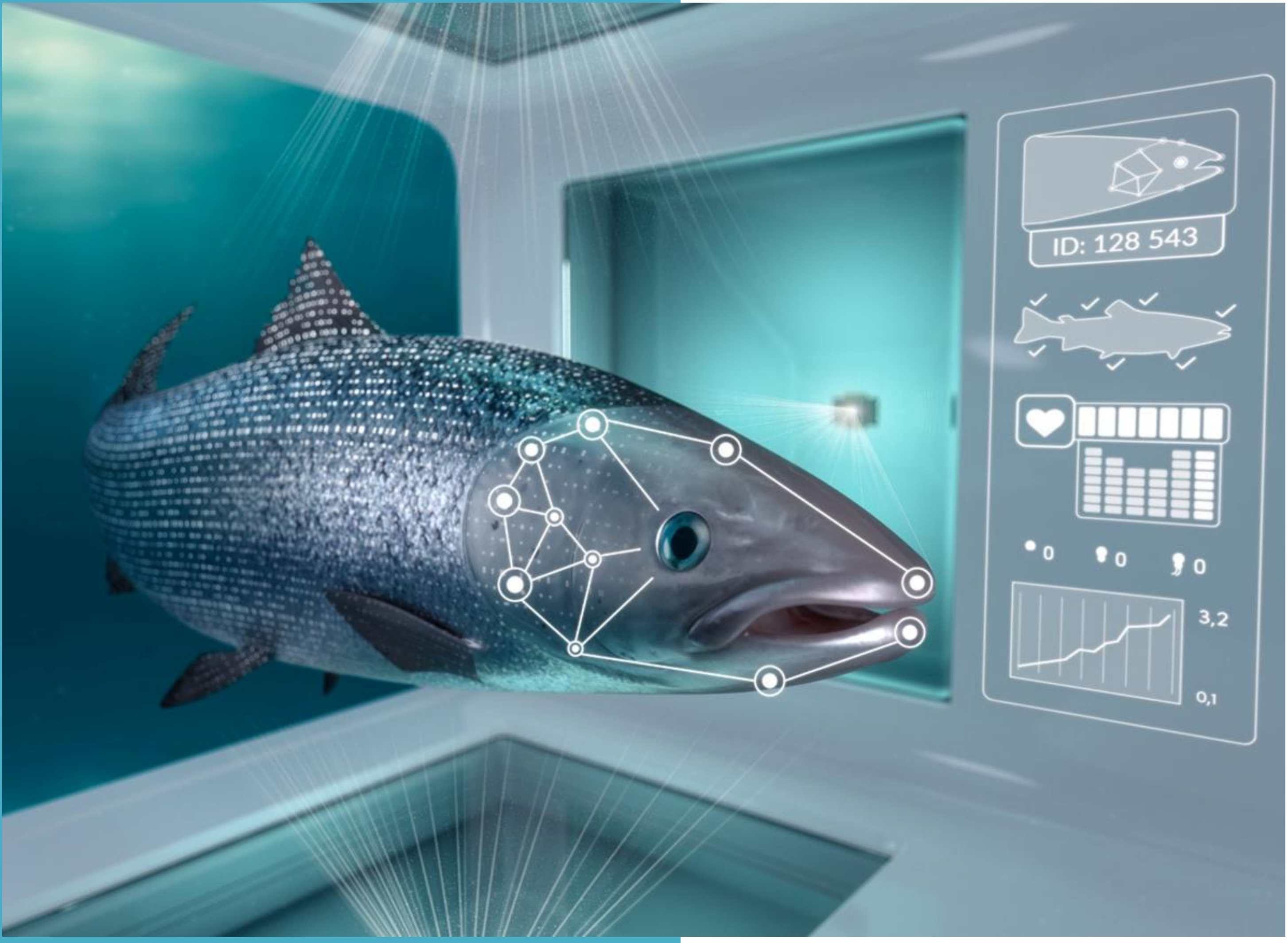
CERMAQ

iFarm: Final report documenting the biological and technological results from Phase 2 (Prototype B) – Cermaq Utvikling avd Langøyhovden



Cermaq Utvikling AS

22.09.2023

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Summary

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

The iFarm development licences in Phase 2 consisted of 9 cages. Four phases of the iFarm project are planned from 2020-2024. This final report addresses the entire Phase 2 period which started when the first cages were stocked on the 26th of May 2021 until the last cage of fish were slaughtered on 10th February 2023. Spring 1-year smolts were stocked in two periods: a) 26th of May 2021 (cages M1-M2) and b) 5th – 14th of June 2021 (cages M3 – M5). Autumn 0-year smolts were stocked on the 10th and 11th of September 2021 (cages M6 – M9).

This report summarises the technological developments that occurred during the report period in addition to results from the monitoring of biological (fish health and welfare) and production performance during the reporting period.

Background

Cermaq's vision for the Age of Aquaculture

The Norwegian Atlantic salmon farming industry is over 50 years old, beginning in the late 1960's where annual production was very limited, amounting to ca. 100 tonnes in 1970 (Hersoug, 2021 and references therein). Steady growth, seeing annual production reach over 200,000 tonnes in the mid 1990's soon accelerated in the early and mid-2000's reaching an annual sales tonnage of over 1.0 million tonnes in 2011. However, growth has somewhat stagnated over the last decade, with annual sales ranging from 1.1 – 1.4 million tonnes per year (Norwegian Directorate of Fisheries, 2022).

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

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

Regulatory frameworks for promoting sustainable and innovative Norwegian salmon farming

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

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

The iFarm concept

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

The iFarm aquaculture concept is a novel production system that aims to introduce individual-based Precision Fish Farming (Føre et al., 2018) to Atlantic salmon aquaculture. It aims to use advanced illumination/camera technologies and computer vision algorithms to identify individual fish (similar to facial recognition), as well as counting lice on the fish and other parameters related to health, welfare and growth on individual salmon held within adapted aquaculture sea cages from smolt transfer to slaughter. The development licence project also aims to grade and sort fish based on their size. The iFarm prototype B production system consists of an adapted snorkel cage that holds fish 12 m below the ocean surface to limit their interactions with potential lice rich surface waters. Cages are also fitted with lice skirts around the main cage collar (not snorkel) down to a depth of 6 meters. The fish must be able to access the water surface to refill their swim bladder with air and have the opportunity to do so by swimming up through the snorkel to the surface (see Stien et al., 2016a). The aim is that each time the fish swims to the surface it must pass through the iFarm sensor which will then identify it and measure various performance, welfare and health parameters.

The iFarm development licence Phase 1

Pilot and commercial testing of the iFarm concept

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

Development of the iFarm concept for commercial scale cages, within the development licence project, was started in January 2020. In September 2020 a full-scale testing of two iFarm systems with a strong focus on operations, technology and fish welfare and health monitoring was carried out to initiate the first full-scale "proof of concept" for the iFarm system and also to instigate the initial full-scale implementation and application of the farming system and take the first steps to realise it as an innovative product. This testing was carried out in tandem with monitoring a third, adapted snorkel cage at the same farming site. Findings on the testing of Phase 1 of the system have been outlined in the Phase 1 final report, submitted to the Norwegian Directorate of Fisheries on 25th July 2022.

This current report addresses the entire Phase 2 reporting period of the iFarm development licence as outlined below.

Technical design and cage set-up Phase 2

Geographical location

This proof-of-concept commercialisation study was carried out at the Cermaq Utvikling AS Langøyhovden production site 68.48236^{0} N, 14.51975^{0} E (see Figure 1).

