The use of Algorithm-Assisted Feeding for Innovation and Increased Productivity in Aquaculture

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Abstract: The need for innovation in aquaculture has escalated in tandem with the use of advanced production equipment and high-level biological competence. A Norwegian company, NorseAqua A/S, produces sonar equipment that provides both images and data on how the salmon are distributed in the cage. The sonar data provides a basis for calculating algorithms between the depth of salmon in the cage and other key factors used to make decisions about how the salmon should be fed. The first aspect of the project was to investigate how the equipment was working and verify that the sonar data was readable. The second aspect was to analyze the relationships between important variables of significance for the feeding process of the salmon (including the sonar measurements). A third aspect was determining what understanding the feeding operators gained from the information produced. The results show that it is possible to develop algorithms based on the sonar data that improve feeding efficiency.

Keywords: aquaculture, artificial intelligence, sustainability, innovation

1. Introduction

There has been a rapid and significant development towards professionalism, advanced technology developments, and extending the knowledge base of Norwegian aquaculture over the past decade. In addition, it has been in the industry's self-interest to develop sustainable solutions due to the limited number of suitable locations along the coast. The sustainability arguments are specifically aimed at the requirements for fish health, escape safety, and improvement of feeding efficiency. From a nutritional perspective, it is desirable to increase in production based on FAO projections, FAO (2018; 2020; 2021). The Norwegian authorities, Nærings- og fiskeridepartementet (2015), along with industry experts, believe this may be possible under given conditions. To be achievable, the sustainability requirements must be met and this project focuses on more efficient utilization of the feed and thus reduced feed spill. The aquaculture producers also want to increase productivity and income by increasing feeding efficacy so that environmental and corporate interests are aligned. This has stimulated supplier companies like NorseAqua to develop products that can contribute to more efficient production.

NorseAqua produces sonar equipment that provides both images and data on how the salmon are distributed in the cage. The sonar data in turn provides a basis for calculating relationships (algorithms) between how deep the salmon swim in the cage and other key factors used to make decisions about how they should be fed. The first innovative aspect of the project was to check that the equipment was working and that the data streams from it were readable. The second was what relationships can be established between important environmental variables, feeding of the salmon, and the sonar measurements. A third aspect was what understanding was acquired by the feeding operators from the information produced. The most important innovative and competitive aspect NorseAqua has in this context, is the construction of the sonar itself and the software designed to turn the sonar measurements into readable data that can both be used to create images of the distribution of the salmon in the cages and to calculate numbers like average depth of the salmon in the cage.

The research questions for the project were formulated in the following way:

R1: How to develop new and innovative technologies based on hydroacoustics to reduce feed spill and what parameters should be selected to create algorithm-assisted feeding?
F2: How can algorithm-assisted feeding programs using hydroacoustic equipment be integrated in the firm’s operations?

F3: How can equipment from NorseAqua contribute so salmon producers better can comply with the environmental restrictions and increase productivity?

2. Innovations in aquaculture and the hydroacoustic (sonar) project from NorseAqua

There have been many contributions to innovation research literature in aquaculture in recent years, and much of this has been summed up by Joffre et al (2017).

Joffre et al (2017) suggests that we analyze innovations in aquaculture based on the following categories:

- Technology driven
- Systemic
- Based on business needs

Our analysis shows that it is essential to look at how these three categories play together. The hydroacoustic project clearly has a technology-based starting point. The sensors and the software must be able to detect the salmon in the cage and produce readable data. The systemic perspective is related to the integration of the use of the results in the organization and how NorseAqua interacts in the supply chain. The business need revolves around how NorseAqua can contribute so salmon producers better can comply with the environmental restrictions and increase their productivity. The sonar results must therefore be integrated in the salmon producer's feeding programs to reduce the spill of feed. There is limited research literature on the use of hydroacoustic technologies for improving feeding operations in marine aquaculture. Bjordal et al (2020) and Winfield et al (2012) give an overview of different ways to use hydroacoustic techniques in salmon production. Orduna et al (2021) look at how hydroacoustic equipment can be used for monitoring and estimation of biomass in freshwater aquaculture. This is important because estimation of change in biomass as the fish grow is a weak link in the analysis of productivity in aquaculture. Føre et al (2017) use hydroacoustics to study tagged fish in salmon aquaculture. We see progress in using hydroacoustics in salmon production based on different approaches where most of them put emphasis on the integration of the three factors mentioned by Joffre et al (2017).

