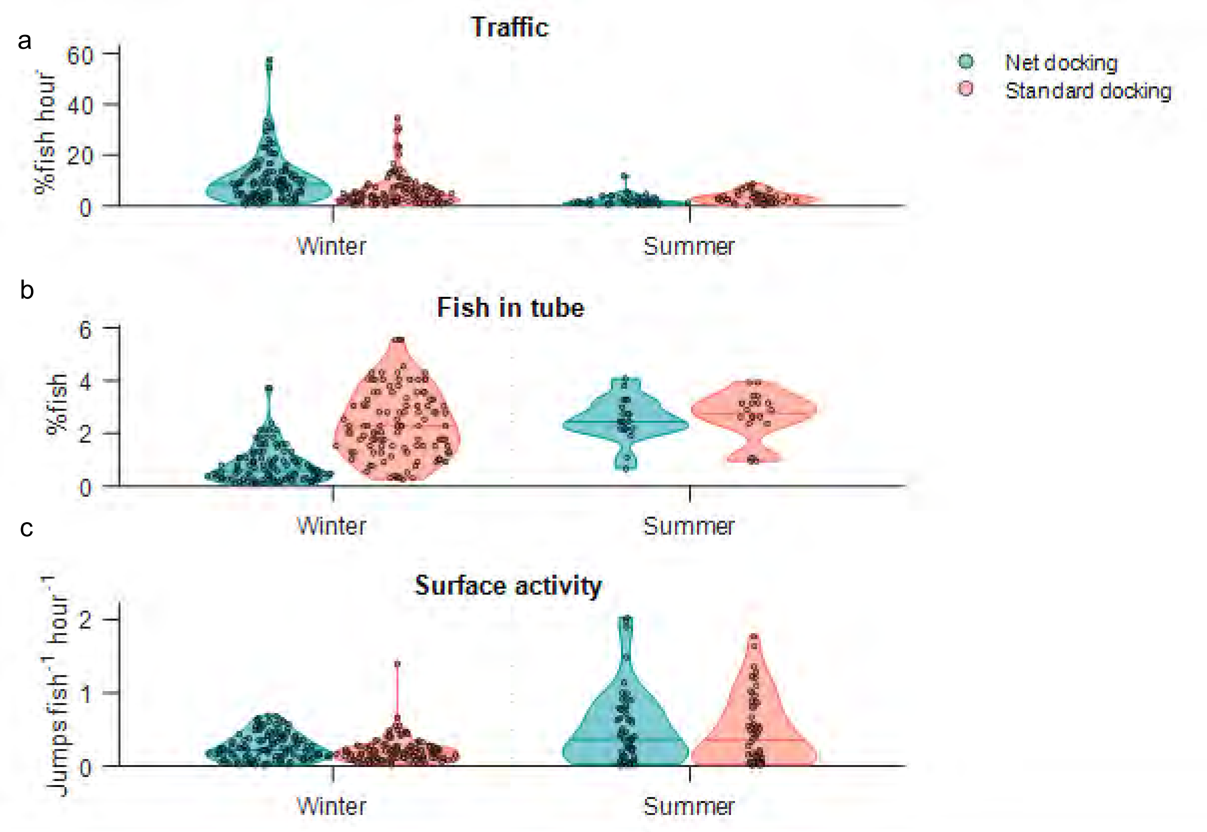

Figure 19: Violin plots outlining the effect of either a net docking or standard docking upon a) fish traffic to the surface, b) fish in the snorkel and c) surfacing activity of the fish during winter or summer periods during phase 3 of the development project. The above behavioral parameters are also plotted for an iFarm cage with docking only.

Water-borne feed delivery was utilized to transport feed from the barge to the cages and feeding primarily occurred beneath the net roof at an approximate depth corresponding to the base of the snorkel, typically ranging between 10-15 meters. After promising tests of shallow feeding (ca. 4 m) during the first months after stocking in phase 3, this was introduced as the standard[5]. Further improvement included placing the feeding points in close proximity to the snorkel opening and integrated in the iFarm house to further stimulate fish return below the net roof in phase 4. Figure 21 show the installation of the iFarm unit in phase 4.

Figure 20: Phase 4 iFarm house installed in commercial cage.

7.1.1 Technical and Operational Improvements

In addition to behavioral parameters guiding product development, solutions to ensure efficient equipment installation and removal, daily operational routines, and fish husbandry was important. Table 1 summarizes the main technical and operational considerations and solutions introduced.

Table 1: Overview of main technical and operational considerations and solutions introduced, categorized in "Fish handling" and "iFarm design".

	Challenge	Improvement and learning
Fish handling	Uncertainty about stocking and unloading fish in an adapted snorkel cage below net roof	Delivering fish into the snorkel gently over the well boat counting rig or by unloading fish with pressure below net roof are both feasible approaches.
	Handling equipment during traditional lice treatment	Tested pulling the floating line during the deployment of iFarm equipment by pulling it below ascended net roof and snorkel. An improved net docking design where no rigid docking structure was needed to connect the snorkel and net roof simplified the removal of equipment before treatment operations.
	Limited access to inner floater for daily fish husbandry	Winch systems for horizontal movement of inner floater finalized with a remote control and handrail stairs were developed by the project allowing safe access to the inner floater.
	Handling mortalities in the snorkel	Phase 3 introduced a design allowing any dead fish in the snorkel to reach the LiftUp system at the bottom of the cage.
iFarm design	Crane lengths and load limitations for installation and removal of equipment	Aimed to keep the iFarm equipment below 7 tons. For crane access, the snorkel was placed 5 m (phase 1) and 10 m (remaining phases) off-center.
	Connect net roof with net wall	Developed zipper solution between net roof and net wall for easy connection.
	Descending and ascending iFarm equipment without service boats for service access	This was solved by integrating air tanks into the iFarm system. The iFarm system can be raised to the surface for service using air, avoiding the need for service boats and cranes.
	Installing the sensor house safely under various weather conditions	Sensor house installation was initially solved with a docking station in the snorkel where the house was mounted in the sea. In phase 4 the docking and house units could be connected to one unit on land. This unit could easily be installed in the net docking with a 6-rope shackle mounting.
	Maintaining clean lights and optics for sensor up-time and general anti-fouling	A robotic anti-fouling (self-cleaning) system with brushes for illumination and optics was introduced in phase 2.
	Mounting equipment below the net roof	Developed sewn-in openings in the net roof for LiftUp hoses, lights, feeding infrastructure, feed camera and environmental sensors.
	Subsea feeding system through net roof and integrated in the iFarm house	Transitioned from having two feeding hoses through the net roof, to six feeding hoses going through net roof to then having six feed hoses organized in a free hanging circle below snorkel. Phase 4 had the feeding system integrated into an iFarm house.

7.2 iFarm Sensor and Computer Vision

The iFarm project has developed a sensor chamber with recognition technology (computer vision) for the identification of individual fish, for counting lice on fish and for registering other parameters such as various welfare indicators and growth. To achieve this, sensor chamber set ups including length, lighting options and camera configurations have been iteratively developed and tested in-house by BioSort. To ensure that all electronics functioned properly with watertight barriers when exposed to underwater pressures, comprehensive testing was conducted prior to deployment in commercial cages.

Concurrently, sophisticated computer vision models for detecting the identity of each fish, lice, estimating fish weight and recognizing abnormalities have been developed. The project has successfully collected data representing all life-stages through a production cycle (overview in figure 22).

	Fish size				
Phase	**100-1000g**	**1000-2000g**	**2000-3000g**	**3000-4000g**	**4000-5000g**
Phase 2					
Phase 3					
Phase 3					
Phase 4					

Figure 21: Overview of fish sizes of which sensor data has been collected data in each phase. Two different cages had sensor mounted in consecutive periods in phase 3.

The objective for the first-generation sensor test in phase 1 was to create a fundamental version capable of capturing high quality underwater images of salmon with focus on establishing baseline image quality and initial functionality. Two different sensor set ups were tested in the house openings. One complete sensor had eleven high resolution cameras and ten illumination units, and the simplified version had three cameras and six illumination units. Initial computer vision algorithms were developed focusing on image capture and processing capabilities, and the early versions of machine learning algorithms for simple fish detection were implemented.

In phase 2, cameras in the second-generation sensor were upgraded to more light-sensitive sensors which provided significant advancements in low-light performance and thereby improved image quality. Front glasses were improved by making them more robust and easier to service, and illumination systems were upgraded to deliver more distributed, diffuse and controlled illumination. The second-generation sensor had eight cameras and eight illumination units organized with cameras and lights both from the top and sides. Software was further developed in terms of adapting the image processing to variable lights, and more advanced machine learning models for fish and head detection and preliminary fish tracking amongst others.

An important milestone was achieved in phase 3 with the full integration of sensor systems across all iFarm house openings, enabling complete surveillance of the fish utilising the snorkel for the first time in a salmon farming cage. Each of the three sensors had eight cameras, three on each side of the sensor and two in the sensor ceiling. Six lamps were placed in the sensor ceiling, and sides and floor surfaces to provide even more uniform illumination. An image of the Phase 4 sensor is found in Figure 23, and an overview of setups in each phase is presented in Figure 24.