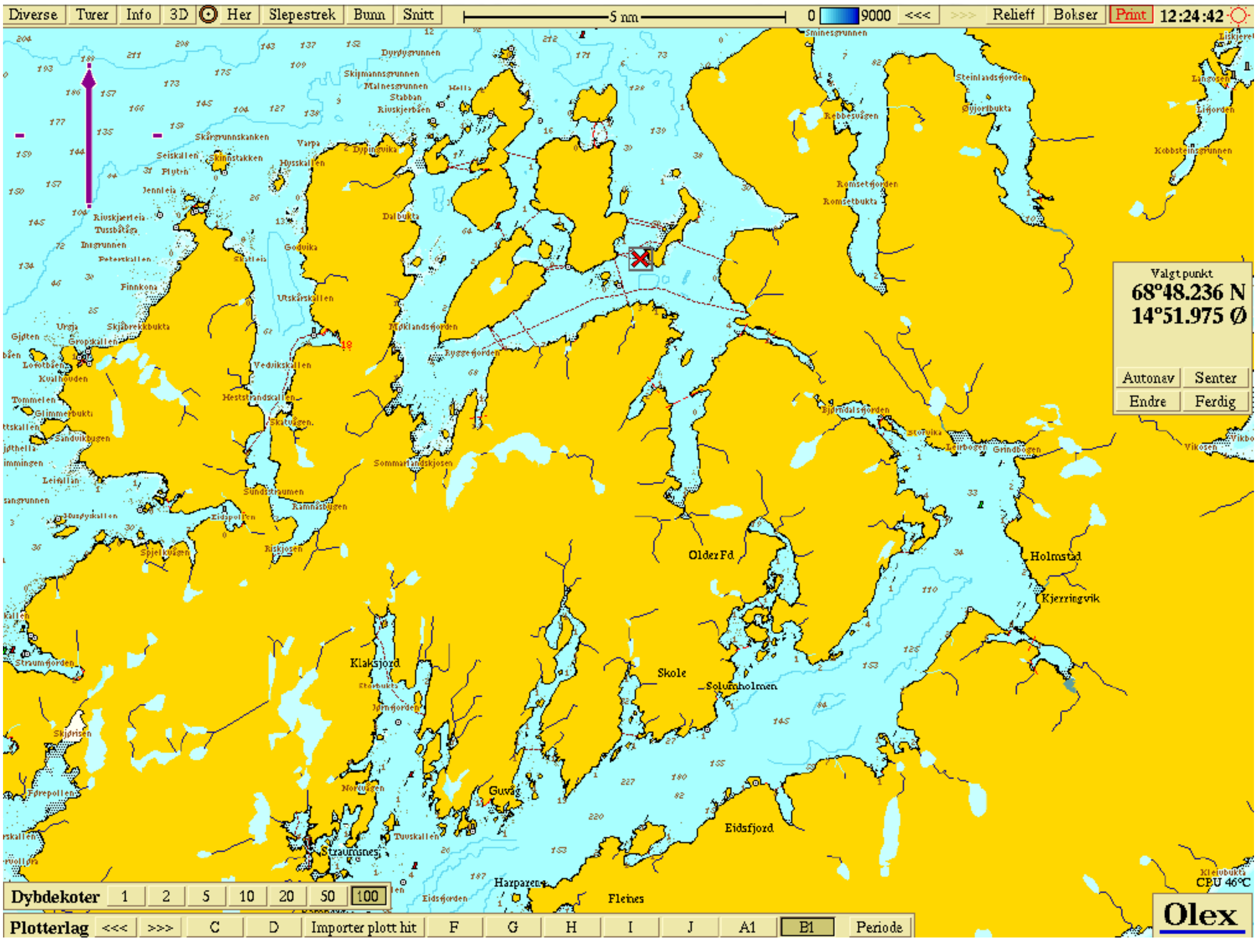


Figure 1 Map showing the Cermaq Utvikling AS facility Langøyhovden, where the iFarm cages are located (map location highlighted with a red boxed x). Map courtesy of Olex AS and reproduced from the Langøyhovden site report by Akvaplan-niva.

Phase 2 timeline and set up

Phase 2 of the project began when the fish were transferred to seawater on the 26th of May 2021. Phase 2 used spring 1-year and autumn 0-year smolts stocked in nine production cages at Langøyhovden, including one associate cage (M5) and eight iFarm cages (M1-4 and M6-9), hereafter termed the associate cage/M5 and the iFarm cages termed by cage numbers above.

Spring 1-year smolts were stocked in two periods: a) 26th of May 2021 (M1-M2) and b) 5th – 14th of June 2021 (M3 – M5). Fish in cages M1 and M2 were from a pooled hatchery AquaGen QTL-Innova SHIELD + HSMB stock from Cermaq Norway AS internal, and fish in cages M3 – M5 were from a pooled hatchery AquaGen QTL-Innova PRIME from an external hatchery. Due to logistical delays with the manufacturing, delivery and deployment of the adapted iFarm snorkel cages M1 and M2, fish were originally transferred into open 120 m net cages at the time of seawater transfer and then transferred into the iFarm cages M1 and M2 on the 16th of August 2021 when fish were ca. 700g.

Autumn 0-year smolts were stocked on the 10th and 11th of September 2021 (M6 – M9) and were from a pooled hatchery AquaGen QTL-Innova SHIELD + HSMB stock from Cermaq Norway AS internal. The stocking details can be seen in Table 1 below.

Table 1 outlining the source hatchery, wellboat, date of stocking and cage destination of fish for iFarm Phase 2 at the Cermaq Utvikling AS facility Langøyhovden 11238. Also shown are water temperatures at time of transfer and fish size and stocking number.

Hatchery	Wellboat	Date of stocking	Cage	Mean water temp. at seawater transfer	Mean weight	Number stocked
Internal	BB Ronja Christopher	26.05.21	M1 & M2	8.0	230 g	151 127 (M1), 149 540 (M2)
External	BB Veidnes	05.06.21	M5	8.1	77 g	160 739
External	BB Dønnland	10.06.21	M3	8.0	75 g	182 550
External	BB Dønnland	14.06.21	M4	8.0	64 g	167 280
Internal	BB Dønnland	10.09.21	M6	6.7	73 g	155 838
Internal	BB Dønnland	11.09.21	M7,8 & 9	6.6	97 g(M7), 75 g (M8-9)	142 445 (M7), 124 081 (M8), 130 278 (M9)

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

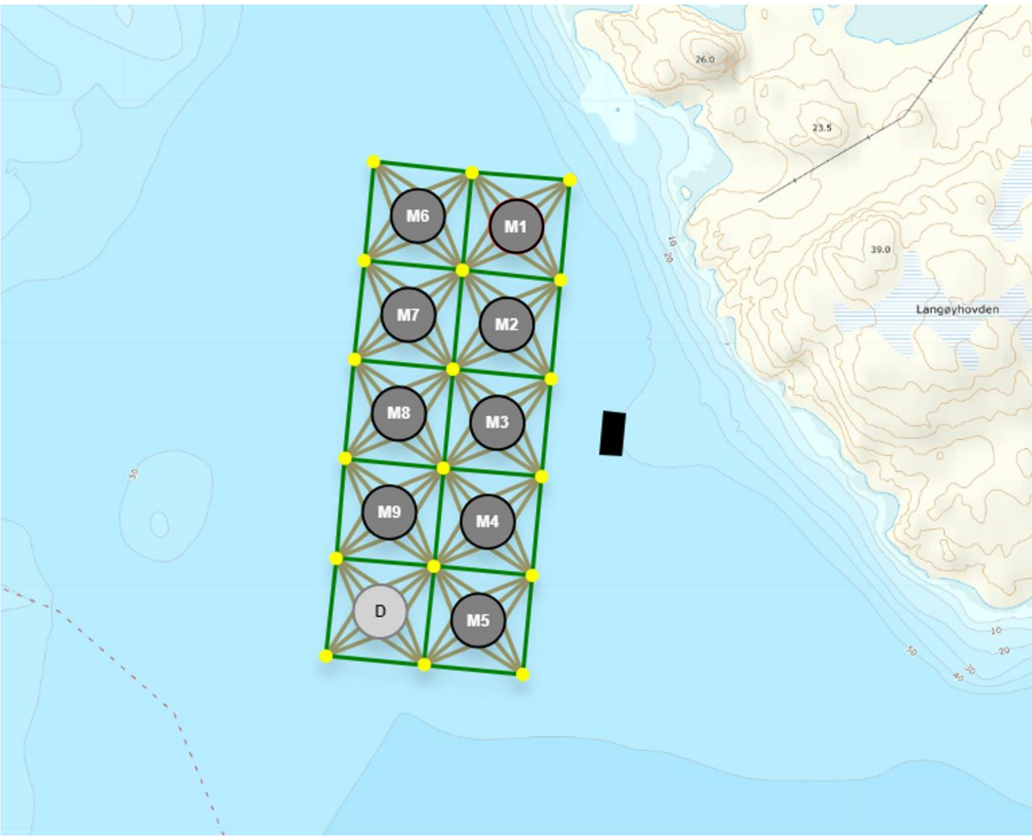


Figure 2 Figure showing the placement of the Phase 2 cages within the Cermaq Utvikling AS facility Langøyhovden 11238.

Feeding systems

Fish were remotely fed from the Sandset feeding center using existing Cermaq Norway AS feeding regimes for the Langøyhovden locality. All fish at the site were fed by an underwater feeding system (AkvaGroup) that distributed feed via six feeding points below the snorkel at a depth of approximately 15 m. The feed distributer is a customized version of AkvaGroup`s "Sjøstjerna", and it has a distribution at the feed points of ca. 0.5 m (see Figure 3a). Fish were fed a commercial diet from seawater transfer utilising: i) Ewos Rapid Asapt 50 40A, 3.5 mm (M3-5) ii) Intro 100 HH 50mg Q, 3.5 mm iii) Intro 100 HH 50mg Q, 4 mm, iv) Power 200 F1 50mg, 4 mm v) Power 500 HO3 50mg, 6 mm, vi) Power 2500 HO3 50mg, 9mm and vii) Power 100 HO3 50gm, 9 mm.