The need for innovations linked to environmental considerations has been a topic of focus for quite some time in the aquaculture sector, Corallo et al (2020), Galappaththi et al (2020) and Bartley (2022), and the reports from FAO (2018; 2020; 2021). Most of the projects mentioned above and the sonar equipment from NorseAqua in particular have an environmental and sustainability aspect and fit into the potential development of a positive solution to sustainability challenges. But they must be seen together with a large number of complementary innovative developments for more complete solutions.

3. The sonar equipment from NorseAqua

Sonars used by fishing boats have a well-known technology. To further develop the equipment for use in aquaculture it was necessary to produce new circuit boards to create new transponders. Unique and innovative aspects of the sonar equipment from NorseAqua are the circuit boards (hardware) and the new signal processing software. For NorseAqua's sonars they had to find a solution to the technologically advanced problem of surface detection. A common sonar discover easily when the signal reaches the bottom, but when we send sonar signals upwards, it needs a completely different technology for the system to detect the surface of the water. The research development over the last 20 years has, in principle, solved this technological problem. NorseAqua has put this technology into operating equipment both for the hardware and software so that we get detection of fish in all levels of the cages. This development has gone through several "generations". In the project we have used generation 4, called NA_G4. At the beginning of 2022 the company has reached NA_G6 and the system is now stable and reliable.

When the system is in operation, there are four sonar signals (beams), two sent downwards and two sent upwards, see Figure 1, from two sensors, one mounted at the top of the cage and one lower down in the cage. These signal flows are transformed into readable data, which can be turned into images displaying how the salmon are distributed in the cage. (The source of all information in figures and tables are project data, see Westeren (2022)). The data streams are in real time and a dataset/image is created every 12 seconds. This gives 7200 observations per hour and each observation set/image contains information about fish distribution, in depth meter intervals, for the site of Storskjeret from 1 – 25 meters. In total, this yields 180,000 observations per hour.