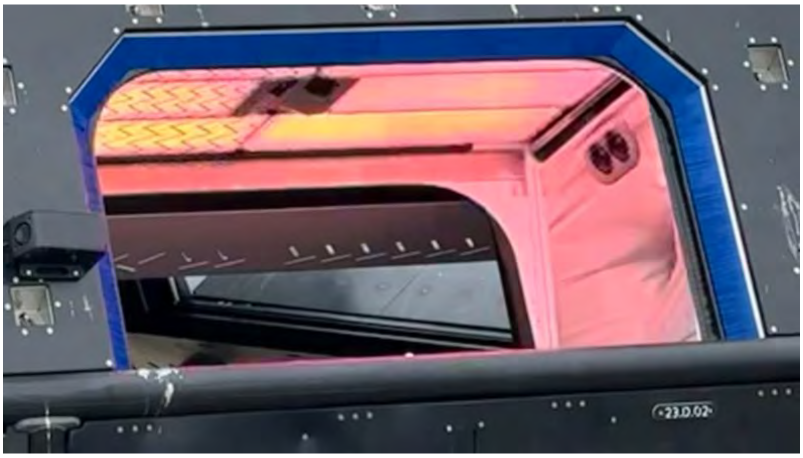

Figure 22: The iFarm sensor and sorter opening in phase 4. Cameras are placed in the top and bottom of the sensor sides and in the sensor ceiling.

The sensor has been designed to perform under harsh conditions, through several production cycles and allows for easy maintenance of both hardware and software components. Uptime has been consistently high, attributed to both the implementation and enhancement of the anti-fouling system and to comprehensive acceptance tests of each sensor prior to deployment in the commercial cage, ensuring the reliability of all electronic components. An example of a sensor image is presented in Figure 25.

The large amount of sensor data collected, stored, and processed required a robust software infrastructure system, which has greatly evolved during the project. This connects edge computing, barge processing, cloud storage and front-end interfaces (Figure 26).

le en cameras, ith high resol tion and ide field of i e en c stom designed lamps pro i ding road spectr m ill mination. l aced in the sensor ceiling and on the sensor sides	ight cameras, pgraded to more light sensiti e sensors, ith c stom designed front glass i ght ill mination nits pgraded to deli er more diff sed and controlled ill mination. laced in the sensor ceiling and on the sensor sides	ight cameras ith ne camera ho sings and an pdated electronic o de e loped to accommodate all po er s pplies and control cards i ill mination nits mo nted only in the sensor ceiling ith diff se side and floor panels to gi e optimal light conditions	ight to ten cameras. mpro e d ith c stom designed lenses e chanical str ct res and hard are of the camera system, lighting nits, and electronic o es ere enhanced for etter d ra ility and ser i cea ility i ill mination nits mo nted only in the sensor ceiling ith diff se side and floor panels to gi e optimal light conditions

Figure 23 Overview of the sensor set-up in each phase of the project highlighting the main features of the sensor, optics and illumination design.

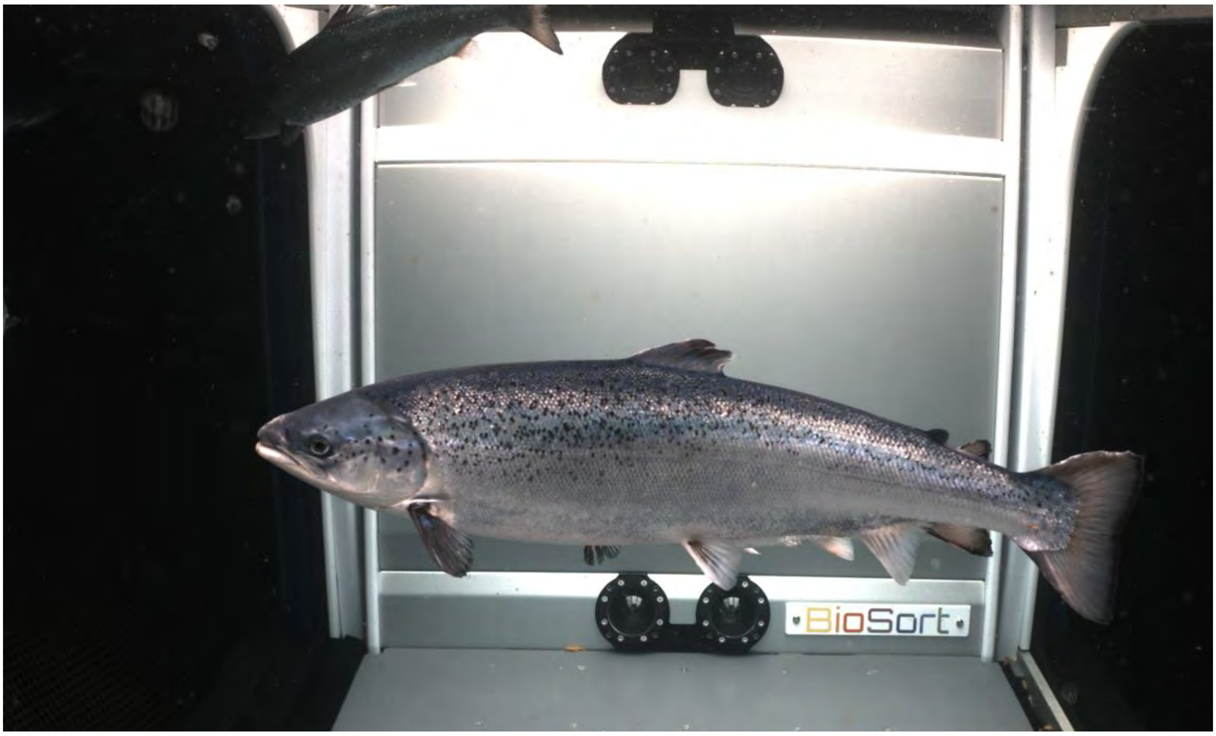

Figure 24: Image of fish from the iFarm sensor.

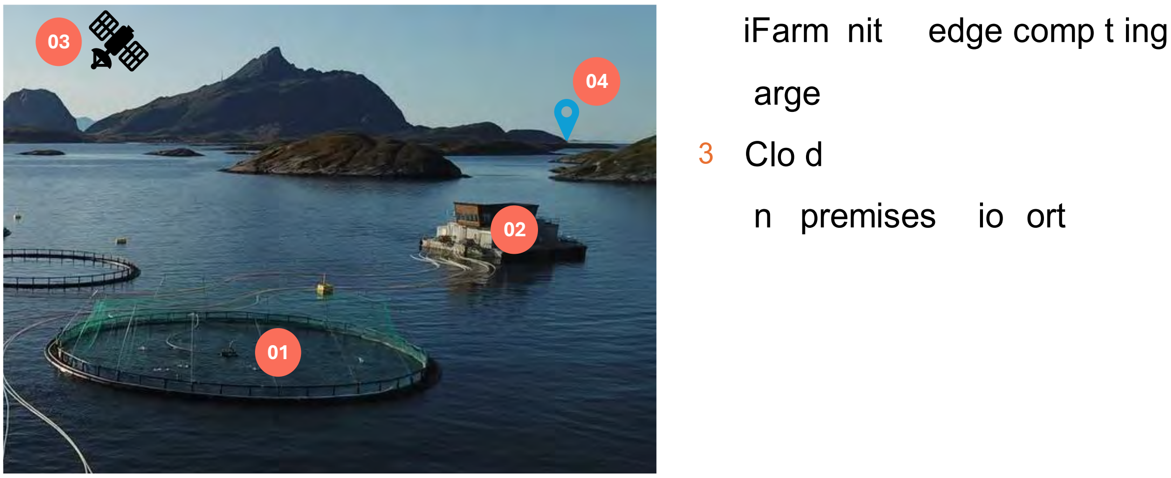

Figure 25: Overview of iFarm software infrastructure.

The core iFarm computer vision models are in operational use and their performance will keep improving as time progresses. Over 20 million images were collected and saved during the sensor's lifetime in phase 3 alone. In addition to field trials, larger subsets of saved images were used for expert/human labeling, called annotation, to further train and improve the performance of computer vision models. This process was continued in phase 4 and will continue beyond the development license project. The computer vision models feature the functions summarized in table 2 (visualized in figure 27). An overview of main software developments is found in Figure 28. Figure 29 and Figure 30 shows two examples of output statistics from the iFarm sensor and an illustration of the process of generating individual health records.

Table 2: Overview of the current machine learning models and their functionality.

Computer vision model functionality	**Description**
Multi-camera image capture	Groups images from different cameras captured and processed at the same time.
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, and features on the fish, across several cameras, and over several camera frames (time).
Fish key points/stereo/biomass	Detection of specific key points on the fish.
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 selected welfare-indicators according to the Laksvel protocol (Nilsson et al., 2022).
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 indicators, weight). This record goes into the so called “ almon dentification er ice” D , here it is related to pre i o s records from the same fish. The complete health history of this indi i d al is stored in the “ ealth Record Data ase”.

