Exposed Aquaculture In Norway

Technologies For Robust Operations In Rough Conditions

Hans V. Bjelland, Martin Føre, Pål Lader, David Kristiansen, Ingunn M. Holmen and Arne Fredheim
SINTEF Fisheries and Aquaculture
Trondheim, Norway

Dariusz E. Fathi
Department of Maritime Transport Systems
SINTEF MARINTEK
Trondheim, Norway

Esten I. Grøtli
Department of Applied Cybernetics
SINTEF ICT
Trondheim, Norway

Frode Oppedal
Department of Animal Welfare
Institute of Marine Research
Matre, Norway

Ingrid B. Utne and Ingrid Schjølberg
Department of Marine Technology
Norwegian University of Science and Technology
Trondheim, Norway

***Abstract*—Farming of Atlantic salmon in exposed areas poses unique challenges to operations, structures and equipment due to severe and irregular wind, wave and current conditions, and sheer remoteness. Many of the operational challenges seen at present sheltered sites are likely to be amplified when moving production to more exposed locations. There is, however, a strong Norwegian industrial interest in utilizing such areas. A new research center, the Exposed Aquaculture Operations center has been initialized to develop competence and technology to address the challenges. Six core research areas are identified that will be crucial to address the challenges with exposed farming, with a focus on the industrial status in Norway. Four areas target technological innovations that will enable safe and reliable exposed aquaculture operations: 1) Autonomous systems and technologies for remote operations, 2) Monitoring and operational decision support, 3) Structures for exposed locations and 4) Vessel design for exposed operations. Two areas represent core requirements for sustainable production: 5) Safety and risk management and 6) Fish behavior and welfare. This paper describes the research needs and the research strategy planned for the Exposed Aquaculture Operations center.**

Keywords—component; aquaculture; Norway; exposed locations; engineering technology; marine operations.

I. Introduction

Producing sufficient amounts of healthy food for a growing world population is a global challenge. Fish farming will play a major part in meeting future food needs. By 2030, the World Bank projects that 62% of all seafood consumed will be farm raised [1]. Norway's salmon farming industry is a key success story in global aquaculture production. From humble beginnings in the 1970s, the Atlantic salmon industry has expanded throughout fjord and coastal areas in Norway to produce 1.3 million metric tons of fish in 2013 with an export value of 39.8 BNOK. Fish farming is now a significant employer and a socio-economic pillar supporting regional communities throughout Norway [2]. Further expansion is possible; Norway could farm 5 million tons of fish per year by 2050, if key production and environmental challenges are met [3]. The United Nation's Fisheries and Agriculture Organization recognizes that technological development will play a major role in future industry expansion [4].

The production cycle within most industrial enterprises aimed at the aquaculture production of finfish begins with a hatchery/nursery period which starts with the hatching of fish fry from fertilized eggs. When the fish are deemed sufficiently large and developed they are moved to the grow-out phase, during which they will grow until market size and ultimately be harvested and delivered to processing and distribution. Within marine aquaculture, the grow-out phase is typically conducted in sea cages that are placed in floating fish farms moored to the seabed or the shore. An example of a modern Norwegian fish farm for Atlantic salmon is shown in Fig. 1. Besides feeding, farming in the grow-out phase involves a variety of tasks; size grading and distribution of fish to maintain acceptable stocking densities, monitoring of water quality and fish welfare, net cleaning and structural maintenance. All these operations are important to obtain good growth while ensuring fish welfare, and in order to have a profitable and sustainable production it is necessary to have a high degree of regularity on all these operations.

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Figure 1: Large Norwegian fish-farm. Each of the circular net cages can have a volume of up to 50 000 m3 and hold up to 200 000 farmed Atlantic salmons (1000 metric tons).