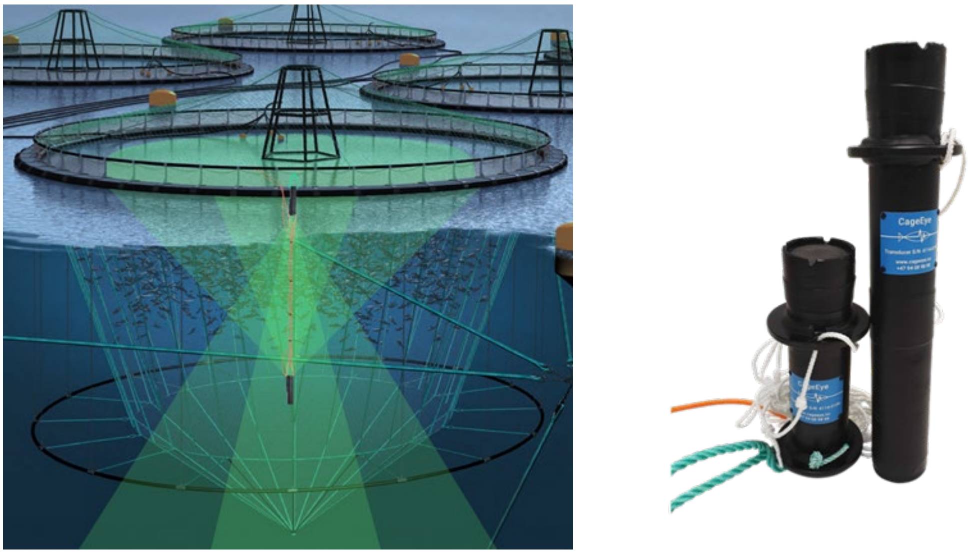


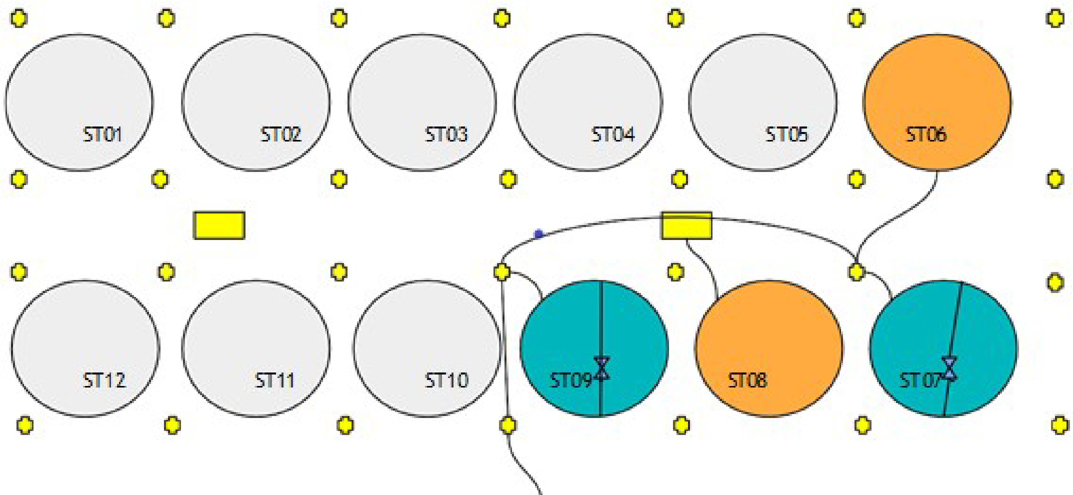
Figure 1: The sonars and their position in the cage

In the project we use the term algorithm-assisted feeding, which uses algorithms (software-based computational methods) computing at two levels:

- (1) The algorithms in the hydroacoustic equipment NA_G4 at the site Storskjeret.
- (2) The algorithms necessary to compress, adapt and compile data so that they become operational in connection with all other data.

4. Analysis of hydroacoustic data based on data from Storskjeret

Storskjeret is a salmon aquaculture production site belonging to the company Salmar A/S and it is located on the south side of Smøla in Mid-West Norway. It has 12 cages and the fish group we have analysed in this project is R-22.01.20-2. This group of fish was launched in Cage 9 and production took place in the period from 22.01.2020 to 27.04.2021. The key element of the research is that we have followed this fish group throughout the production cycle, see Figure 2. During the production cycle, the company also did additional tests of some characteristics of cages 6-8, but those are not reported in this project.



Fish group	Cage	Average weight at start (g)	Number of fish in the cage at start	End day of production	Number of production days
R-22.01.20-1	ST06	162,8	197 696	14.01.2021	358
R-22.01.20-4	ST07	177,6	196 342	21.04.2021	455
R-22.01.20-3	ST08	186,3	197 784	17.03.2021	420
R-22.01.20-2	ST09	163,8	197 757	27.04.2021	458

Figure 2: Data from Storskjeret

We received data from the sonars (hydroacoustic measurements) from 01.04.2020 to 22.01.2021. Due to interruptions in connection with delousing, we lack data for a few days (a total of 9 days) and for most of December 2020, but this has not had any influence on the results since we have large amounts of data from the production cycle. All the hydroacoustic data we received had date, hour, and minute identification. The first thing we did was to turn the data into hourly data. We collected data for each depth from 1 to 25 meters in the cage. To get comparable data we had to calculate the average depth for each hour, which was challenging.