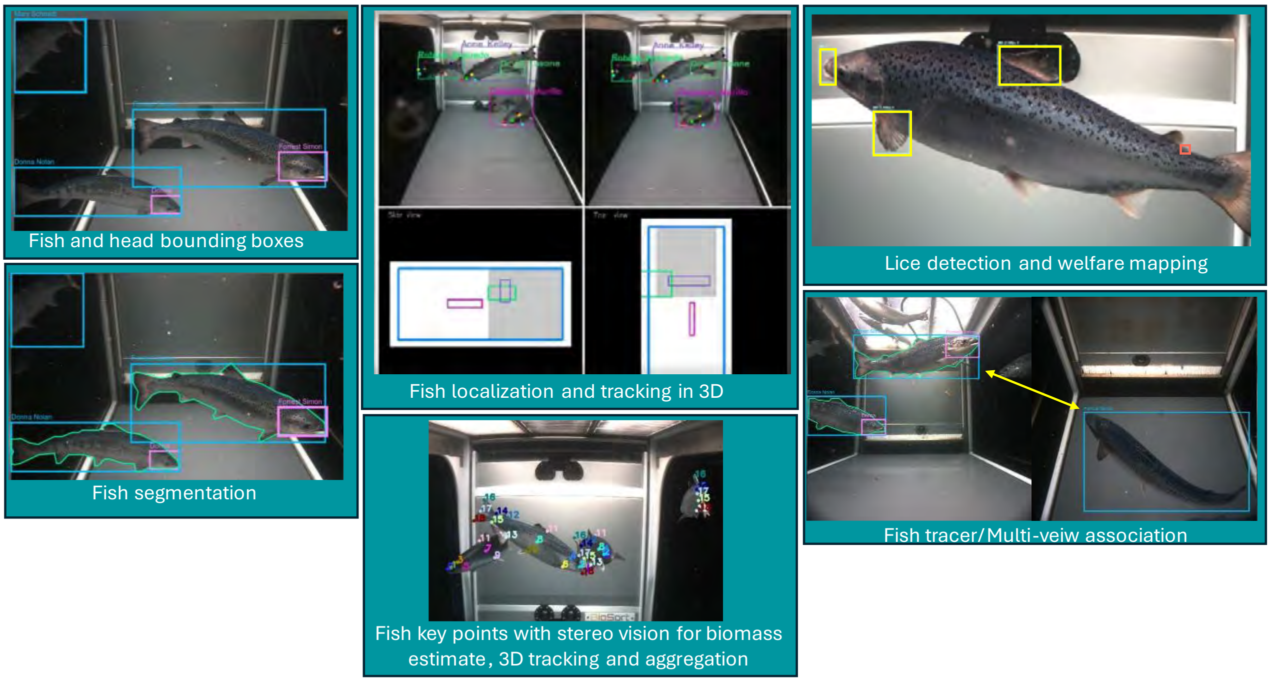

Figure 26: Visualization of selected iFarm computer vision models; fish head and bounding boxes, fish segmentation, fish localization and tracking in 3D, fish key points for biomass estimate, 3D tracking and aggregation, lice and welfare detection and fish tracker/multi view association.

Phase 1	De eloped initial comp t er ision algorithms foc s ed on as ic image capt re and processing capa ilit ies. mplemented early ersions of machine learning algorithms for simple fish detection. Created a r dim entary data handling frame ork to manage image storage and retrie al.
Phase 2	pgraded image processing algorithms to adapt to aria le lighting conditions. ntegrated more ad anced machine learning models for fish and head detection, preliminary tracking, image alit y classification, etc. egan de elopment of real time edge processing pipelines to handle higher data thro ghp t and impro e system responsi eness
Phase 3	De eloped and optimi ed integrated soft are sol t ions that com ined image capt re , real time processing, and machine learning analysis into a cohesi e system. ntrod c ed sophisticated algorithms for iom ass estimation and stereo ision to acc rat ely meas re fish iom ass. De eloped comp t er ision algorithms for fish detection and lice and elfare detection nhanc ed the fish identification system ith deep learning techni es , s c h as Face et and implemented clo d storage sol t ions and data retrie al pipelines for sa ing indi id al data
Phase 4	mpro ed control algorithms for sorter actions and a t omated s s ea antifo ling mpro ed em edded soft are to manage all electronics De eloped pipelines and s er interfaces for displaying li e pop lat ion statistics

Figure 27: Overview of the main characteristics and development steps in software for each phase of the project. The algorithms have evolved over the phases ending up in mature algorithms for individual health recordings and population statistics.

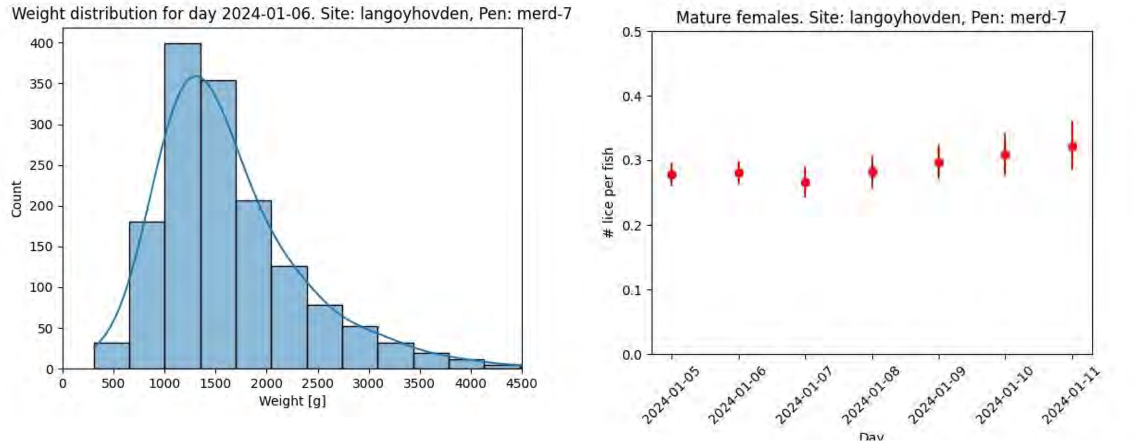

Figure 28: Example of output statistics from the iFarm sensor. To the left weight distribution from site Langøyhovden, cage 7 06.01.2024, to the left estimated lice counts with confidence intervals from the same cage between 05.01.2024-11.01.2024.

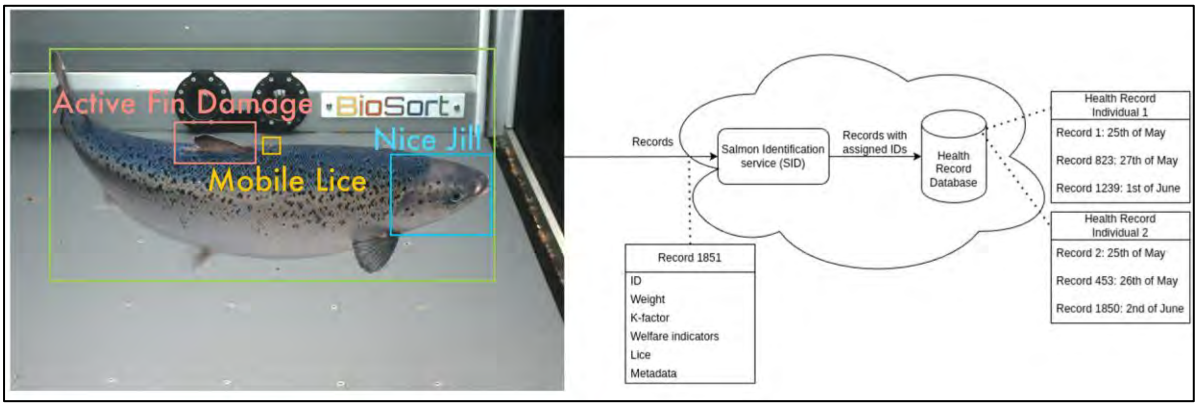

Figure 29: Data from individual fish is collected and stored each time an individual passes the sensor to build individual health records for each fish. Individual fish is identified by the unique spot pattern, and ID together with other detections (e.g lice, welfare-indicators, weight) is consolidated to a record. 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".

7.3 iFarm Sorting System

The sorting concept is a unique part of the iFarm system, and the purpose of the system is to facilitate singulation of individuals with pre-defined traits. A gentle sorting mechanism for live fish has been developed, in addition to a solution for fish transport and infrastructure post-sorting. This has marked a significant milestone in salmon farming, demonstrating for the first time the feasibility of remotely capturing and transporting single fish within a pen under full human supervision to monitor fish welfare. This represents a notable achievement for both the project and the aquaculture industry. The overall set-up and main learning points for each iterative step of the sorter development is described in table 3.

Upon the first sorter evaluation in a commercial cage, a range of sorter concepts were evaluated and two were tested in a tank by BioSort at Fornebu. The main learning was that non-rigid capturing walls had high risk of fish evading capture and were discarded as an option.