Significant parts of the Norwegian coast are unavailable for industrial fish farming due to geographical remoteness from onshore infrastructure and exposure to harsh wind, waves and current conditions. While farming of salmon and trout started in more sheltered coastal environments, fewer such areas are today available for salmon farming, both due to competition with other coast-based industries such as tourism and fisheries, and due to the radical growth the salmon industry has seen during the last decades. This has led to a gradual move towards also using more exposed coastal areas for salmon farming. Exposed farming locations could be ideal for production and simultaneously reduce key environmental effects. Exposed areas may feature more stable water flow conditions than sheltered sites, which may in turn lead to more stable culture conditions and greater dispersal of wastes, both of which improve the production environment [5]. Further, exposed farms would be more distant to wild salmonids in coastal waters than conventional sites, which could contribute to reducing the negative ecological consequences of sea lice [6] and escapees [7]. There is a large industrial interest in enabling safe and sustainable seafood production in exposed coastal and ocean areas. Except for a few proposed concept solutions, no concrete plans to move production into the open ocean environment have been published. Rather, the industry has focused on utilizing the limited shelter and bathymetry of outer coastal areas.

Fish farmers who have started utilizing exposed areas report considerable difficulties in maintaining reliable production [8]. Farming in exposed areas poses unique challenges to operations, structures and equipment due to severe and irregular wind, wave and current conditions, and sheer remoteness. Furthermore, many of the operational challenges seen at present sheltered sites are likely to be amplified when moving production to more exposed locations. There are sites that have been abandoned because of difficulties to perform key operations effectively and when necessary, which is a fundamental requirement for profitable and sustainable farming.

While aquaculture production has moved towards more exposed locations, few significant technological and operational changes have accompanied this transition. Exposed farming requires novel technical solutions combined with operational concepts to maintain safety and ensure reliability. Norwegian maritime industrial clusters and research institutions are at the forefront of innovation and competence focused on demanding maritime operations and can play a significant role in this task.

This paper will focus on the technological challenges of salmon and trout farming at the most exposed locations currently in use in Norway (with significant wave height of around 2.5m and current speeds up to 1.0m/s, corresponding to class 3 defined by [9]) and future farming at more offshore sites. A new research center for Exposed Aquaculture Operations is presented, where these technological challenges will be addressed. Research needs for realization of exposed aquaculture are discussed and planned activities at the center together with expected impact of results are presented. This will also be relevant for exposed aquaculture internationally.

II. The Exposed Centre

The Research Council of Norway has a funding scheme called Centres for Research-based Innovation (SFI). The main objective for the SFI Scheme is to enhance the capability of the business sector to innovate by focusing on long-term research based on forging close alliances between research-intensive enterprises and prominent research groups. SINTEF Fisheries and Aquaculture together with numerous research and industry partners proposed a center for Exposed Aquaculture Operations, and were awarded funding for this for five years, with the possibility of a three year extension. The research center Exposed Aquaculture Operations (EXPOSED for short) was initiated in the spring of 2015, and is now in the starting phase of its operation. More information is available at http://exposedaquaculture.no/.

The new research center, Exposed Aquaculture Operations, has identified six core research areas (see Figure 1) that will be crucial to address the challenges described.

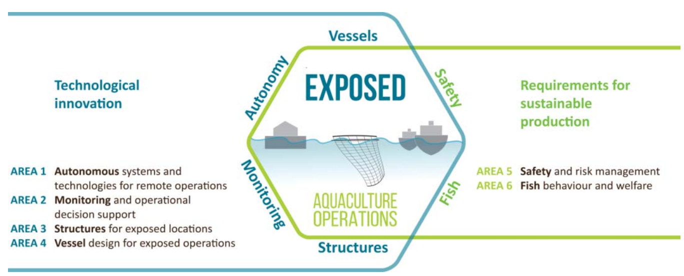

Figure 2. Four Areas target technological innovations that will enable safe and reliable exposed aquaculture operations. Two Areas represent core requirements for sustainable production.

Four Areas target technological innovations that will enable safe and reliable exposed aquaculture operations:

- Area 1: Autonomous systems and technologies for remote operations – Daily routine work and periodical operations must become less dependent on close human intervention.
- Area 2: Monitoring and operational decision support – Severe weather conditions and remoteness impede access and increase the need for robust monitoring of

structures, systems and fish welfare to assess system state and support operational decisions.

- Area 3: Structures for exposed locations – Aquaculture structures need to be operational at exposed sites with respect to sea load response, personnel safety and fish welfare. Flexible and rigid systems, active regulation, and new concepts will be studied.
- Area 4: Vessel design for exposed operations – Vessels, on-board equipment and logistical solutions must be designed to enable safe and efficient operations in exposed areas.