Artificial lighting systems

Fish in each cage were subjected to artificial underwater lighting throughout the natural diurnal and nocturnal period from time of stocking until slaughter. Underwater lighting was provided via four underwater lights (AkvaGroup, Akva Aurora SubLED Combi) placed in the feeding zone, under the net roof at a depth of approximately 15 m (see Figure 3b).

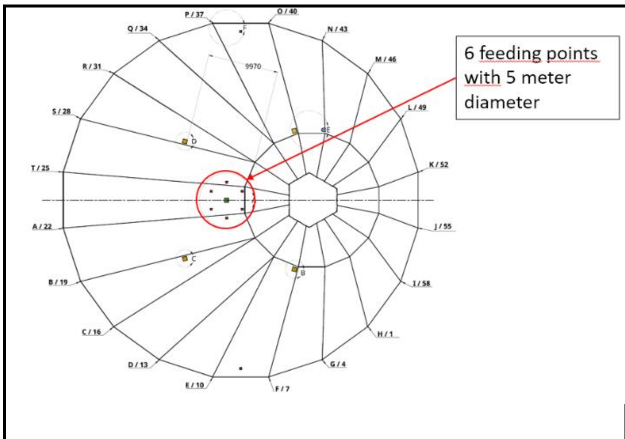
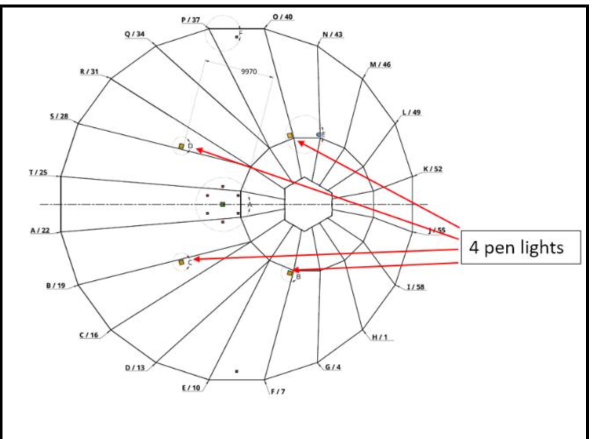
	

Figure 3a, showing feeding points within each cage	*Figure 3b, showing the position of lights within each cage*

Daily operations and husbandry

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

Net cleaning

Net cleaning followed the Langøyhovden site's cleaning plan, and any extra cleaning was carried out when needed. Cleaning was carried out by a service boat using net cleaning robot rigs. The iFarm and associate cages were cleaned a total of six times during the production cycle (see Table 2) and the cleaning procedure included the cleaning of the main net, snorkel net and roof for iFarm cages, and the main net for the associate cage.

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

Cleaning week	Service boat
2021 - 28	M/S Breidsund
2021 - 42	M/S Breidsund
2022 - 16	M/S Breidsund
2022 - 24	M/S Breidsund
2022 - 28	M/S Breidsund
2022 - 39	M/S Breidsund

Net changes

Cages M1, M2, M3 and M4 underwent a net change (smolt net to larger post-smolt net) in June 2022. The fish in M6 and M9 were moved from a smolt net to a larger fish net in October 2022. Nets on the associate cage (M5), M7 and M8 were not changed during the production cycle.

Project plan

The iFarm project goals and objectives will be addressed over three phases (see Figure 4 below). This final report addresses the first half of Phase 2.

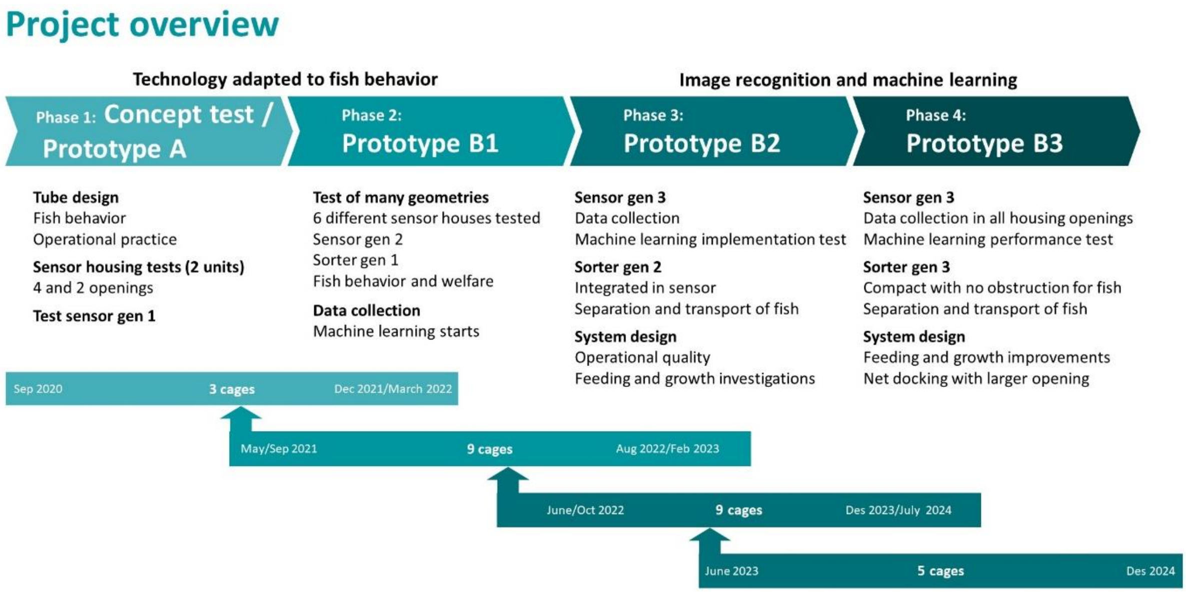
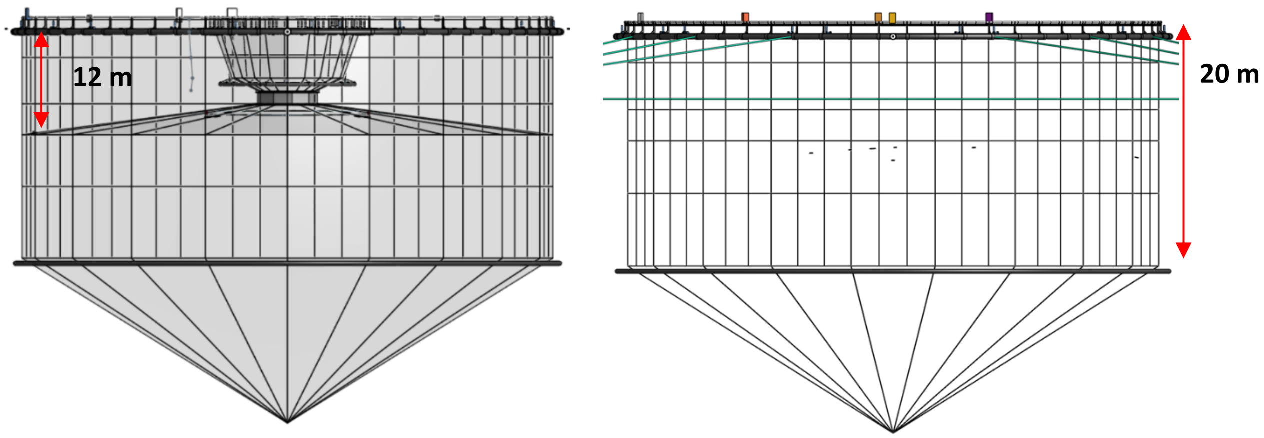


Figure 14 Overview of the iFarm project and Phase 1-4 timeline from 2020-2024. This final report addresses the entire Phase 2 period from May 2021 until February 2023.

Technical development

Cage design and rearing system characteristics

The eight iFarm production systems in Phase 2 were adapted snorkel cages with a net roof that starts 12 m below the water surface to limit fish's interactions with potential lice rich surface waters (Figure 5). Cages were also fitted with lice skirts around the main cage collar (not adapted snorkel) down to a depth of 6 meters. Fish could access the ocean surface to refill their swim bladder with air through the snorkel. Within each iFarm snorkel at a depth of 8 m was the iFarm docking station which had a circumference of 19 m and a diameter of 6 m. The circumference of the snorkel at the water surface was 44 m. The solitary associated cage was planned to have a snorkel and net roof that started at 11 m deep, but due to logistical delays with delivery and assembly the associate cage remained a skirted open cage for the duration of Phase 2 that was fed using underwater feeders (the same was the rest of the iFarm cages) and served as an important reference for fish growth analyses.



iFarm M1-M4 and M6-M9 with the roof net starting at 12 m depth

The Associate cage, M5, open access to surface with underwater feeding

Figure 5 Technical specifications and information for each of the iFarm and the planned associate cages utilised in Phase 2 of the iFarm project.