In the first sorter tested in a commercial cage, the sorter chamber was positioned following the sensor chamber, thereby extending the passage through the iFarm house, and limiting sorting to instances to when fish were swimming in a specific direction. The sensor and sorter chambers were therefore consolidated into a single opening with a depth of 1 m. The capturing mechanism of the first-generation sorter consisted of 14 motorized barrier points rising from the sorter chamber floor. However, this design was found to be too complicated and not robust enough for commercial farming. Therefore, the second-generation sorter was redesigned and had five raising walls; two on each side of the sensor/sorter opening and one raising from the middle of the opening used to guide fish in the desired direction. This design proved to be suitable, and a number of fish were successfully sorted in phase 2 and 3 under full supervision of Cermaq and BioSort staff to ensure that tests were in compliance with fish welfare. No negative effects were seen when fish was mechanically captured and guided towards one side of the sensor/sorter openings. Images from this sorting event are presented in Figure 31. The third-generation sorter was further developed, whereas the five raising walls have been replaced with roller-curtain-like walls to simplify the sorter, which also eliminated the need for extra space below the docking. This sorter has been validated in field-tests and will be installed in a commercial pen during 2024 and is presented in Figure 32.

For the infrastructure post-sorting, several alternatives have been tested. Since the sorting project focused on removing fish with poor health or underperforming fish, targeted sorting of single individuals and further transport to a smaller holding entity was prioritized. In the first-generation sorter, fish were directed either back into the open snorkel volume or into a confined net volume. The second-generation sorter infrastructure involved utilizing suction to gently transport the sorted fish from the iFarm house to a surface holding volume. Post trial-welfare evaluations by Cermaq and BioSort showed a minimal effect on the fish, and improvements were introduced to the third-generation sorter to mitigate the identified risk elements in the transport system related to sharp edges in the valve solution for creating suction.

Table 3: Summary of set-up and main learning points for each iterative step of the sorter development.

	Set up	**Main learning points**
Phase 1 Pilot test	• Workshops with concept discussions. • Tank trials evaluating multiple concepts.	• High risk of fish evading capture with non-rigid walls.
Phase 2 Gen 1	• The sorting mechanism was 14 raising fingers. • Fish guided into a small net volume or directly back in snorkel. • Sorter unit placed after sensor unit.	• Capturing volume had to be bigger. • More speed was needed in enclosing walls. • Complete walls needed since fish escaped though point barriers. • The sorter unit should be integrated in sensor unit to be able to sort both when fish swims in both directions.
Phase 3 Gen 2	• The sorter mechanism was five raising walls. • Fish guided back in snorkel or transported to a tank in the surface. • Sensor unit and sorter unit was integrated.	• Transport system should be improved with better valve function for suction. • Enclosing walls should extend all the way to the sensor ceiling. • Sorter walls should be collapsable.
Phase 4 Gen 3	• Collapsable sorter walls. • Improved fish transport system towards a gentler design and increased hose size from 200 to 250mm.	

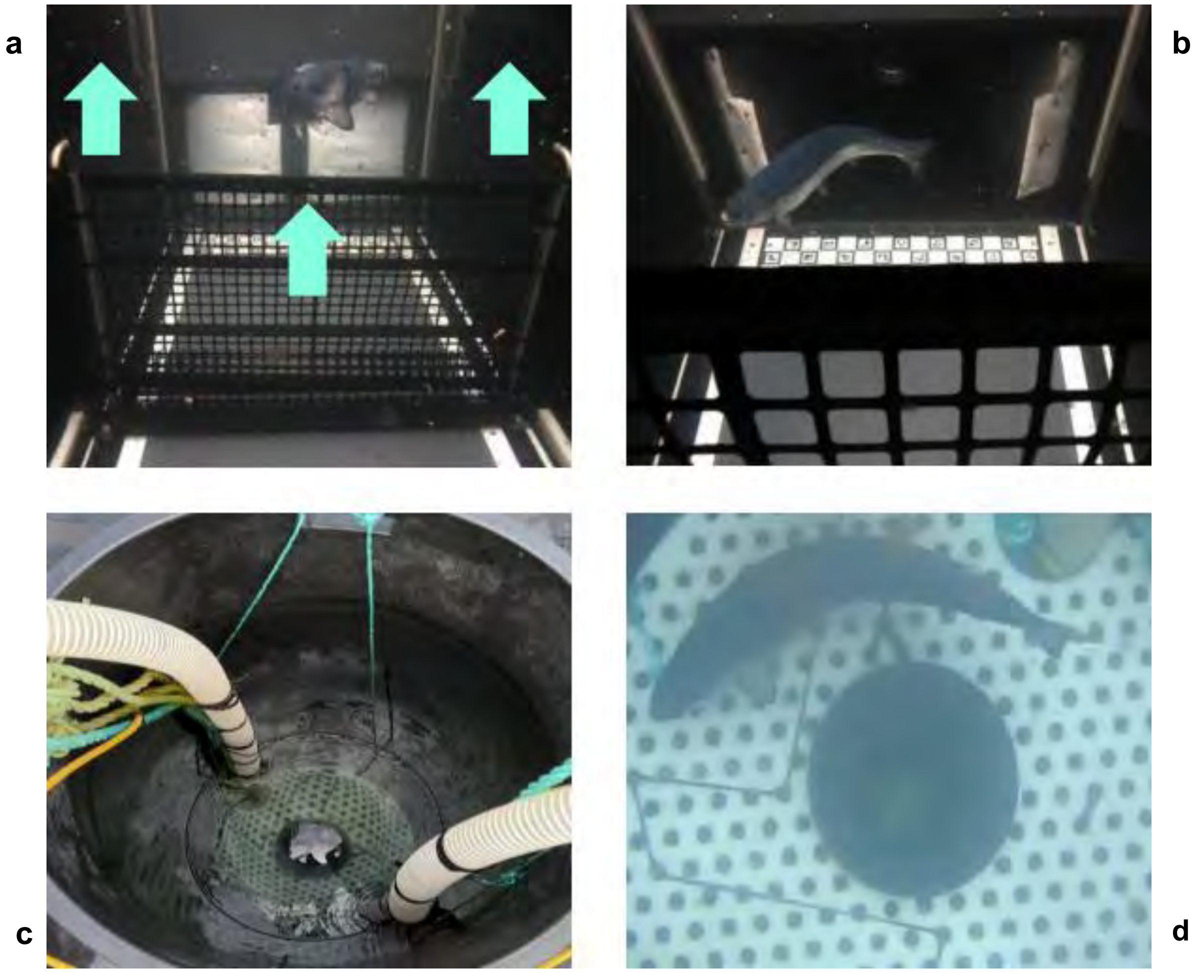

Figure 30: Images from sorter and fish transport test in phase 3, a) fish is captured with three emerging walls within the sensor/sorter opening, b) the mid wall guide the fish to the sensor side where shutter walls are opened, c) suction is generated by opening a valve to a surface tank, d) fish is transported with suction and ends up in the surface tank.

Figure 31: iFarm sensor and sorting opening unit on land. Foldable sorting walls lay in resting position in the middle of the sensor.

7.4 Location Certificate and Functional Testing

Through all phases of the iFarm project, there has been close collaboration among the project partners, 3rd party suppliers and the authorities to ensure a concept that satisfies all safety requirements for aquaculture facilities. DNV was engaged early to provide third-party verification and approval of the iFarm concept. The approval included evaluations, third-party verification and certification of components included in the iFarm concept according to the NYTEK2012 regulation and NS9415:2009. ScaleAQ has presented the necessary analyses and design documents related to the facility, mooring, nets, floaters, and the global design. BioSort has produced detailed construction drawings and analyses for the iFarm components. DNV`s independent review of the presented documentation, and inspections at the sites resulted in new facility certificates for each of the phases in the project. Product certificates have been issued for nets with roof net and snorkel, docking, sensor house, inner floaters in addition to verification of other additional equipment used in the project.

Functional testing of all relevant operations has been performed before each new phase of the project. This is to ensure that all critical functions and operations were in alignment with their intended purpose. Following each testing phase, a functional test report describing the tests and results has been produced. A user manual for the iFarm is also available on Cermaq`s website, along with the functional test reports (Cermaq.no/iFarm). DNV has reviewed and approved the user manual and functional tests according to NS9415:2009.

8. Biological Documentation

Biological performance has been followed with operational welfare indicators (OWI's) and laboratory-based welfare indicators (LABWI's) that focus on project specific parameters such as behavioral monitoring, and production performance. Biological documentation has been a critical component in the project to guide development of the iFarm technology in the right direction and assure responsible testing of new technology in commercial scale. The monitoring program was designed to examine risks associated with snorkel and submerged cage production, i.e. issues related to consequences of limited surface access for the fish to refill the swim bladder with air (Korsøen et al., 2009; Stien et al., 2016; Oppedal et al., 2019; Sievers et al., 2021). A range of OWIs from the FISHWELL handbook (Noble et al., 2018), primarily for snorkel and submerged cages (Kolarevic, Stien et al., 2018) were utilized, which were supplemented with monitoring from the Cermaq Welfare Scoring protocol (CWS, 2018). Further OWIs and LABWIs were added to the monitoring program as the project progressed.