Two areas represent core requirements for sustainable production:

- Area 5: Safety and risk management – Exposed operations require improved risk management strategies and systems.
- Area 6: Fish behavior and welfare – The technologies and new operational solutions must ensure fish performance and welfare in exposed conditions.

III. Status And Challenges

To shape a suitable research strategy aimed at exposed aquaculture operations, it was necessary to first identify the primary research and innovation challenges associated with this subject. This was done by conducting a survey on the present status within the industry, and within relevant research disciplines, thus ensuring that the planned research activities were in tune with both contemporary industrial needs and research horizons. Although many of the identified challenges are of a cross-disciplinary nature, it is possible to distribute them between the six research Areas identified.

A. Autonomous systems and technologies for remote operations (Area 1)

1) Industrial status

Current state-of-the-art technologies and operations for sea-based aquaculture farms are highly dependent on manual labor and close human interactions with the process and cage structures. Moving to more exposed areas renders this difficult and highlights the need for operations that are more autonomous. Autonomous systems and operations are in this context systems and operations with different levels of self-governance and self-control, reducing the need for human interaction. Feeding systems are in most cases fully remote controlled from a feeding barge, and is one of the few examples where manual labor has become redundant. Operations such as dead fish removal, and inspection, maintenance and repair routines are required daily and are done manually for each individual cage. Inspections are conducted with Remotely Operated Vehicles (ROV) or divers, while net cleaning is performed with high pressure cleaning rigs operated by cranes or ROVs. Many of the periodical production control operations, such as delousing, fish handling and well boat transfer, are extremely complex, require numerous personnel and service boats, and involve potentially hazardous heavy crane operations. To ensure reliability and robustness under harsh environmental conditions, new and adapted enabling tools, technology carriers and platforms with a larger extent of autonomy are needed. Many exposed sites struggle with regularity and planning of operations, such as fish handling and lice treatments. Autonomy and remote control options in auxiliary tools like ROVs, vessel control and cage-integrated intervention tools will expand the time window for operations in exposed locations.

Most operations and systems at fish farms are strongly dependent on a reliable electrical power source. Problems due to power supply failure will be more likely at exposed sites as they are associated with more severe weather conditions and longer distances to shore than sheltered locations. Power supply failures will also be more serious at exposed sites as stable power supply is a prerequisite for autonomous systems handling operations when human presence at the farm is inhibited or undesirable. At fish farms today, power is either supplied through combined communications/power land cables or by local diesel generators at the farm site. As exposed sites are high-energy environments, alternative energy sources, such as wave energy plants, wind energy plants or current turbines, could be viable options.

2) Research status

There are mainly two classes of unmanned underwater vehicles, ROVs and AUVs (Autonomous Underwater Vehicles). ROVs are employed widely for drilling operations, inspection, maintenance and repair on subsea oil infrastructure and well inspection. However, today's ROVs depend on qualified operators performing the operations efficiently and safely. Weather windows for vessel-supported operations may be short and efficiency in operations is an essential factor. While ROVs are tethered, highly maneuverable vehicles often with the ability for intervention using a robotic manipulator arm, AUVs are untethered, slender and underactuated vehicles typically conducting survey missions without operator intervention. Although not as widely used as ROVs, they are increasingly being used for inspection tasks with roles and missions constantly evolving.

Robust and efficient guidance, navigation and control (GNC) systems are one of the most important components in autonomous or semi-autonomous underwater vehicles [10]. GNC and control of robot manipulators for aquaculture operations are in many aspects particularly complex. Vehicles operate in very demanding environments with currents, large waves and flexible structures changing geometry in an undetermined pattern. This implies that the vehicle has to navigate and plan trajectories relative to non-fixed structures, and also interact with them during maintenance operations. Commercial off-the-shelf technology for safe and efficient GNC systems to conduct inspection, maintenance and repair routines in such environments does not currently exist.