With regard to the horizontal placement of the snorkel collar ring, the iFarm cages at Langøyhovden had the snorkel placed 10 meters off centre within the outer collar of the 160 m circumference net to aid boat-crane access and staff access to the iFarm collar. This was an update to the initial placement of the snorkel in Phase 1 (5 meters off centre) where crane and work access was somewhat difficult. The separate working platform that was used to access the snorkel in Phase 1 was replaced with a working platform that was integrated with the iFarm collar in Phase 2.

Phase 2 utilised a less labour-intensive method than sewing to connect the net to the docking stations. A good design was found that gives smooth transitions between net and structure and ensures that no fish can swim into the outer upper volume of the cage. The Phase 3 design will build on this experience but use other materials to improve the cost effectiveness of the approach and add functionality.

iFarm docking station housed within the snorkel

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

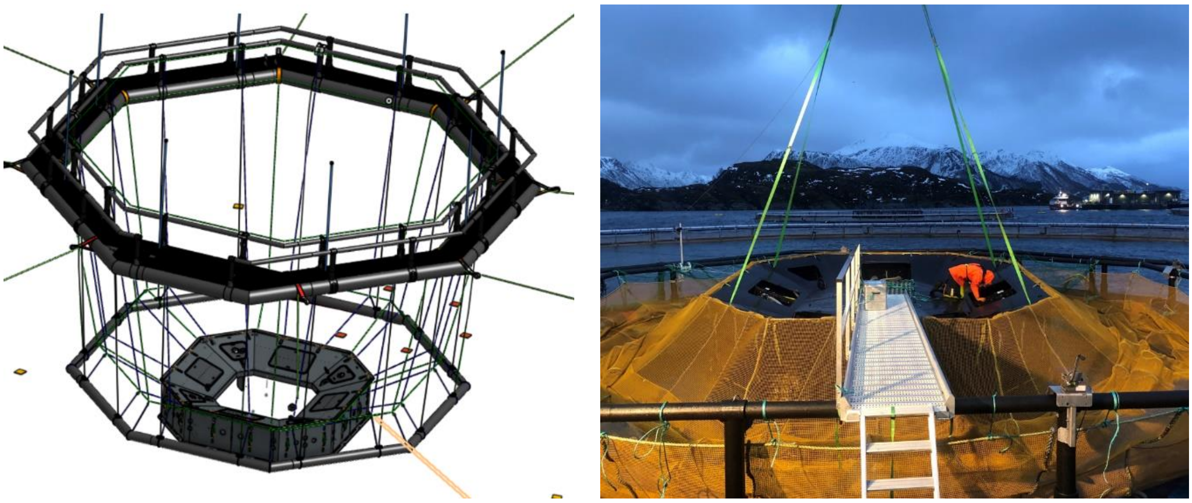
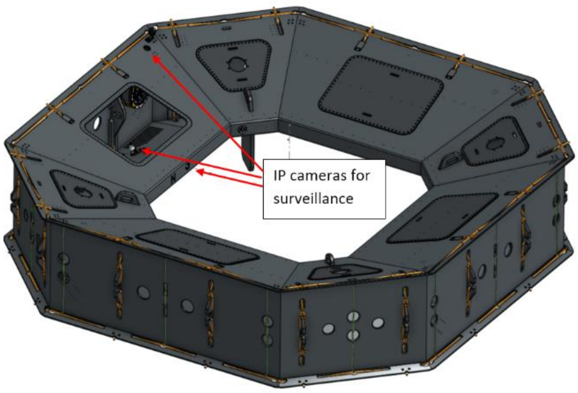


Figure 6 Technical specifications and information for the iFarm floater, snorkel, bottom ring and docking stations (Figure 6a, left) and a picture (Figure 6b, right) showing the installation of a docking station for Phase 2 in one of the iFarm cages. Note the inflated air tube at the base of the docking station.

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

To be able to monitor the behaviour of the fish in and around each iFarm snorkel, docking station and sensor house, especially in relation to system design choices, the iFarm docking units are equipped with 5 (in periods 7) surveillance cameras. These cameras are used to e.g., monitor fish traffic through the iFarm docking station, the number of fish in the snorkel above the docking station and also the behavior of the fish immediately below the snorkel (see Figure 7 for the placement of the cameras in the docking station). The footage from these cameras was also supplemented with footage from the feeding cameras installed in each cage and also with two overhead cameras mounted on the inner snorkel ring and outer cage ring for e.g., monitoring fish surfacing activity (see Figures 8 for an example of the camera output from each iFarm cage).



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

Figure 7 Technical information regarding camera placement for each of the iFarm docking stations utilised in Phase 2 of the iFarm project.

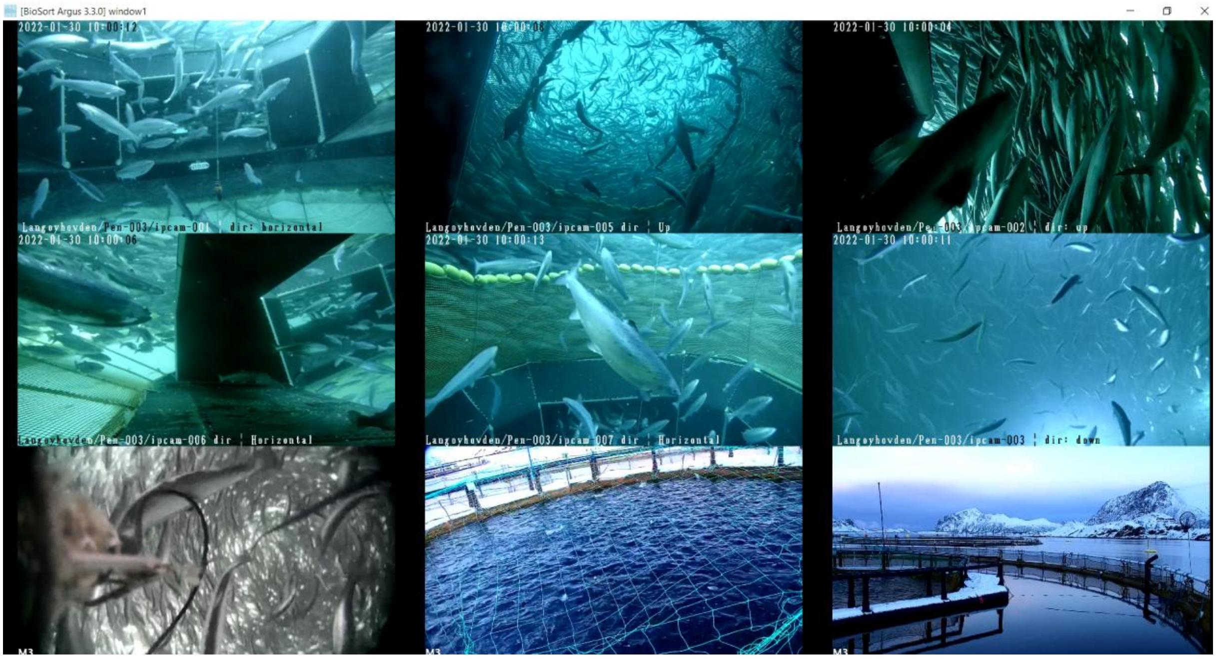


Figure 8 Photo collage showing relevant fields of view for each camera from cage M3 with the sensor house installed

iFarm sensor housings

With regard to testing the geometry of the iFarm sensor house, six different iFarm sensor house units were tested at Langøyhovden: the Spider (cage M1), the Dome (M2), the Two-way (M3), the Pyramid (M4), the Sorter (M8) and the Triangle (M9) (Table 3 and Figure 9). These sensor houses differed both in their shape and number of openings. Cages M6 and M7 were iFarm cages that housed the iFarm docking station within the snorkel but did not have sensor houses mounted for the entire Phase 2 period.

Sensor houses were deployed in cages M1-M4 between 9th - 12th of November 2021. Sensor houses were also deployed in cage M9 on the 17th of December 2021 and in cage M8 on the 8th of February 2022. Due to problems with surface activity/ traffic and the number of fish in the upper volume in three of the iFarm cages, a decision was taken to remove some of the sensor houses during the Phase

2 reporting period. Sensor houses were removed from cage M9 (7th of January 2022, after ca. 3 weeks), cage M4 (7th of January 2022, after ca. 9 weeks) and cage M3 (8th of February 2022, after ca. 13 weeks). Due to problems with winter sore development in cages M1 and M2, a decision was made to remove the sensor houses from these cages on the 11th and 12th April 2022. The sorter was removed from cage M8 on the 18th June 2022, and the dome house was re-mounted on cage M1 from 17th June to the 16th September 2022. The Phase 3 design utilised the experience gained in Phase 2 to design houses that resemble cages M1, M2 and M8 but with only three openings and slightly greater angles of the opening.

Table 3 key criteria and features of each of the sensor housings in Phase 2.