The OWI and LABWI tool box were evaluated both during and after each project phase to consider the insights the tools gave into each of the development objectives. Tools either offered good or mixed insight and were retained, or if insight was lacking, they were demoted in the next phase (see Figure 33 below). For example, in phase 2 a full organ package monitoring plan was implemented to get a wider overview of the health status of the fish and further internal OWIs including liver and digesta status were also introduced later in phase 2.

Evaluation at the end of the phase led to the removal of the full organ pack and a return to histological monitoring of the heart and gill, but the retention of internal OWI scoring.

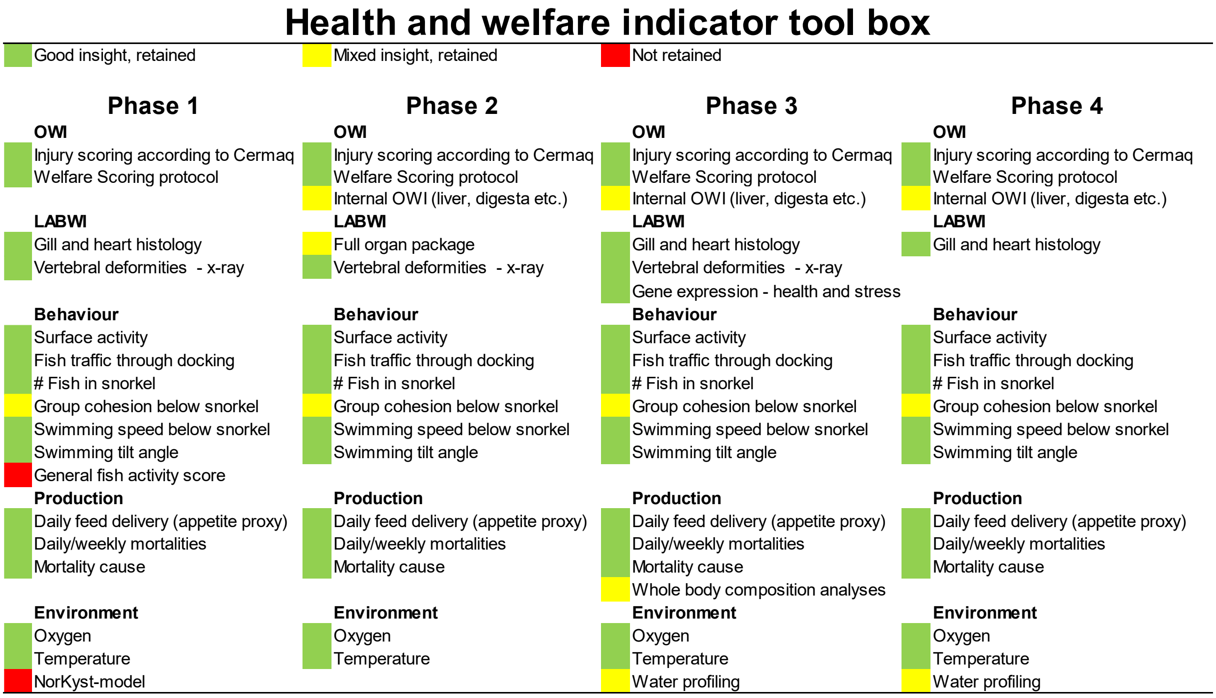

Figure 32: Developments in the OWI and LABWI toolbox over differing phases of the iFarm development project.

For behavioral monitoring, the video tool Argus, described above under chapter 5.1 Project tool was employed. Where possible and depending upon the project phase, behavior was monitored 2-4 times daily or 3 times weekly. Water quality was monitored using up to 3 sensors per cage in each project phase. Histological and morphological OWI and LABWI data was collected on a monthly to quarterly basis in and around various testing steps within each phase of the project. Monitoring for vertebral deformities occurred twice during relevant phases on up to 40 fish near the start of monitoring and up to 60 fish as the fish approached harvest. Gene expression (44 genes) and whole body composition analysis in phase 3 occurred on 10 fish per cage, ca. 3 months into the dome sensor house deployment period.

8.1 Fish Health and Welfare Monitoring

The project has documented the effects of iFarm upon welfare parameters with an aim to identify potential health, welfare and production related risks. These will be summarized in relation to environmental and animal based welfare indicators.

8.1.1 Environmental OWIs

Dissolved oxygen saturations were generally over 80 % in the snorkel and deeper within the cages and did not drop to levels that are sub-optimal in relation to differing water temperatures (Remen et al., 2016). Temperature and salinity levels were within a normal range for the geographical placement of iFarm farming trial sites.

8.1.2 Behavior

iFarm sensor house deployment reduces surface activity for at least part of the deployment period. This, in tandem with reduced growth and feeding efficiency could be an indicator of sub-optimal surfacing activity, which will be considered in future design iterations and operational decisions of iFarm. However, there were no observations of fish with tilted swimming angles, and no marked changes in swimming speed during this time. This suggests that fish did not exhibit long-term problems with buoyancy and no fish were sampled with vertebral deformities that have been previously associated with long-term submergence (Korsøen et al., 2009). Fish numbers in the snorkel also often increased following house deployment.

8.1.3 Appetite

Daily feed delivery within different smolt groups was generally matched between cages over each production period. However, growth and feeding efficiency were impacted by iFarm snorkel production.

8.1.4 Individual-based OWIs

Attention was paid to morphological OWIs that are especially applicable to snorkel cages (snout damage, wounds and fin damage, after Stien et al., 2016 and Oppedal et al., 2019). There were generally no major differences in these OWIs between cages in phase 1 except for wound incidence which increased when the dome sensor house was mounted (outlined in figure 34). There was also a higher prevalence of snout damages in snorkel cages in phase 3 (outlined in figure 35) which is an established risk of snorkel production (Kolarevic, Stien et al., 2018). Fin damage severity levels (corresponding to the condition of the worst fin on the fish) were mostly moderate and no improvements were observed as the development project progressed. Severe fin damage was also highest in the cage with the dome sensor house in late summer in phase 3 and absent in the open cage. Wright et al., (2018) reported that between 60 and 65 % of fish exhibited severe fin damage at the end of their study period in both snorkel and standard cages. Oppedal et al., (2019) reported no significant difference in dorsal and caudal condition indices between control and snorkel cages and average fin condition could be classified as moderate for the caudal fin and mild for the dorsal fin.

Figure 33: Bar chart summarizing the numbers of fish affected by fin damage, snout damage and wounds in a traditional snorkel and iFarm cage in phase 1. The x-axis represents the number of fish affected (%). The y-axis outlines each sampling point. Injuries are benchmarked against the Cermaq Welfare Scoring protocol and Levels 0, 1, 2 and 3 are represented by green, yellow, orange and red respectively. Note the potential effect of non-medicinal delousing on fin damage at the second to final sampling point. Vertical blue/purple bars illustrate cage figurations (light blue = traditional snorkel, darker blue = iFarm snorkel, purple = dome house deployment).

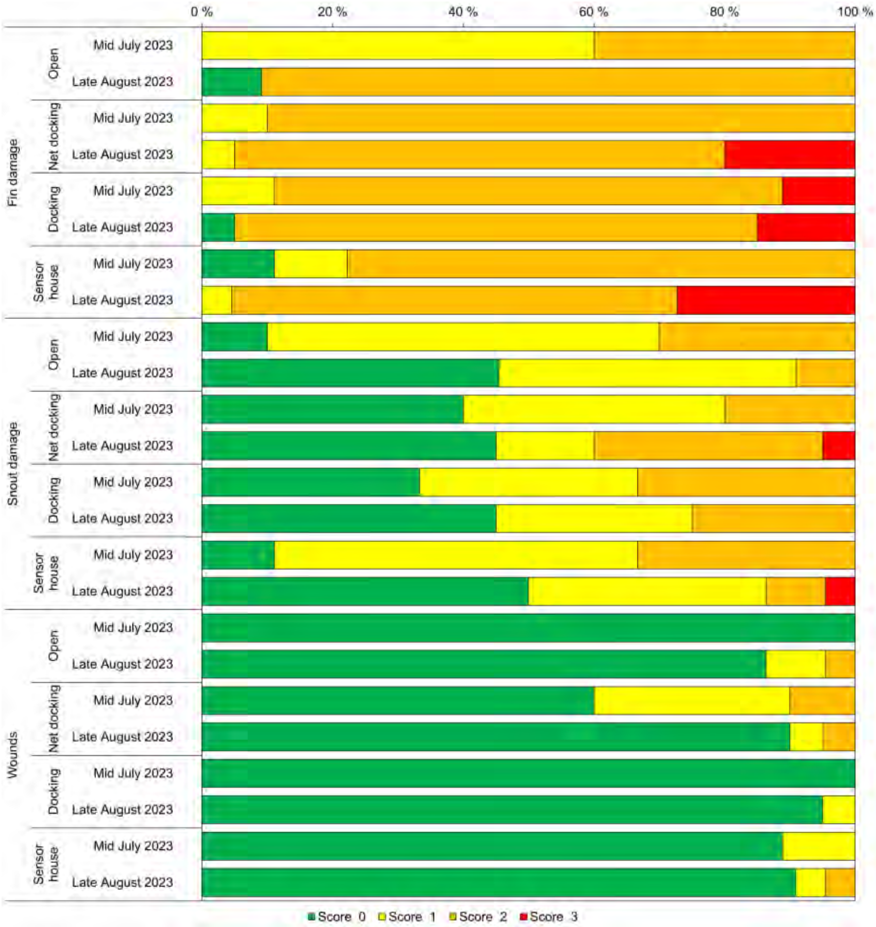

Figure 34: Bar chart summarizing the numbers of fish affected by fin damage, snout damage and wounds in during summer in phase 3. Corresponding data are shown for the open cage, the iFarm with the net docking, the iFarm with a standard docking and the iFarm with a dome sensor house deployed. The x-axis represents the number of fish affected (%). The y-axis outlines each sampling point. Injuries are benchmarked against the Cermaq Welfare Scoring protocol and Levels 0, 1, 2 and 3 are represented by green, yellow, orange and red respectively.