Although many aquaculture operations could be performed by free-swimming platforms such as ROVs/AUVs, these are currently not suited for larger operations such as fish handling and well boat transfer. Performing these types of operations autonomously or remotely controlled requires new integrated cage solutions.

3) Research and innovation challenges:

Develop tools and platforms for robust autonomous and remote operation of daily routine work and periodical operations to reduce the need for close human intervention.

B. Monitoring and operational decision support (Area 2)

1) Industrial status

Sensors for monitoring sub-systems in modern fish farms are used to support operational and strategic decisions. Moving farming operations to more exposed areas will increase the importance of such systems as more severe weather conditions and remoteness will impede access to the farm site, and thus render direct observation of the system more difficult. Data from sensors is collected and stored through local ICT infrastructures at the farms, typically featuring a combination of wireless links and cabled communication links and local servers/workstations. Wireless or cabled links connect the site to shore installations. Lack of redundancy for sensors and communication links is often a challenge. Data-assisted decision making at fish farms may be conducted by directly applying the information provided by the sensor system. An example of this is when a farmer decides to reduce feeding because the oxygen saturation in the cage drops beneath a pre-defined limit.

2) Research status

Traditionally, sensor data actively used in the industry have mainly been limited to visual observation (cameras) and parameters directly influencing fish growth (e.g. temperature, oxygen). Additional types of sensors are gradually implemented, such as hydroacoustics, increasing the information available both for monitoring the environment, fish welfare and structural integrity (e.g. water current profiles and anchor loads). Each sensor system typically produces information on a limited sub-system or component within the farm, reducing the potential of using data from a single sensor as a basis for decision support on farm scale. An alternative approach would be to combine data from different sensor systems with numerical models to produce an estimate of the total system state of the fish farm. This can be combined with knowledge-based methods, such as case-based reasoning (CBR), drawing on experiences from research on decision-support systems in other application domains (e.g. oil and gas [11], finance [12], and medicine [13]).

3) Research and innovation challenges

Develop robust and flexible monitoring systems that can be adapted to severe environmental conditions, and decision support tools to assess system states and drive the scheduling and performance of key operations.

C. Structures for exposed locations(Area 3)

1) Industrial status

A large variety of concepts for fish farm structures for exposed locations exist today [14]. However, when it comes to farming of Atlantic salmon in Norway, the dominant concept is flexible floating net-cage systems. Such systems consist of net enclosures containing fish, with a weight system to provide sufficient volume within the cage. The nets are attached to circular plastic collars to keep the structure floating. This design concept has existed since the early years of the salmon industry and has become the industry standard. Through the years, as production has moved from sheltered sites, the trend has been to use up-scaled conventional systems, dimensioned to withstand the increased load-level. A modern fish farm, as exemplified in Fig. 1 by the full scale test facility Aquaculture Engineering[1] (ACE), consists of several net-cages mounted into a rope-based frame-mooring system and can produce 15000 metric tons of salmon per production cycle. A feeding barge, including a control room for monitoring of the feeding process, is usually anchored in the vicinity of the fish-cages.

Strength and reliability of the structure are not the only design criteria of farm structures. It is equally important that the fish farm personnel are able to perform the necessary operations in a safe, efficient and cost-effective manner. Further, the structures must provide good habitat for the fish, ensuring adequate stocking densities and environmental conditions. Technical design requirements for Norwegian fish farms are specified in the Norwegian standard NS9415 [15].

2) Research status

Research activity on aquaculture structures has increased in recent years to provide better knowledge on load levels, flexible deformations and dynamic behavior of conventional floating net-cage systems when subjected to dimensioning currents and waves [16-19]. New knowledge is typically sought through numerical simulations, scaled model tests and full-scale measurements. Improved design concepts of fish farm structures for operation at exposed sites have met increased research interest. The use of stiff steel structures based on technology from the offshore industry represent one design approach. A second approach is to use structures that reduce their exposures through flexible deformations of the structure into a less vulnerable shape [20], or by submergence of the structure below the wave-zone in heavy weather [14].

3) Research and innovation challenges

Develop aquaculture structure concepts that are operational at exposed sites with respect to sea load response, personnel safety and fish welfare.