Cage	House type	Number of Openings	Angle degr.	W (m)	H (m)	Net roof on the sensor	Light	Tunnel length	Comment
M1	Spider	4	NA	3	3	NA	N	0.2	IP camera in centre
M2	Dome	4	20	1.8-2.6	1	Y	N	1.3	
M3	2-way	4	20	2(3)	1	open	N	1.4	Opening cone outwards
M4	Pyramid	2	20	1.5	2	Y	N	1.4	
M6	Docking		NA	3	3				
M7	Docking		NA	3	3				
M8	Sorter	4	20	1.9-2.6	1	Y	N	1.3	
M9	Triangle	3	70	2	1	Y	Y	1	

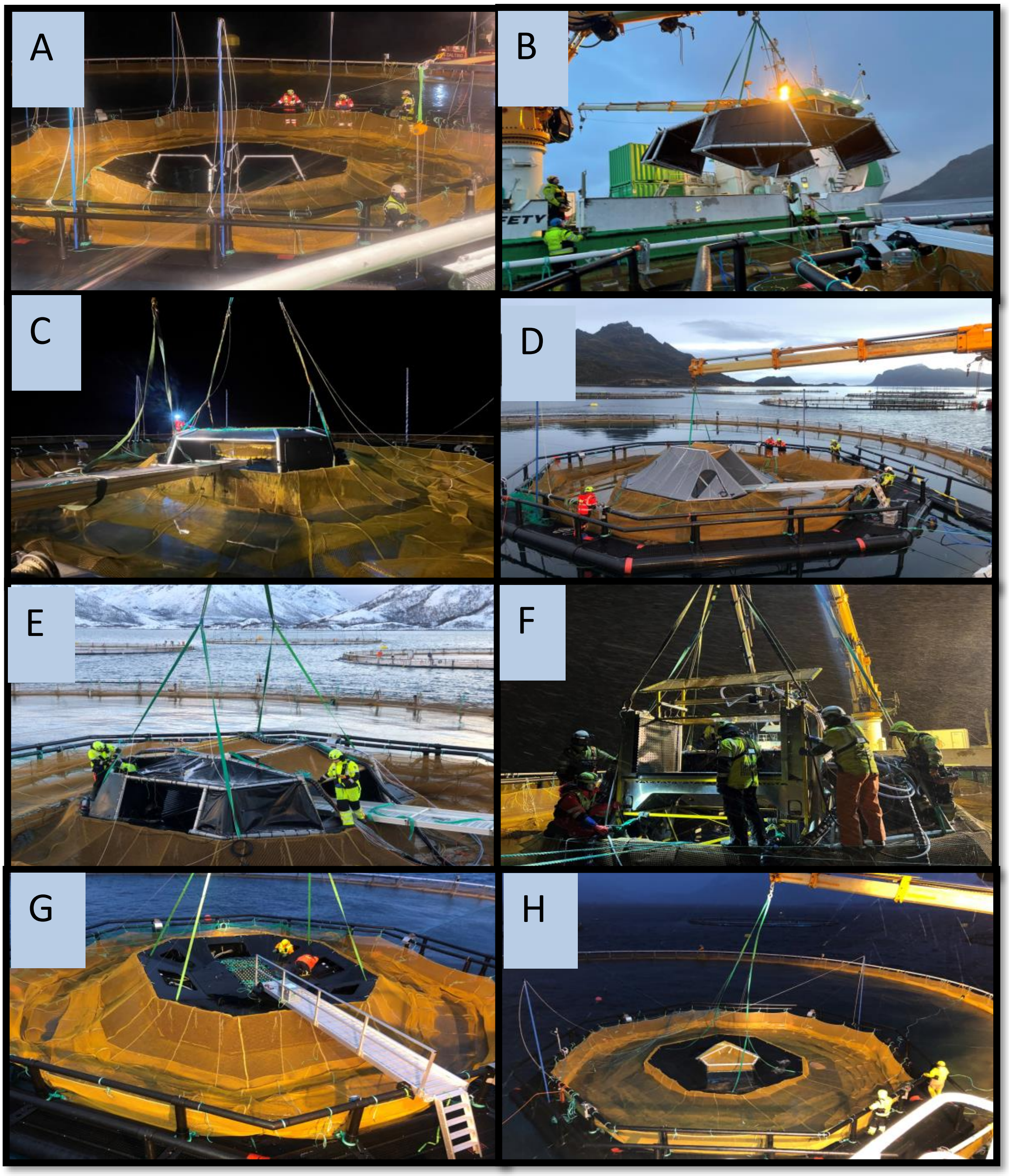


Figure 9 Photo collage showing the installation of the sensor houses to cages a) M1 – spider house, b) M2 – dome house, c) M3 – 2-way house, d) M4 – pyramid house, e) and f) M8– sorter house, g) and h) M9 – preparations and installation of the triangle house.

iFarm machine vision sensor arrangement

The sensor test of Phase 2 began on June 16th 2022. The deployment of the sensor was delayed, primarily due to making sure it was watertight and to reduce the risk of water ingress the sensor has had to be modified. Sensor deployment lasted 14 weeks until the 16th of September 2022.

iFarm sorter

Operational in-cage testing of the first iFarm fish sorter was carried out at Langøyhovden in February 2022. The goal of this first sorter test was to investigate the possibility to catch and sort fish in the cage and learn what needs to be improved to make a fully functional fish sorter. Important learning opportunities and experiences were gleaned from the sorting attempts:

- The majority of fish that entered the sorter did not appear to exhibit behaviours that were indicative of high stress (e.g., high speed swimming/panic behaviour) during sorting. In fact, in some scenarios, fish did not exhibit any escape type or stress related behaviours when the digits were moved sideways partly above the sorter floor. However, some fish that were in too close proximity to the sorter exhibited startle related behaviours. Some fish did come in contact with the digits/sorting door when the sorting process was initiated, although this contact was milder than what can be expected during most normal handling procedures.
- The parabola shapes created by the digits are sometimes too small and the movement and deployment of the digits need to be faster. There also needs to be less space between the digits to prevent fish escaping from the sorter.

In summary, the sorting test was deemed successful by BioSort and Cermaq. The test showed that it is possible to sort fish as they swim through the iFarm sensor house without touching them with no or minimal contact with the fish. The next step is to transfer experience from the current sorter and design the second-generation sorting prototype that will be tested out in the Phase 3 of the project.

Operational routines

Regular operational routines, such as manual fish health monitoring and net cleaning operations worked well in all the iFarm cages. However, bringing the iFarm docking and sensor housing to the surface for cleaning was still a challenge since it was hard to get all fish in the upper volume down through the docking. Based on experiences with de-licing and harvesting of the fish in Phase 1, the docking stations of Phase 2 were redesigned air tanks to aid buoyancy. In terms of regular cleaning, the first automated cleaning for the sensor illumination and cameras was tested in the Phase 2 sensor and will be improved in Phases 3 and 4. The crowding of fish for e.g., harvesting, net changing or other reasons, is manageable but still need further improvements. For example, getting a representative sample of fish from the cages is challenging as it is not possible to sample fish below the snorkel with existing sweep nets or existing operational practices. This may mean that fish that aggregate at the surface e.g., moribund fish, are over-represented in manual sampling events.

Fish health and welfare

Fish health and welfare monitoring plan

Cermaq Norway's fish health monitoring plan was applied throughout Phase 2 for the Cermaq Utvikling AS Langøyhovden farming site. Compared to regular farming cages, the fish in the iFarm system have reduced/smaller openings to the surface. The purpose of fish health monitoring is therefore to assess the extent to which this affects the fish in the iFarm system.

The health of the fish is monitored in two ways:

1) As a part of operations all relevant production parameters were registered daily. This included environmental parameters, feed consumption, mortality and growth. There was also daily camera surveillance and recording of fish behaviour at multiple depths within the iFarm systems (iFarm cages M1 – M4 and M6 – M9)
2) The fish health situation at the facility was followed up with monthly fish health visits by authorized fish health personnel. For a detailed description on the fish health situation in at Langøyhovden, see the fish health report (attachment 1, not public).

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

Fish health and welfare monitoring

Unlike during Phase 1, fish health was a challenge on the Langøyhovden farm site. Fish health and welfare was reduced/poor for some cages in Phase 2, mainly related to different health diagnoses or events for each of the fish groups. The main reason for mortality in the period covered by this report can be linked to IPN outbreaks in cages M3-M5, mortality following seawater transfer due to algae exposure during transport in cages M7-M9, and mortalities due to Tenacibaculosis and Parvicapsulosis in cages M6-M9. There was also an acute gill related health problem in cages M7-M8 during September 2022 that led to high mortalities and the expedited slaughter of fish in these cages. There were also some delousing related incidents in some cages that led to high elevated post treatment mortalities. Over the winter there was an increase in ulcers, most likely winter ulcers in all cages at Langøyhovden and also some potential contact sores/wounds related to abrasion, which, together with other diagnoses, has led to increasing mortality. In Phase 1, increasing ulcer development was also observed over the winter, and this was the main reason for mortality at the Martnesvika site during Phase 1.