8.1.5 LABWIs

Gill and heart pathologies during periods where the sensor houses and snorkels were mounted were mainly absent or mild. When gene expression was investigated ca. 3 months into sensor house deployment in phase 3, there were no differences between cages in the average expression levels of 44 immune and stress genes. Whole body composition evaluation of these fish found no major significant differences with respect to fat, protein, energy, ash and dry matter. However, the protein level of salmon from the cage with the dome sensor house was higher compared to a cage with the open docking solution, which correlates with a lower whole body fat level and a visceral fat score indicating a leaner fish, but average condition factor was still 1.27 in this cage at time of sampling.. In phase 3 the majority of fish sampled from the open, net docking, standard docking and dome house cages during sensor house deployment had an orange/brown liver color (with orange livers classified as normal). The proportion of fish with empty stomachs decreased after winter until harvest and visceral fat levels suggested fish in all snorkel cages were lean in late winter but got less lean as time progressed.

8.1.6 Mortalities

When comparing weekly mortality trends between cages and phases, levels were generally below 0.1-0.2% when the dome sensor house was mounted, and any marked increase in mortality levels during a given production period correlated with non-medicinal delousing events (see figures 36 and 37). However, total mortalities were often slightly higher in the iFarm dome house cages than associate or open cages (5.2% vs 3.4% in phase 1 and 7.1% vs 4.1-7.7% in phase 3). There were also more wound related mortalities in the iFarm dome house cage during sensor house deployment than other cages (ca. 2% at the end of phase 3), and trends in wound related mortalities were seasonal and driven by minor increases during the winter months (e.g. figure 36).

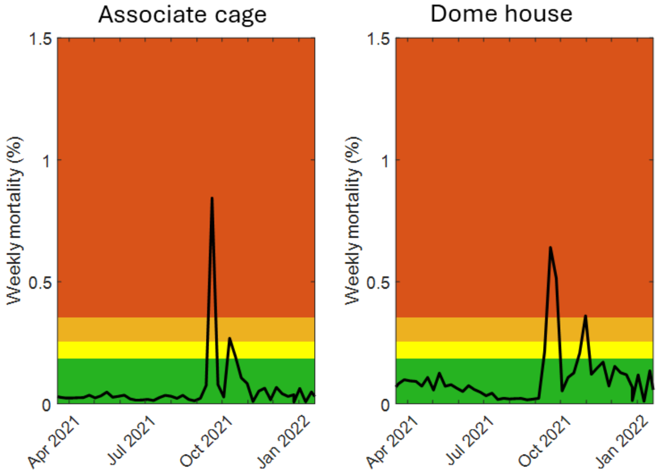

Figure 35: showing trends in weekly mortality percentages for the period of sensor house deployment for the iFarm dome cage from 18th March 2021 until its removal prior to harvest on the 20th January 2022. Mortalities are benchmarked against the Cermaq Welfare Scoring protocol and Levels 0, 1, 2 and 3 are represented by green, yellow, orange and red, respectively.

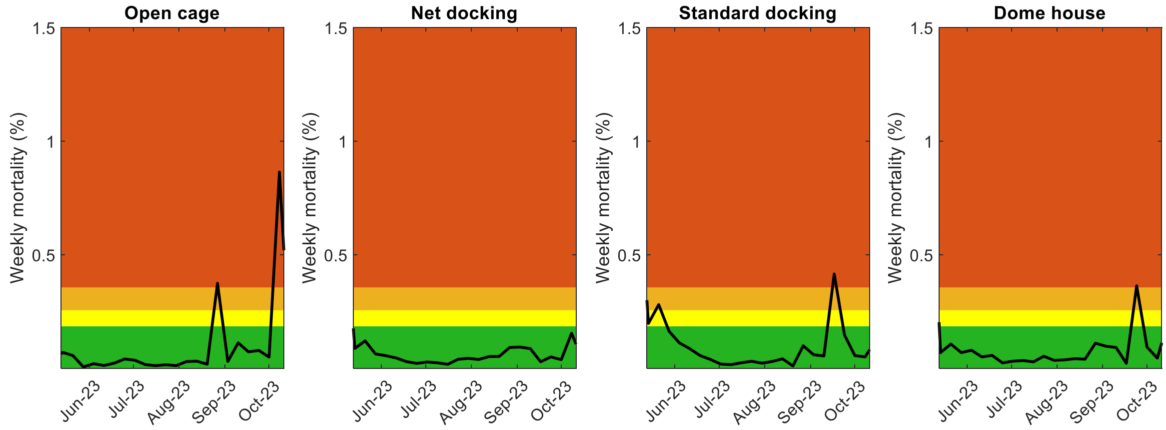

Figure 36: showing trends in weekly mortality percentages for the period of sensor house deployment for the iFarm dome cage from 13th May 2023 until 11th October 2023. Corresponding weekly mortalities are shown for the open cage, the iFarm with the net docking and the iFarm with a standard docking. Mortalities are benchmarked against the Cermaq Welfare Scoring protocol and Levels 0, 1, 2 and 3 are represented by green, yellow, orange and red, respectively.

8.1.7 Fish Health and Welfare risks

All risk factors identified during the project that could have an effect on the health and welfare of the fish were considered on a regular basis for product development priorities and for operational routines during everyday farm activities. Particularly risks in relation to planned operations on site like the deployment of different equipment, specific iFarm infrastructure (roof-nets, iFarm sensors) and if required delousing operations were paid close attention to, so that appropriate measures could be taken to prevent or correct unwanted incidences.

Increased winter aggregation of fish in the snorkel was considered a potential risk factor for ulcer/sore driven mortalities, hence it was implemented as a risk factor and an important learning was to act early on wound/sore developments even if they are related to winter ulcer outbreaks, as increased fish number in the snorkel may be a risk factor for driving or exacerbating the problem. iFarm sensor house deployment reduces surfacing activity for at least part of the deployment period. Severe risks were not observed (tilted swimming, vertebral deformities) but in phase 1 and phase 3 there were higher incidences of wounds and severe snout damage in the iFarm cage compared to the associate/open cage, which is risk of snorkel production (Kolarevic, Stien et al., 2018; Oppedal et al.., 2019). Although mortalities were generally low for differing phases of the development project when benchmarked against historical data from all farms in the corresponding farming region (P09) (Sommerset et al., 2024), there were examples of minor percentage point differences in total mortalities and wound related mortalities between the iFarm dome house cage and associate cages. There were also some fish health challenges in phase 2 which contributed to elevated mortality in a number of cages that were not related to cage configuration or type, but to an infection with Infectious Pancreatic Necrosis (IPN) and Parvicapsulosis. In recap, with regard to these previously known risk factors and to those that have emerged during the project, both Cermaq and the commercial partners have attempted to develop routes to mitigate against them. The house design itself has been updated with materials, geometries and operational solutions to reduce the risk of potential injuries to the fish if they were to come into contact with iFarm infrastructure. These risks will also be monitored and considered closely in future design iterations, operational decisions and procedures of iFarm.

Table 4 outlining the main risk factors and observations in the project.