In Figures 3 and 4 and in Table 1 we display data from the sonars for 30.09.2020 at 0:00 (Serie 1) and for 30.09.2020 at 1:00 a.m. (Serie 2), that is, midnight and an hour after at the end of September. As can be seen from Figure 3, indicator values (on the Y-axis) are given for how salmon are distributed in the cage (depth on the Y-axis). We must "normalize" the observations so that the area under the curve is = 1. The average depth then becomes the number of the X axis that divides the area under the curve into two equal parts. We created a computer program to do this. Furthermore, it is interesting to get a measure of the extent to which the fish are evenly distributed throughout the cage or whether the fish swim together around the average depth. We have calculated the standard deviation around the average as a measure of this. Large standard deviations tell us that the fish are distributed evenly across all depths, while small standard deviations say that most fish are around the average depth.

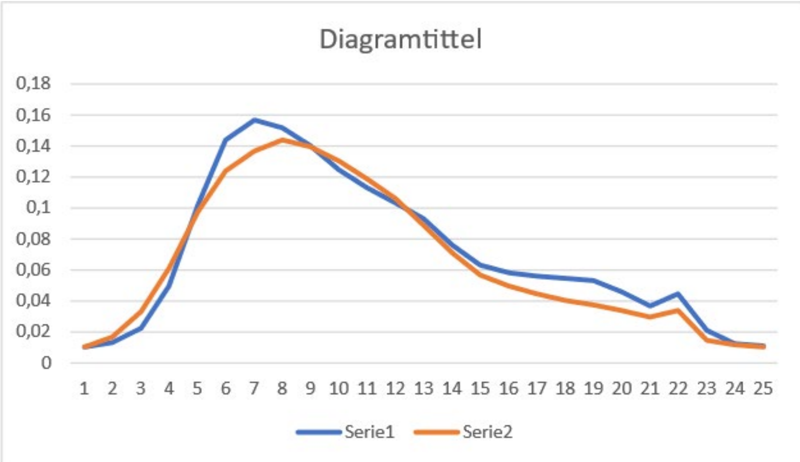


Figure 3: Acoustic data directly from the sonars, depth on the X-axis and indicator value on the Y-axis

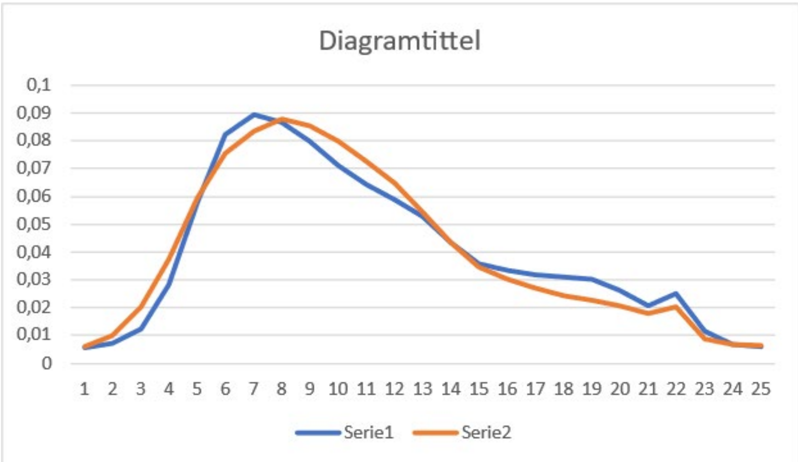


Figure 4: Acoustic data "normalized" so that the area under the curve =1

Table 1: Calculated values from the acoustics data for two hours

Time		Average Depth	Standard deviation of the observations
30.09.20 0:00	Serie 1	11,26175235	0,026608553
30.09.20 1:00	Serie 2	10,82282911	0,027627425

As can be seen from the example in Figure 4 and Table 1, the fish distribute a little deeper at midnight than one hour later, but the difference is very small. Because the depth distribution is very similar, the standard deviations are virtually identical.

In Figure 5, we see observations directly from the sonars every 12 seconds for October 26, 2020. This day the average depth of the salmon was about 7.5 meters. The sonar picture runs from 00:00, midnight to midnight. Feeding goes from approximately 08:00 to 10:30 and from 14:00 to 15:30 as can be seen from the pillars.