Input-based OWIs

Environmental OWIs (Dissolved oxygen, DO and water temperature) were monitored at three depths in all iFarm cages and the associate cage. DO saturations were generally over 80 % for the entire reporting period and did not drop to levels that are sub-optimal in relation to water temperatures the fish were exposed to (Remen et al., 2016) at the depths and locations they were documented within the cage. Median daily water temperatures at all depths in all cages peaked during July-August in both 2021 and 2022 at ca. 9-12°C in 2021 and 12-14°C in 2022. The lowest temperatures were recorded in February-March 2022 at ca. 3-4°C. This was a similar trend to the input OWIs monitored during Phase 1.

Outcome-based OWIs at the individual level

Morphological OWIs from a selection of cages were followed a minimum of every 2-3 months throughout Phase 2 using the Cermaq Welfare Scoring scheme for scoring 11 external injuries according to a 0-3 scale. The morphological OWI situation was often worse for Phase 2 than in Phase 1, with a higher frequency of severe injuries at many timepoints. Whilst some of this could be linked to the health situation at Langøyhovden and other delousing related incidences, specific attention was paid to three OWIs, snout damage, scale loss and fin damage as these are particularly relevant OWIs for fish raised in snorkel cages and can be indicative of fish colliding with aspects of the rearing structure such as the net roof (Stien et al., 2016a; Kolarevic, Stien et al., 2018; Oppedal et al., 2019). The prevalence of wounds and sores was also monitored as these can be exacerbated by collision/abrasion injuries. As the drivers for the prevalence of all of these OWIs are multi-factorial and can be linked to abrasive injuries during handling (Nilsson, Stien, Iversen et al., 2018), it cannot be discounted that the effects of the OWI sampling procedure itself may also have an impact upon the prevalence of at least minor scale loss and fin damage (see also Stien et al., 2016a). *However, more extensive wounds/sores and snout damage are more likely to be evidence of problems the fish are facing within the cages and not the sampling procedure.*

Snout damage

Severe snout damage was generally low at all time points in 0+ smolts in iFarm cages M1 and M2, aside from in cage M1 just prior to slaughter. This was also the case for 1+ smolts in iFarm cages M3 & M4, fish in the associate cage M5 and for the 1+ smolts in cages M6-M9. In Phase 1, it was generally the case that no fish had severe snout damage in either of the iFarm or associate cages and when they did it was a minor percentage of fish and no clear cage trend was apparent.

Scale loss

Severe scale loss was generally low at all time points in 0+ smolts in iFarm cages M1 and M2 and also for 1+ smolts in iFarm cages M3 & M4, with the exception of cage M4 in March and May 2022 just after the ulcer outbreak and high ulcer related mortalities in this cage. Severe scale loss in the associate cage M5 was generally low aside from in November 2021. Sever scale loss in cages M6, M7 and M9 was most prominent during March 2022. In Phase 1, it was generally the case that no fish had severe scale loss in either of the iFarm or associate cages for the majority of Phase 1 and when they did it was a minor percentage of fish with no clear link to a particular cage.

Skin haemorrhaging

Severe skin hemorrhaging was not widespread in Phase 2 and when it did occur there was no clear link to a particular cage or treatment.

Fin damage

Severe fin damage was generally low at all time points in 0+ smolts in iFarm cages M1 and M2 aside from in cage M1 just prior to slaughter. This was also the case for 1+ smolts in iFarm cages M3, M4 and the associate cage M5, with the exception of cage M3 in May and August 2022, cage M4 in March, May and August 2022 and cage M5 in May, August and October 2022. Severe fin damage appeared in November 2021 in cages M6 and M7 and was high in autumn and winter 2022 in cage 6 and varied in frequency in cage M7. Severe fin damage in cages M8 and M9 became prominent in March 2022 (especially cage M9), before decreasing in frequency in Summer 2022. In Phase 1 only minor percentages of fish exhibited severe fin damage until late summer 2021 and these low levels increased to ca. 1/3 of the fish in all cages during November 2021 following two (mechanical and bathing) de-licing events in autumn 2021.

Wound status

The frequency of severe wounds/sores was highest in cages M1, M2 and M5 just prior to slaughter (which may be related to a seasonal outbreak of ulcers - all cages were slaughtered at approximately the same time period and cage M5 never had a snorkel mounted within the cage). When comparing the 1+ smolt stocked in iFarm cages M3 and M4 with the corresponding open cage M5, the frequency of fish with active wounds/sores in the iFarm cages was generally higher than the associate cage for the majority of the documentation period aside from just prior to slaughter. For cages M6-M9, the frequency of severe wounds/sores was highest in cages M6-M8 just prior to slaughter. When considering wound status in relation to wound-linked mortalities in Phase 2 (see group-based OWI section above), wounds were a common cause of mortalities in all iFarm cages and **the least number of wound related mortalities were registered in the associate cage similar to the findings in Phase 1**. It appears that potential mechanical trauma e.g., the fish coming into contact with the sensor house, or the increased fish aggregations in the snorkel in late winter/early spring may be a driver for developing ulcers. In addition, in cages where mortalities were some of the lowest on the farm, the primary causes of mortalities in these cages were wounds/sores, both related to common winter ulcers and also sores potentially due to contact/mechanical injuries. As stated above, **fish aggregations in the snorkel during low temperatures periods have been identified as a risk factor for fish welfare and will be monitored closely and considered in management decisions in further phases of the development project.** For iFarm Phase 3 and 4, design changes have been implemented, to address the challenges with wounds in Phase 2. Net roof angel is improved, tube depths can be altered, all surfaces are smoother, less equipment is mounted in the tube and cleaning procedures are improved. These issues will be monitored closely in the next phase of the project.

Eye status

The rare incidences of cataracts were generally mild and not linked to a specific cage until March 2022, where the outbreak of Parvicapsulosis led toa high number of individuals with cataracts Cages M6-M9. In Phase 2, severe incidences of other types of eye damage were generally isolated aside for November 2022 in cage M1, and cage M5 in May 2022 and not linked to a specific cage. In Phase 1 incidences of cataracts were generally mild and not linked to a specific cage.

Opercular damage

Opercular damage was generally low, irrespectively of cage and in several sampling events there were no fish with opercular damage for the entire Phase 2 period.

Condition factor

Condition factor of the fish at the end of Phase 2 was lower than desired in the iFarm cages. Condition factor at the end of the Phase 2 reporting period was higher in the associate cage (M5) (1.30) an, than for M3 and M4 (1.28 and 1.20 for M3 and M4, respectively). Condition factor in M6 and M9 was 1.31 and 1.44, respectively. It should be noted that the Condition factor estimates are done on 30 fish before slaughter. Mean condition factor values in all cages were higher than the threshold considered to indicate emaciation in Atlantic salmon post-smolts (> 0.9, Stien et al., 2013). Condition factor in this study was also similar or higher than that reported in other studies on snorkel cages. As stated earlier, whilst the poorer condition factor observed in the iFarm cages may have been linked to the feed management and distribution performance of the underwater feeding system, the effect of cage design/rearing system cannot be discounted.

Gill status

Gill pathologies from the sampling during periods where the sensor houses and snorkels were mounted (various timepoints between November 2021 – August 2022) were mainly absent or mild. Increased gill pathology was observed from November 2022 until slaughter, and by this time all iFarm installations were removed and the fish were held in open cages (but still with underwater feeders). The drivers of gill pathology in this period can be linked to the increased number of delousing treatments with both medical (bath) and non-medical (Thermolicer and Hydrolicer), all requiring increased handling of the fish (in addition to pumping, crowding etc). Another driver for decreased gill health was environmental (plankton, jellyfish etc.) during the course of the study. With regard to the gill related challenges that led to the expedited slaughter of two iFarm cages in September 2022, whilst recent work has reported that fish farmed in snorkel cages can have more pronounced gill problems than fish produced in open cages (Oldham, 2023), we did not see the same trend in this project and gill pathologies during periods where the sensor houses/adapted were mounted (various timepoints between November 2021 – August 2022) were mainly absent or mild. However, in light of this recent knowledge it cannot be discounted that long-term snorkel usage in tandem with the earlier health issues facing these fish, may have contributed to acute gill health problems in these fish, and **gill health will be followed closely in Phases III and IV.**

Heart status

The heart histopathology observed during Phase 2 was consistent with the diagnosis of heart and skeletal muscle inflammation (HSMI) that was outlined in the fish health reports for Phase 2 at Langøyhovden. The high cardiac scores observed in certain cages during points between November 2021 and May 2022 were mainly HSMI related and this was in line with the clinically diagnosis of HSMI in the farm. There did not appear to be a clear relationship between cage configuration (snorkel/sensor house deployment) and this data. Cages M7 and M8 did have high cardiac scores in May 2022 (linked in part to HSMI), but this score decreased in August 2022. HSMI is one of the most common diseases in farmed salmon in Norway (Sommerset et al., 2023). Cardiomyopathy syndrome (CMS), normally affects large fish late in the production cycle (Sommerset et al., 2023), as we see this in cage M9 where a suspected CMS diagnosis were made in November 2022 (T4) and may be one of the drivers contributing to elevated mortalities in this cage at that timepoint and onwards until slaughter.