	Risk factors for fish health and welfare	**Key parameters for monitoring in the tool box**	**Observations**
Risk factor identified before project	Reduced opportunities to refill the swim bladder in snorkel or submerged cages (Korsøen et al., 2009; Stien er al., 2016; Oppedal et al., 2019; Sievers et al., 2021)	• Surface activity • Traffic through sensor house • Tilt angle • Swimming speed • Vertebral deformities	• Marked decrease in surface activity when sensor house deployed in some cases. • Traffic through sensor matched trends in surfacing activity. • No observations of tilted swimming. • No observations of increased swimming speed over time. • No indication of any relationship between cage configurations and vertebral deformities.
	Contact type injuries (Korsøen et al., 2009)	• Snout damage • Fin damage • Wounds	• Generally, no major differences in these OWIs between cages under welfare scoring except for wound development in phase 1 and snout damage during parts of phase 3. • Slightly higher mortality related to wounds in iFarm cages.
	Water quality in snorkel (Kolarevic, Stien et al., 2018; Oldham, 2023)	• Monitoring of water quality parameters Gill OWI status and histology	• Dissolved oxygen saturations were generally over 80% for the entire project period. • Generally, no major differences in gill damage between cages. • Gill histology status generally scored no to minor changes for all cages.
Risk factor identified in project	Increased aggregations of fish in snorkel (Kolarevic, Stien et al., 2018)	• # Fish in snorkel	• Increase of number of fish in snorkel when the sensor house is deployed. • Risk is elevated at low water temperatures with an increased risk of ulcer development

8.2 Production Performance Monitoring

Production performance has developed in a positive direction throughout the project. In commercial production, the main KPIs for performance are survival, feed conversion ratio (FCR), growth and product quality. The results of the project have been assessed against commercial production. Survival through the generations has mainly been good, and the majority of the cages have had a survival rate of >90%. The average survival in PO9 is 87.1% (Sommerset et al., 2024), which is a little lower than that observed in the project. A positive effect on lice levels in iFarm cages compared to open units has been observed. During phase 1, the number of delousing events was reduced by 50% compared to the ordinary cages at the site. For phases 2 and 3, on average one lice treatment was saved in iFarm cages. Average percentages of Superior fish have been 90%, where the best performing iFarm cage had 97.7%. Superior fish at harvest has increased throughout the project period, from an average of 89% (± 4.4) in phase 1, to 89.3% (± 7.9) in phase 2 and 90.5% (± 7.4) in phase 3. The remaining fish were downgraded to Production A grade. The dominant proximate cause of downgrading through all phases has been deformities and ulcers. There is a tendency towards a slightly lower Superior share in the iFarm cages compared to the open cages, where the iFarm cages have a higher share of downgrading related to ulcers. This correlates with the increase in wounds (in some cases) and wound related mortalities during production in the iFarm cages, but differences in Superior fish between iFarm cages and open cages can also be linked to time of harvest, as the iFarm cages have been harvested to a greater extent in winter when the prevalence of ulcers is generally higher. Alvestad (2021) similarly found ulcers to be the main cause of downgrading in 341 production cycles completed in Northern Norway, with an average of 7.4% of harvested fish being downgraded due to ulcers.

Strategic work has been done on development of the feeding system, feeding strategy and placement of feeding points to improve harvest results throughout the project, which has led to better results. Although iFarm units are somewhat higher in eFCR (economic feed conversion ratio) compared to open units with underwater feeding, eFCR has improved by 0.19 from phase 1 to phase 3. In phase 3, slightly better eFCR was recorded in a cage with iFarm equipment mounted for part of the generation compared to an open cage (iFarm 1.17, open cage 1.2). Similar tendencies are seen for accumulated growth, measured as TGC, where TGC has improved by 0.32 in the iFarm cages from phase 1 to phase 3. Still, the iFarm cages are approximately 0.10 and 0.27 behind the best performing open cages on eFCR and TGC, respectively. Based on the progress made through the project on production performance, it is reasonable to assume that eFCR and TGC in iFarm cages will improve in the future.

9. Project Communication

Throughout the whole project period the project has had a clear strategy to communicate the development, milestones, achievements and learnings to both internal and external stakeholders on a regular basis, and in accordance with the requirements set to communication in the target criteria. The communication activities can be summarized in figure 38.

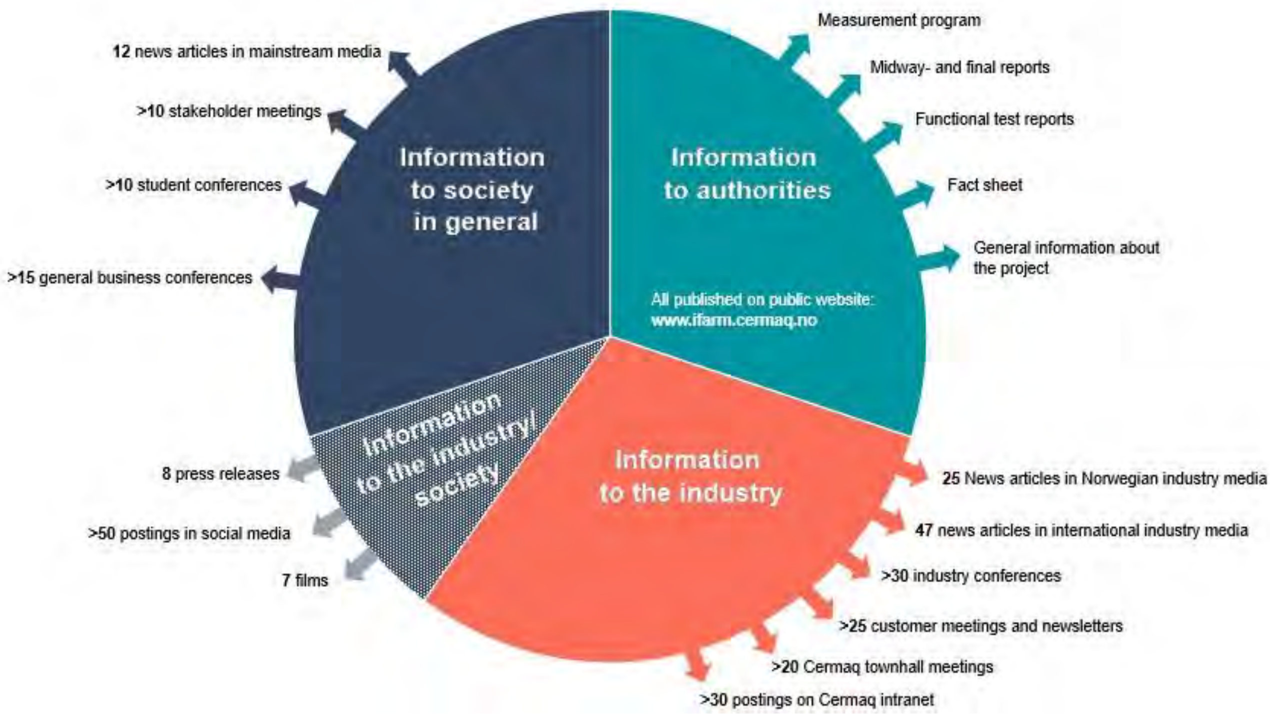

Figure 37: Overview of the total of communication activities during the project period, categorized in three main categories.

The iFarm project differs from the majority of other development license projects being the only project based on developing and implementing new production technology and exploring possibilities related to artificial intelligence and computer vision for documenting and responding to changes in fish health and welfare. This has made it both challenging, but also rewarding to communicate about the project. Challenging in the sense that it is difficult to explain what cannot be seen or shown in a submersible solution. Rewarding in the sense that iFarm conceptualizes a new way of farming fish; from stock management to individualized aquaculture.

Intriguingly, international industry media has followed the project closely throughout the project period. A total of 47 news articles have been published in international industry media and 26 news articles in Norwegian industry media. The interest from conferences both in Norway and abroad shows that iFarm has attracted interest beyond borders and industry, and the iFarm concept has been presented in over 30 conferences throughout the project period.

The iFarm project has contributed to profiling Cermaq in a positive way and has increased the focus on husbandry of individual fish in large populations. The project is recognized as a lighthouse initiative regarding the development and use of AI to document fish health and welfare in aquaculture.

10. Project Evaluation

In this large-scale innovation project, several development processes have been carried out in parallel to achieve high paced innovation. The incremental and iterative approach to product development has facilitated controlled enhancement of iFarm's main elements - cage and house design, sensor and computer vision, and the sorter. The best performing solutions have been identified by iteratively addressing weaknesses and validating effective solutions, as well as by testing and discarding solutions that did not work as intended. The great innovation pace has been achieved by having close feedback loops from validations of overlapping phases of field test and the design, product development, construction, and analytical teams, respectively.

In addition to the development of iFarm's main elements, the project has de el oped sol tio ns that have already been taken up by the aquaculture industry. An example is the zipper system for net roof connection and net roof openings for in-pen equipment like cameras, lights and the LiftUp system. The health and welfare monitoring program has provided valuable learning about how to apply existing tools when adapting production systems in a commercial setting, especially in systems where the fish have reduced access to the surface. In terms of executing large-scale innovation projects within the aquaculture industry, lessons were learned that can be valuable to the industry. For example, the advantage of involving a wide range of stakeholders from the salmon farming organization and the benefit of conducting small-scale pilot projects for refining design alternatives. The working method where technology is iteratively developed in tight cooperation between suppliers, salmon farmers and documentation partners were successful in this project.

The project has successfully navigated a spectrum of risks, where risk management of among others OHS, biology and environment have had a big focus. The absence of serious OHS events on iFarm sites demonstrates that the implemented operational safety solutions have functioned as intended. In terms of environmental risks, two incidents in the project both revealed new equipment-related risks and highlighted the importance of industry best practices to avoid undersized individuals at stocking. COVID19 had the potential to impact the project greatly, but with planning and facilitation of alternative solutions where necessary, the project could be carried out as planned.