D. Vessel design for exposed operations (Area 4)

1) Industrial status

Existing aquaculture sites are regularly serviced by three different vessel classes; well boats (live fish carriers), feed carriers and service boats. Visits from well boats are limited to operations where fish are transported, treated, or moved between cages, while feed carriers regularly dock at sites to replenish supplies. Service boats are in constant operation at the sites and are used for the day-to-day operation and maintenance of the site, as well as support for visits from the larger vessels when required, fish carrier operations in particular.

The most common aquaculture service boats today are vessels of less than 15 m in length equipped with a high capacity crane. The service boats are dimensioned as to allow

[1] http://aceaqua.no/

access throughout the site. This means restricting draught to avoid interference with the mooring and a reduced freeboard to ease access from the deck to the floating collar. The length is usually restricted due to regulations which require certification for operation of boats in excess of 15 m, but legislations are being finalized that will open up for new designs and capacities. Catamaran designs are popular due to the increase in the work deck area and intact stability. The capacity of the cranes and winches on the service boats have increased with industry requirements, while the service vessel dimensions remain constrained by adaptation to regulations. This has led to dangerous situations, loss of life and equipment due to a mismatch between equipment power and vessel performance.

The feed vessels visit aquaculture sites regularly and carry feedstock from production plant to fish farms coordinated with site feed storage and consumption. Feed is transported from the vessel to the feed barge by crane or pumped through hoses. The more advanced feed carriers may use a simplified dynamic positioning (DP) system for mooring-less transfers of cargo.

Fish carriers are larger vessels and have increased in size and complexity along with the industry as a whole with a design reminiscent of coastal tankers. The fish carriers interact directly with the floating collar and fish cage. The largest fish carriers barely fit between the collar moorings and are capable of transferring large forces both from their propulsion system and from the environment to the floating collar and mooring lines.

2) Research status

Exposed aquaculture sites will experience harsher environmental conditions during operations, which in turn will impose requirements on the strength of the fish farm, mooring system [21] and the sea-keeping ability of support vessels if service regularity is to be maintained [8]. Vessels servicing an exposed site are expected to encounter larger and more persistent wave and wind loads which have been extensively studied. Current theory and tools should guide the design process for new aquaculture vessels, since the sea-keeping ability of vessels is largely dependent on hull design. While additional support systems such as dynamic positioning controls the mean position and heading, the magnitude of wave-induced oscillations about this position may prove detrimental to operational regularity. Vessel designs optimized for exposed operations are expected to build upon existing experience, analysis tools and design concepts (such as wave piercing and SWATH designs). Analysis software for structures, hydrodynamics [22], computational fluid dynamics, and power systems are currently in use in the design process. System simulators such as FhSim [23] have proven beneficial in both design and analysis. New analysis capabilities must be developed in order to analyze aquaculture vessels during operations in an exposed site regime.

A large body of work exists for the development of the merchant shipping and offshore energy industry and should be transferred to aquaculture setting where applicable, while new tools and theories are developed to service the special characteristics of the industry.

3) Research and innovation challenges

Design vessels, on-board equipment and logistical solutions that enable safe and efficient operations in exposed areas. Ensure safe interaction between vessel and fish farm.

E. Safety and risk management (Area 5)

1) Industrial status

The aquaculture industry is the second most risk exposed occupation in Norway [24]. Today's farms already operate at the safety limit of available technology and management systems [25]. Adverse weather conditions, suboptimal human-technology interaction and a number of organizational aspects are known risk factors [26]. Moving fish farms further offshore will increase the challenges to the work environment and the management of operations. This will demand greater operator skills and the ability to take correct actions when required to avoid equipment failure, escapes of fish or occupational accidents. The management of the fish farming companies rely on the operators to make all practical safety-decisions during operations [27]. Fish farming is associated with shift work, long working hours including night work, which all negatively affect cognitive performance and sleep quality for workers in other industries [28]. For exposed locations, new technological solutions are necessary for ensuring safety as well as efficiency [29].

The aquaculture industry is obliged to fulfil requirements set by the laws and regulations controlled by four different authorities. Development of management systems that satisfy legal requirements and achieve coordination among farmers and their service providers is challenging. These systems are crucial for the companies' ability to manage risks and maintain acceptable safety levels in the operations.