Internal OWIs

Liver colour is a multifactorial iceberg indicator and its exact drivers need further scientific evaluation. An orange liver is here viewed as a sign of normal liver and for the majority of cages and timepoints, a high portion of sampled fish had orange livers. Scoring of visceral fat levels in May 2022 suggests all sampled fish in cages M3-M9 were lean at this timepoint, and the highest amount of visceral fat was seen in cages M1 and M2. In August 2022, no fish were scored as lean in cage M1 and there was more visceral fat noted in these fish than in May. Cage M2 also had a limited number of lean fish although these were of a higher frequency than in May 2022. Cages M4 and M8 also had less lean fish in the sample and the open associate cage visceral fat scores were higher than its corresponding iFarm cages and comparable to cage M1. Visceral fat scores (and therefore amounts) increased in all cages in November 2022 but decreased again in some cages at slaughter, where ca. 50% of fish were again classified as lean. The increase in visceral lipid storage observed during sampling in November 2022 and slaughter may be a natural increase seen in farm salmon prior to winter (Mørkøre and Rørvik, 2001, Alne et al., 2011, Dessen et al., 2017). The digesta score was especially poor in March and May 2022, except in cage M5, the open associate cage. The Parvicapsulosis diagnosis, and earlier IPN diagnosis, can cause a reduction in feed intake (Damsgård et al., 1998, Nylund et al., 2018), and this may have been the case here, especially if the sampled fish in the snorkel were some of the ones most affected by these (there were a high number of moribund fish sampled in the snorkel at some time points). Fish sampled from cage M6 at slaughter had a cast digesta score but this was to be expected, as a result of feed deprivation 3 days prior to slaughter. This was not the case in the rest of the groups sampled at slaughter where fish had mainly firm faecal consistency and this may have been due to the fish being sampled prior to/early in feed deprivation.

Vertebral deformities

There was a low, but consistent prevalence of vertebral fusions recorded on X-ray at T0 (November 2021). The lesions were small and immature. These observations correspond well to the lack of observed vertebral deformities on external examination (OWI), at this point in time. At the final sampling, the prevalence of X-ray lesions had considerably increased. Most lesions were still small and immature, but there was an increase in the number of fish with four or more deviant vertebrae, i.e. of a size that may be detected on external examination at harvest. The location was, however, predominantly in front of the dorsal fin, a location which may be difficult to judge correctly on external examination. Fusions are the most common type of pathology in farmed salmon. They may be induced at any life stage and will as a rule continue to develop until harvest. The numbers in this material were high, but the severity was low, and the interpretation of this pathology is that it is a result of intensive rearing conditions in general, and quite typical for farmed salmon. One fish was recorded with a severe case of cross-stitch pathology (Holm et al., 2020). This type of pathology is associated with use of certain oil-adjuvanted vaccine products. In fish vaccinated with a standard vaccine without PD-component, our experience is that cross-stitch vertebrae may develop, but with a prevalence of 1% or less. In this context, this condition is not considered to be relevant. Possibly more relevant is the observation of three of 30 fish (10%) from M1 with axis deviation in the neck. This is not a common observation in Atlantic salmon. Whether or not these changes can be attributed to cage rearing conditions, possibly restricted access to the surface, should be discussed. We did not observe any deviations in relative vertebral length in the vent area that could support Korsøen et al., (2009). In Phase 1, deformities were observed in all three cages at both the first sampling point and slaughter. The recorded lesions were comparable to the common types of pathology which are typical for farmed salmon in recent years. There were no apparent differences in type and prevalence of deformities between cages, except for a higher prevalence of cross-stitch pathology in the associate cage. Cross-stitch vertebrae were found at termination, but not in the earlier sampling. This corresponds well with current knowledge about this condition, which is that cross-stitch pathology gradually becomes visible on X-ray only as fish grow past 1 – 3 kg in size. The seemingly higher prevalence of cross-stitch pathology in the associate cage may result from the fact that these fish were more than 6 kg at the time of slaughter, compared to ca. 3.9 kg and 3.3 kg in the iFarm cages.

Melanin spots

Melanin spots in the fillets at slaughter were found in 7.5-21.5 % of the sampled fish fillets and of these spots, 2.5-5% were classified as deep. The proportion of fillets with melanin spots in Norway in 2014 was reported to be 19 % on average (Mørkøre et al., 2015) with Cermaq Nordland has an averaging roughly at 1/3 of that.. Thus, the values reported here are not extraordinary (but 21.5 % is somewhat on the high side) and are lower than average in cages M1 and M3-M5. Whilst the aetiology of melanin spots is difficult to determine and can be linked to handling and/or smolt robustness, both Bjørgen et al., (2019) and Malik et al., (2021) have reported that Piscine orthoreovirus 1 (PRV-1), the causative agent behind HSMI, has been related to their occurrence.

Group- based outcome OWIs

Behavioural OWI and LABWIs

Fish surfacing activity

Surface activity was somewhat variable in relation to sensor house deployment in different cages. In the majority of cages, surface activity decreased as winter progressed and either remained low for some cages or increased as summer approached in others. In iFarm cage M9 (triangle sensor house) There was a marked and prolonged decrease in fish surface activity when the sensor house was mounted, revealing a reluctance for the fish to utilise the snorkel after sensor house installation. In three of the other iFarm cages (cages M1, M2 and M4) surface activity decreased with time over winter after sensor house deployment but this trend may be seasonal and was also noted in cages M6 and M7 that did not have any sensor house mounted during Phase 2. In cage M8, where the sensor house was deployed during summer 2022, surface activity was reduced for the majority of the summer before increasing again just prior to sensor house removal. Therefore, *a drop in fish surface activity in cages M8 and M9 when the sensor houses were mounted (and when temperatures were rising in cage M8) suggests a reluctance for the fish to utilise the snorkel after sensor house deployment for certain iFarm sensor house configurations*. In addition, when comparing the dome housing configuration that was similar between Phase 1 and Phase 2, fish surface activity exhibited similar seasonal trends irrespective of snorkel cage design or timing of sensor house deployment.

Fish aggregating in the snorkel

It has been reported that fish can aggregate in the snorkel when held in snorkel cages and this may lead to reduced oxygen saturations in the snorkel (Kolarevic, Stien et al., 2018). Aggregation of fish in the iFarm cage snorkel did not seem to have a detrimental effect upon oxygen saturation levels at 5 m deep which were generally above 80 %. However, the increase in fish number/density in the snorkel was believed to have contributed to the increase rate of ulcer/sore development (and associated mortalities) in cage M4 and led to the sensor house being removed in January 2022. A later, but acute increase in fish numbers in the snorkel of cage M3 also led to the removal of this sensor house in February 2022 to prevent a repetition of the issues observed in M4. Phase 1 also saw a general increase in the number of fish in the snorkel during winter (and a corresponding increase in the incidence of mortalities related to wound/sores) and an increased winter aggregation of fish in the snorkel is emerging as a potential risk factor for ulcer/sore driven mortalities. A lesson learned from Phase 2 is to act early on wound/sore developments, even if they are related to winter ulcer outbreaks, as increased fish number/density in the snorkel may be a risk factor for exacerbating the problem. As the wound/sore driven mortality in cage M4 was so severe, fish number/density and sore development was monitored very closely over the rest of the winter, and this will be a big focus in Phase 3.