It is important to emphasize the substantial amount of time dedicated to analysis, documentation and component construction even before the iFarm equipment was introduced in commercial cages. BioSort has built iFarm houses, sensors and computer vision technology with a high degree of tailor-made solutions. The planning of large cage components with ScaleAQ was carried out months prior to equipment deployment in sea and throughout the project several hundred pages of analysis were provided to DNV to document equipment compliance with legislation.

This final report presents key achievements and evaluations with the aim of sharing relevant knowledge with the industry and contributing to innovation and sustainable growth. The project has succeeded in conducting tests of system designs on cage level (Prototype A) and determining the best product design to achieve iFarm functionality (Prototype B). The main goals, milestones and achievements are shared in Tables 4 and 5.

Table 4: The table summarizes the main project subgoals, milestones, and achievements that address the project criteria.

	Subgoal	Milestone	Achievements
Project criteria	Test geometrical designs of pre-chamber and openings, including number of openings in the pre-chamber to get the fish through the sensor unit.	• Test minimum two design alternatives and map fish behavior in field trials.	Fish swim through pre-chamber when seeking the surface to fill the swim bladder with air and down again for feeding. Out of eight alternatives, the best result was achieved with the Dome design with wide and slightly tilted openings.
	Test geometrical designs of return openings to guide fish back down below the net roof.	• Test minimum one design with specific return openings and map fish behavior.	Fish return from the upper volume down below the net roof, but specific return openings have proven to be less effective for fish return than common entry and return openings.
	Test solution for singulation (sorting) of fish and test post-sorting infrastructure with transport to a holding volume.	• Test minimum one sorter solution to evaluate if sorting of fish in relation to the sensor is possible. • Test fish transportation system from sorter to holding volume. • Test solutions for holding volumes after sorting.	Two sorter solutions have been tested in cage trials and a third sorter is developed. Single fish is sorted and transported without introducing injuries or wounds in a scalable concept for large number of fish.
	Test sensor chamber with recognition technology (computer vision) for identifying individual fish, counting lice on fish and registering other parameters related to health and growth. Test variable length of sensor chamber, illumination alternatives and camera configurations. Data and images should be collected throughout a production cycle.	• Test minimum two alternatives for camera settings mounted in the sensor and tested on fish. • Test sensor system that delivers quality images the computer vision models can be based on. • Test software to collect images from cameras in cages, to servers at BioSort, to enable large scale data and image collection.	Several sensor set-ups have been tested and images of fish through a life cycle were taken in optimized conditions. Algorithms for estimating fish weight and for detecting lice (categorized by stage) and other welfare parameters were built and are running operationally. Algorithms for fish ID were built and individuals were followed over time. Sophisticated software architecture was built

		• Test computer vision tools to enable model building. • Carry out trial for computer vision model for FishID. • Carry out trial for computer vision model for lice counting and separation of lice by stage. • Carry out trial for computer vision model for size/shape of fish. • Carry out trial for computer vision model for detection of wounds on body and snout.	running on the cage, on the barge and on the Cloud.
	Test a complete system with pre-chamber, sensor chamber, sorting unit, return openings and transportation system	• Deliver a complete iFarm system with sensors. • Deliver an iFarm system with sorter and post-sorter infrastructure.	iFarm system equipped with sensors in all openings, a sorter and a transportation infrastructure were installed in a commercial cage.
	Operational effectiveness	• Deliver solution to maintain sensor and sorter up-time. • Deliver solution for safe installation. • Deliver solution to safely carry out daily fish husbandry. • Test operational routines.	iFarm installation and removal, daily operational routines, and fish husbandry is well-functioning.

Table 5: The table summarizes the main project subgoals, milestones, and achievements that address the biological prerequisites.

	Subgoal	Milestone	Achievements
Biological pre-requisites	Develop a complete system which supports good fish health and welfare	• Document fish health, welfare, survival and lice levels and map environmental conditions through each project phase. • Observe fish behavior related to system design choices for each development step.	Fish health and welfare were documented thoroughly throughout the project. Environmental conditions were documented according to standard regulations. An extended program for fish behavior assessment was used to guide system design towards optimal fish performance. All documentation was used to identify risks and improve design and operating procedures.
	Develop a feeding arrangement suitable for the iFarm production system	• Test at least two feeding approaches.	Feeding system is technically functioning and best practices developed.

11. iFarm – Future Outlook

The development license project has shown that iFarm has the potential to be realized as a commercial product. Systems for tracking individual fish over time by creating ID-based health records, in which, fish weight, condition factor, welfare indicators and lice status are recorded, are developed. The next step involves unlocking the unique insights yielded by this information. Understanding the actual growth response of individual fish, in addition to the population as a whole, can be instrumental in understanding and optimizing feed utilization. Systems will be designed to enable continuous assessment of feeding operations, allowing for real-time adjustments. Precise insight in cage biomass and size distribution will be an important tool to optimize harvest planning. Accurate daily estimates of lice and welfare can provide early warnings about emerging issues in the cage, allowing time to initiate mitigating actions. This proactive approach may reduce mortality, prevent lice treatment events, and save costs.

BioSort and Cermaq see the opportunity to simplify iFarm when moving towards a commercial product. Core technology elements of iFarm, like custom illumination and camera systems with automatic cleaning, together with corresponding multi view software, real time processing, and cloud systems are mature and can easily be reconfigured in many ways. An iFarm unit that is smaller, lighter and cheaper is already well underway and is important to transition iFarm to a commercial product. This approach also addresses identified welfare risks with increased surface access among others. Focus on growth and feeding results will continue and the simplified design is expected to bring benefits to production performance. A centralized snorkel and feeding arrangement that resembles the cage structure seen in air dome systems, or other submerged solutions will be investigated.

Beyond iFarm insights, the capability for individual lice treatment within iFarm will be of high priority. This functionality extends beyond the development license project but is important for a commercial iFarm. The goal is to eliminate the need for group treatments and to remove lice before they can reproduce, thereby keeping lice propagation low within farm sites and regions.

Reducing mortality and achieving higher superior shares are the original and existing main goals of iFarm. Removing fish that can transmit disease to others or fish that have welfare issues can give a more robust population. These functionalities are driven by the ability to capture individual fish with the iFarm sorter and moving them to the surface which has been demonstrated in the development project. However, removing fish from the cage involves introducing hoses and holding volumes, and it will be explored whether this can be done on an as-needed basis instead of being permanently present in each cage.

The goal is that iFarm systems installed in 2025 and beyond will provide value creation through lower production costs with less lice treatments, better fish welfare and health, while providing an unmatched insight into growth and health in the population, driven by individual health records. Following these developments, and a documentation of the final product's effect upon fish health, welfare and production performance, iFarm will be made available for salmon farmers beyond Cermaq.

12. Project Partners

The iFarm project would not have been possible to carry out without the employees at Cermaq. The project group is grateful for all the time and expertise that have contributed to the success of the project. Special thanks are directed to the employees at the sites Martnesvika, Langøyhovden and Hellarvika who have worked purposefully every day to move the project for a rd. h e employees on Cerma 's ser i ce o ats and the ser ice o ats l ti afety and Multi Arctic have been essential for the implementation of the project. Cermaq is also very grateful to BioSort, a serious and skilled project-partner, and all their dedicated personal for their timely and accurate contributions and deliveries throughout the project. In addition to these, Cermaq and BioSort wishes to give special thanks to the following:

Development project partners

BioSort

BioSort is grateful to all employees contributing with expertise within computer vision, embedded solution, edge and cloud service, mechanical engineering, production, cage system design and project management. All these disciplines and more have been instrumental in the project. Additionally, several suppliers/sub-contractors have contributed to deliver and facilitate all tailor-made technical solutions. BioSort is thankful for all dedicated efforts, both internally and externally, to realize the iFarm product.

SCALE AQ

ScaleAQ has been an important collaboration partner in the project and has been the main supplier of equipment, including iFarm specific cage arrangements. ScaleAQ has also been in o l ed in the process of defining the project's risk points, e ipment-specific analyses, and logistics of equipment throughout the project. The project is gratef l for caleA 's contributions and wishes to extend a special thanks to Ida Strand, Martin Søreide, Åsmund Skjærvik and Vidar Skarpnes.

Documentation partners

Nofima

Nofima has been essential for supporting the biological follow-up in the project with the development of important parameters for monitoring fish health and welfare, conducting sample collection and data analysis. Nofima has also played an important role as a third party in the riting of the project reports. h e project is gratef l for ofima's contributions to the project and would like to give special thanks to Chris Noble, Renè Alvestad, Ingrid Måge and Gunhild Seljehaug Johansson.

DNV

DNV has played a central role in the project, contributing with documentation review, third-party verification and certification of the iFarm system. The project has been dependent on, and is gratef l for, the contri tions that ha e led to the deli ery of the project's target criteria. The project wishes to give a special thanks to Frank-Aage Vikedal, Per Tommy Roten and Svein Erik Endresen.

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