Figure 6 shows calculated hourly values for the period from 02.08.20 to 05.08.20. The hourly calculations compress the data, but the structure of salmon behavior is shown reasonably well. The general pattern of the salmon during the entire production period has some structural results, Westeren (2022). The salmon are deeper in the daytime than at nighttime and the variation in the depth of the salmon is greater in the first half of the production cycle than in the second which indicates that larger salmon have more stable behaviour than smaller salmon.

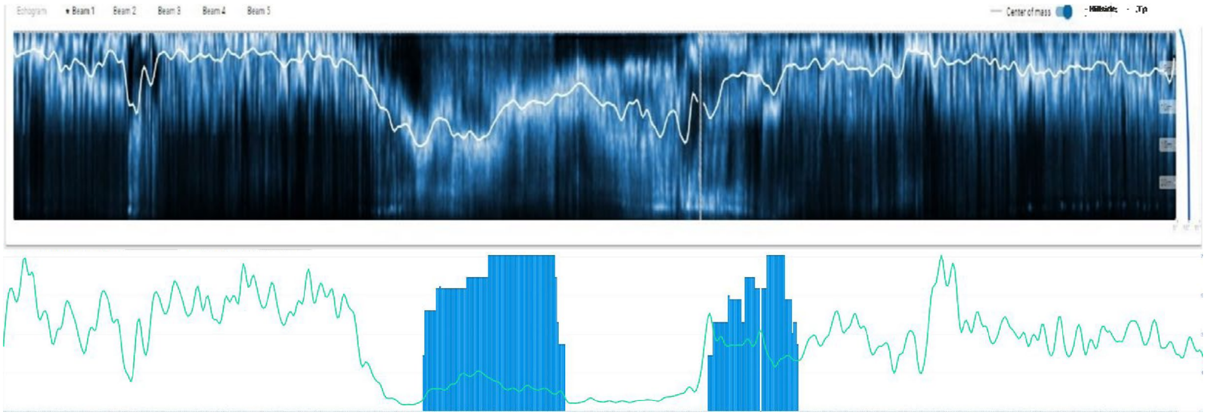


Figure 5: Observations within 24 hours with the bars in the lower part of the diagram representing the feeding periods. The line in the lower part of the chart is represents depth measurements of where the fish stand just below the feed spreader

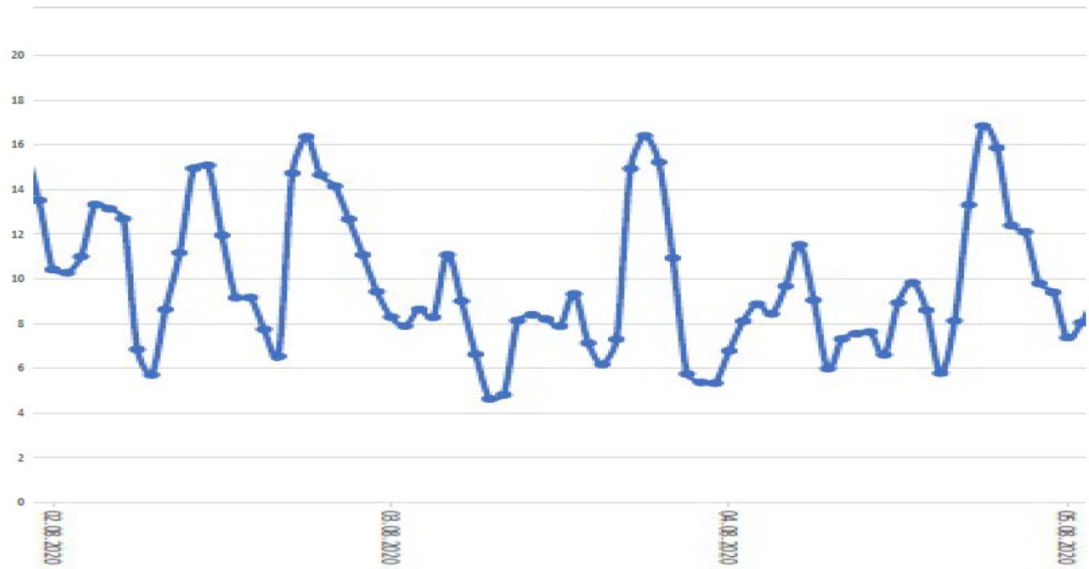


Figure 6: Depth distribution of the salmon in the cage from 02.08.2020 to 05.08.2020