Fish traffic

The reduced surface activity of the fish after sensor mounting was not always reflected in the traffic data through the docking station/sensor house, unlike in Phase 1. Sensor house deployment led to a short-term drop in traffic for cage M1, and the traffic pattern differed from the surface activity in this cage, that decreased as winter progressed. Hereafter, the removal of the sensor house from M1 had a clear effect on fish traffic and it decreased. When the dome sensor house was mounted on this cage in summer 2022, fish traffic increased until ca. 7-8% fish/hour until September 2022. Traffic levels in M2 decreased after sensor house deployment and removal did not have an effect on the fish traffic. Fish traffic for cages M3 and M4 were similar prior to sensor house deployment for cage M3 and reduced after sensor house deployment for cage M4. Sensor house deployment led to short-term drop in traffic for both cages for ca. one week before returning to levels that were comparable to those before the sensor house was deployed, although traffic in cage M3 was consistently slightly higher than for cage M4 for the majority of the remaining data collection period and increased acutely for a short-term period to just prior to snorkel removal. Fish traffic levels heading to the surface through the docking station in cages M6 and M7 (docking station only) were relatively consistent between both cages and exhibited a different trend to surface activity by increasing as winter progressed and decreasing during summer. Fish traffic to the surface for cage M8 (sorter) also exhibited a similar trend even with the sensor house deployed. However, after sensor house deployment, traffic in cage M8 remained stable at 1% fish/hour for ca. one week before returning to 4-5% fish/hour until May 2022. Traffic then decreased as summer approached with the only exception of a sudden increase to ca. 10% fish/hour during one week in early August just prior to sensor removal. Traffic was generally below 5% fish/hour for the rest of the data collection period. Fish traffic to the surface for cage M9 (triangle) was also similar to cages M6-M8, increasing during winter and decreasing as summer approached. *When the sensor house was deployed there was a long-term marked drop in traffic and this drop contributed to the decision regarding the removal of the sensor house after 3 weeks. After removal, there was a high short-term increase in traffic activity and this may have been driven by a need of the fish to compensate for low snorkel utilisation during sensor house.* Fish traffic activity in Phase 1 at Martnesvika was somewhat different than that documented in Phase 2, although as there were only two cages in Martnesvika Phase 1, and the majority of sensor house configurations and snorkel design were different in Phase 2, data should be interpreted accordingly. However, when comparing the dome housing configuration that was similar between Phase 1 and Phase 2, fish traffic exhibited similar seasonal trends irrespective of snorkel cage design or timing of sensor house deployment.

Swimming speed and cohesion

If fish are exhibiting problems with buoyancy, they can increase their swimming speeds to generate lift (Sievers et al., 2021). In general, sensor house deployment had no effect on swimming speeds of the fish just below the snorkel in the iFarm cages and these were generally medium/cruising speed for the majority of the data collection period. In cages M6-M9, swimming speeds generally increased from October to January 2022 when medium/cruising swimming speed were established and this may have been due to them being late summer 1+ year smolts who had recently been transferred to the cages when the data collection commenced. In Phase 1, swimming speeds were mostly matched between iFarm cages after sensor mounting and dropped at all time points and both cages from mid-May onwards until the end of the Phase 1 reporting period. Swimming cohesion below the snorkel generally increased over time towards uniform circular schooling for the majority of iFarm cages, both for feeding and non-feeding periods, irrespective of whether the sensor house was deployed or not, with some minor exceptions. No marked changes in cohesion were detected after the removal of the sensor house in any of the cages, except for cage M8, although there is little data available. In Phase 1, different iFarm set-ups affected group cohesion in different ways. Group cohesion was generally lower in the iFarm cage with the 10 m snorkel compared to the 15 m snorkel cage, especially at night and during non-feeding periods. In Phase 1, trends in cohesion data appeared to be also affected by water temperature in both Phase 1 iFarm cages and dropped when temperatures were at their lowest. This was not apparent in Phase 2. There are two things to consider when interpreting the Phase 2 swimming speed and cohesion results. Firstly, documentation of swimming speeds was only audited just below the snorkel and this documentation may not be representative for the whole group of fish under the snorkel. Secondly, if changes in swimming speed are minor, our operationalised scheme may be a little too crude to pick up these differences when compared to other methods (such as swimming speed expressed as body lengths per second) and the current format of this toolbox will be further evaluated in Phase 3.

Tilt angle

No tilted (head-up/tail down) swimming behaviour > 25 ° was observed during a minimum of twice daily audits of fish behaviour near the bottom of each iFarm cage during Phase 2, by Cermaq feed staff both before and during feeding, aside from the observation of 1 fish exhibiting tiled swimming behaviour in cage M3 on July 26th 2021 (before the sensor house was mounted). Thes results are similar to those reported in Phase 1 of the iFarm project. However, it should be noted that even though tilt angle documentation was carried out in the area of the cage that we would expect that fish with buoyancy issues would aggregate (the bottom of the cage), tilt angle was only documented twice a day from a limited viewpoint from feed cameras and was not documented at night.

Appetite

Daily Feed delivery

Fish were remotely fed to apparent satiation using existing Cermaq Norway AS feeding regimes for the Langøyhovden locality using mobile underwater feed cameras. No marked differences in daily feed delivery were observed between the associate, or iFarm cages for the majority of the reporting period and daily activity scoring of fish at the start and end of feeding was generally scored as similar by the Cermaq feed staff.

eFCR

Feeding efficiency at the end of Phase 2 was lower than desired in the iFarm cages in comparison to the associate cage. This also occurred in Phase 1. Interestingly, the lowest eFCR registered for the iFarm cage, was produced by the cage that only had a docking station and was also subjected to adapted snorkel production for the shortest period before being switched to an open cage. As all cages were fed using the same underwater feeding system, the effect of cage design/rearing system and operational decisions (such as the timing of the sensor house deployment in addition to its design) appears to have a marked effect upon feeding performance and feed conversion performance.

Growth

TGC

Growth rate at the end of Phase 2 was lower than desired in the iFarm cages and TGC values at slaughter were higher in the associate cage, than any of the iFarm cages. This also occurred in Phase 1. *As stated above, all cages were fed using the same underwater feeding system, and the effect of* *cage design/rearing system and operational decisions (such as the timing of the sensor house deployment in addition to its design) appears to have a marked effect upon feeding performance and feed conversion performance.*

Mortality

Cumulative mortalities

Cumulative mortalities were very variable during the Phase 2 reporting period and high mortalities were recorded in cages M3-M5 and some very high mortalities were recorded in cages M7-M9. The health situation at Langøyhovden was often challenging, and contributed markedly to mortalities in Phase 2, as did isolated delousing events. However, the design and implementation of the iFarm rearing system did unfortunately affect mortalities in some cages. For example, aggregation of the fish in the snorkel during mid-winter in cage M4 was a driver for/or at least exacerbated the risk of developing ulcers and was a driver for ulcer related mortalities in this cage. The cage M4 sensor house configuration will not be taken forward into Phases 3 and 4, and **fish aggregations in the snorkel during low temperatures periods have been identified as a risk factor for fish welfare and will be monitored closely in further phases of the development project.** Some sensor houses were removed from other iFarm cages during winter at low temperatures in relation to concerns regarding ulcer developments in the cages. When comparing the results of Phase 1 against Phase 2 there is a marked contrast in mortality data between each Phase of the project.

Cause specific mortalities

As stated above, a large portion of mortalities in some cages at the Langøyhovden site could be attributed to health challenges or operational challenges associated with i) a confirmed case of Infectious Pancreatic Necrosis (IPN), ii) algal exposure during smolt transport iii) Parvicapsulosis, iv) gill related challenges in cages M7 and M8 that led to the expedited slaughter of both these cages, and v) isolated delousing treatments. However, wounds were also a common cause of mortalities in all iFarm cages and **the least number of wound related mortalities were registered in the associate cage**. This was also the case for Phase 1, where there more wound/ulcer related mortalities in both iFarm cages than in the associate cage. It appears that potential mechanical trauma e.g., the fish coming into contact with the sensor house, or the increased fish aggregations in the snorkel in late winter/early spring may be a driver for developing ulcers. In addition, in cages where mortalities were some of the lowest on the farm, the primary causes of mortalities in these cages were wounds/sores, both related to common winter ulcers and also sores potentially due to contact/mechanical injuries. As stated above, **fish aggregations in the snorkel during low temperatures periods have been identified as a risk factor for fish welfare and will be monitored closely and considered in management decisions in further phases of the development project.** Snorkel cleaning routines have also been updated in relation to potential mechanical trauma risks from biofouling organisms.

Health status

Disease status

The fish health situation at Langøyhovden was often challenging, with unfortunate health problems that led to high mortalities in some of the cages, and with some incidences of elevated numbers of moribund fish that needed culling. Screening and histology taken throughout this period has shown Infectious Pancreatic Necrosis (IPN), liver necrosis, gill changes due to algae exposure, bacterial ulcer infections, Heart and Skeletal Muscle Immflamation (HSMI), Tenacibaculosis (caused by *Tenacibaculum finnmarkense*), and Parvicapsulosis (caused by the myxosporean parasite *Parvicapsula* *pseudobranchicola*), branchiomas and gill related challenges that led to the expedited slaughter of two iFarm cages in September 2022. Whilst recent work has reported that fish farmed in snorkel cages can have more pronounced gill problems than fish produced in open cages (Oldham, 2023), we did not see the same trend in this project and gill pathologies during periods where the sensor houses/adapted were mounted (various timepoints between November 2021 – August 2022) were mainly absent or mild. However, in light of this recent knowledge it cannot be discounted that long-term snorkel usage in tandem with the earlier health issues facing these fish, may have contributed to acute gill health problems in these fish, and **gill health will be followed closely in Phases III and IV.**

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