5. Relationships between production data, environmental data, and depth measurements

More generally, growth of salmon is influenced by two main groups of factors, feeding and environmental factors, Aas et al (2019) and Handeland et al (2008). The calculations we will present in this section also support this. In our analysis we have identified the following groups of factors.

Environmental factors

Water temperature: Is measured by temperature inside the cage at the depth of 5 meters (Temp_5m), at a depth of 12 meters (Temp_12m), and outside the cage at a depth of 12 meters (Temp_raw_12m).

Oxygen saturation: Inside the cage at a depth of 5 meters (O2_5m [%]), at a depth of 12 meters (O2_12m[%]) and measured outside the cage at a depth of 12 meters (O2_raw_12m[%]).

Water salinity: Water salinity (ppt).

Current, measured in 2 ways: (1) Based on water tables about flood and spring, Tide1 and Tide2. (2) Water current velocity x (m/s) and Water current velocity y (m/s).

Light conditions: Here we have used observations at the cages. This variable shows how far down into the water (the sea) that light penetrates measured in meters: Sunlight penetration depth (m).

Feeding variables

We have information about feeding in kilograms per day: Feed tot/day.

Result variables

For the site of Storskjeret (including the cage we analysed), Salmar has data from a system called Optoscale that calculates the weight (biomass) of the fish on a 24-hour basis. From these observations, we have calculated how much the salmon grow from one day to the next - % weight gain. We have “smoothed” these observations to hourly results based on knowledge about how the fish grow during a 24-hour period, and this variable we have called: % weight smoothed.

The advantage of carrying out these “smoothing procedures” are obvious. We have observations from about 240 days. On an hourly basis that means about 240 X 24 = 5760 observations. For some variables, 24-hour variation is central – for light, temperature, oxygen saturation and acoustic measurements. This means that we must have hourly data for all variables to do a relevant analysis. If we look at the data quality for the different variables, it is the data on how salmon grow (biomass in kg) that is the weakest link.

A key objective of this project is to show what possible connections we can find between the different types of data. An important innovative aspect for NorseAqua is to be able to show customers what characteristics the acoustic data has and how it can be used in conjunction with other data to optimize the feeding process.

The regression calculations reported in Table 2 have "% weight smoothed" as dependent variable so we can analyze the factors that influence how salmon grow during the production period based on 4735 valid observations. The results we find are similar to others like Aas et al (2019) and Handeland et al (2008), namely that growth is explained by feeding and environmental factors. The variable based on the actual feeding, “feed interp” is significant with a high t-value. Environmental factors like "Water current velocity x (m/s)", "O2_5m [%]”, “Sunlight penetration depth (m)", and "Water salinity (ppt)" are all significant with expected signs. We have also included the average depth at which the salmon stand, "Av_Depth", and this variable is also significant with the interpretation that the deeper the fish stand, the more they grow. This must be seen as a preliminary result. We have no similar research results to compare with, so this needs to be analysed in more detail.

Another interesting observation is that the variable "Av_Depth" also shows relationships with other variables when we look at the correlation matrix, see Westeren (2022). This indicates that this variable may well be part of a step-by-step, cause-and-effect chain. To find out more about this, we can use a model framework called SEM (Structural Equation Modelling). Another type of analysis we will proceed with is to examine daily and monthly variations. Salmon have distinct day and night behavioral pattern and we now have a new tool, depth distribution, we can use to better understand these patterns and create advice for more efficient feeding procedures.

Table 2: Regression calculations based on observations for the entire production period

ANOVA					
	Sum of Squares	Df	Mean Square	F	Sig.
Regression	0,054	7	0,008	48,329	.000
Residual	0,752	4728	0,000		
Total	0,806	4735			
	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
(Constant)	-0,002	0,005		-0,387	0,699
Water current velocity x (m/s)	0,010	0,001	0,110	7,495	0,000
Feed interp	1.602E-06	0,000	0,241	12,805	0,000
O2_5m [%]	0,000	0,000	0,181	9,956	0,000
Sunlight penetration depth (m)	0,000	0,000	0,063	4,118	0,000
Water salinity (dpi)	-0,001	0,000	-0,065	-4,428	0,000
Av_Depth	0,000	0,000	0,058	3,955	0,000
Dependent Variable: % weight smoothed					

6. Use and information exchange of sonar data by the feeding operators.

Salmar A/S has centralized feeding from a control center to several sites in Mid-West Norway, including Storskjeret. We have conducted interviews with two feeding operators responsible for the site at Storskjeret for the majority of the project duration. Due to Corona, the interviews took place by telephone.

For the interviews we had an interview guide with the following main points:

- Communication from the feeding responsible at Salmar to the supplier o
- f the equipment (NorseAqua)
- Communication from the feeding responsible to the company management and the site personnel
- How the sonar data was understood and utilized

The situation with Covid resulted in less visits from the supplier to the actual site than initially had been planned. Communication took place mainly through digital media and supplier and user of the equipment met on average once a week. This communication was mainly perceived as focus-based and directed at problem solving. The user was satisfied with the contact with the supplier because (mostly) all issues were resolved quickly.

From the internal company side, the interviews show that the information about average depth and distribution of the salmon in the cage was to a limited extent conveyed from the feed operator and upwards in the company's organization. The results from the system were discussed daily between feeding responsible and the operators at the site. Both the feeding operator and the site responsible at Storskjeret were positive about the system but wanted more "actionable" knowledge about the sonar measurements, feeding procedures, and environment data. Another important exploitation of the sonar system was to get information when the underwater cameras did not provide good enough images, for example when it was dark.

7. Discussion and conclusions

From innovation management, Tidd and Bessant (2020), we learn that the combination of resources (capital, knowledge, and organizational) is fundamental for an innovation to be successful. This is also true for the NorseAqua sonar equipment used at the Salmar site, Storskjeret. NorseAqua had managed to develop sonar equipment that could be placed under water and detect the surface, and send data streams that were transferred into readable data and usable images. NorseAqua was also able to create a system for data collection based on sonar observations and relevant environmental and feeding variables. The project showed a starting point for creating algorithm-assisted feeding. The technology was successful in two ways. It created data that could be integrated and tested together with other data about firm operations like feeding, environmental conditions and outcome of production. This gave new information about the salmons' behaviour during feeding periods, but also gave rise new questions for examination like more in depth testing of seasonal properties of the variables. Many of the important variables also have day/night variations and we have found some patterns from the hydroacoustic data that can be related to this. Here we need more work to be done, especially how stepwise causal chains can be detected.

The other technology and operational advance was that the feeding operators could study the distribution of the salmon in the cage during feeding periods. This was looked at as an addition to the information from the underwater cameras. The underwater cameras have until now been the main source of information about when to start and stop the feeding periods. Especially in winter time with reduced light the combination of cameras and depth images (like in Figure 5) improved the certainty of when to start and end feeding periods. Here we see a business application of the argument from Joffre et al (2017) that technology driven and systemic arguments for innovations are linked together.

Communication and knowledge transfers based on the hydroacoustic equipment took place during the study period without special problems, between NorseAqua and the salmon producer and within the salmon firm. It was clear that the feed operators were the group that gained the best experience with the system and they exchanged knowledge with the employees at the site, although to a lesser degree with management level. Communication with the supplier was perceived as satisfactory. If sonar data shall be utilized more thoroughly and integrated in feeding routines on a more permanent basis, the management level must be involved more directly. The larger future challenge of incorporating hydroacoustic data in feeding is, as earlier mentioned, to find out more about stepwise causal chains related to both day/night variations and seasonal variations.

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