2) Research status

Risk management deals with identifying, analyzing, assessing and controlling occupational risk and major accident risk during the entire system life cycle, i.e., from design and development to decommissioning. In the aquaculture industry human workers and operators are exposed to occupational hazards, such as slips and falls. The major accident potential in fish farming has mainly been related to the escape of fish from the net pens, which may have severe consequences to corresponding wild fish stocks [30]. There is also a possibility for total loss of a fish farm by sinking or destruction of the technical integrity of the fish farm facilities, where the lives of personnel will be at risk. For coastal aquaculture, improvements in technical regulations have led to a decrease in full breakdowns of whole cages or whole fish farms due to floater and mooring failures [7]. However, in the case of exposed aquaculture new constraints will be necessary to prevent breakdowns and major accidents.

There is significant potential for increased safety in fish farming operations by implementing systems for systematic risk management, based on the state-of-the-art methods for risk management, and best practice experience from other exposed workplaces, such as the offshore oil and gas and the construction industry. Management systems have to be developed based on the specific needs, conditions and characteristics of the aquaculture industry. This innovation effort calls for an overall approach with involvement from all stake-holders; industry partners, authorities, research and academia.

3) Research and innovation challenges

Develop improved risk management strategies and systems in fish farming, integrating technical, human and organizational factors, which provide systematic means for designing safe workplaces, as well as monitoring and follow up during operation.

F. Fish behaviour and welfare (Area 6)

1) Industrial status

The welfare of fish is central to the success of any aquaculture operation. Fish health and growth ultimately translate to high product quality and profitability. Understanding fish behaviors is essential to correctly conduct operations such as feeding, de-lousing and harvesting/sampling, so that welfare is maximized [31]. The adult growth phase of wild Atlantic salmon, which is the most common species farmed in Norway, occurs in the surface waters of the open ocean [e.g. 32], implying that salmon are able to handle the conditions at exposed farm sites. However, whereas wild fish can dive to avoid harsh surface conditions when needed, the vertical movements of farmed fish will be limited by the confines of the sea-cage, increasing their exposure to unfavorable currents, waves and the resulting movements of cage structures. Although present day exposed sites have demonstrated acceptable growth and fish welfare in salmon, increased mortalities have occurred during rough weather as a result of stress [33]. This emphasizes the importance of research on fish performance during exposed operations.

Operational solutions to feed, stock and harvest cages, and robust treatment of diseases and parasites at exposed sites will require new equipment and more autonomous procedures; understanding how to implement these for best possible welfare outcomes for fish is vital. A harsher environment will simultaneously modify fish and feed distributions, creating new operation challenges for effective feeding. In addition, feed delivery is likely to be less regular given more extreme weather. Parasites, diseases and predators at exposed sites may differ from those encountered at sheltered locations, leading to operational changes in how these are handled and avoided to secure fish welfare.

2) Research status

While the behaviors and welfare of farmed salmon in sheltered farming locations [31] are well known, few studies have assessed performance at exposed sites where fish are subject to stronger currents and larger waves than at sheltered sites. High current speeds induce changes in salmon behavior, with the fish aligning with the current rather than exhibiting the circular swimming pattern commonly seen in cages at sheltered sites [34]. Even though exercise is positive for fish performance, salmon forced to swim at exceedingly high velocities have been shown to exhibit reduced growth [e.g. 35] and decreased muscle energy stores [36]. When current speeds exceed maximum swimming capacity, salmon may experience a build-up of lactate, and in severe cases, lethal acidosis. Anaerobic capacity is eventually exhausted and the fish will stop swimming, and be forced into the net wall and injured. These effects are clearly unacceptable for welfare, and are more likely to occur at exposed farming sites. How waves affect farmed fish remains unknown, although salmon have been observed to actively avoid stormy weather in sea-cages [37]. A tool for welfare evaluation was recently developed for sheltered fish farms [38]. Similar systems are now required to ascertain fish welfare in exposed aquaculture operations.

3) Research and innovation challenges

Study fish performance and welfare under the conditions at exposed sites, as well as under the new operational solutions.

IV. Research Needs

Since most challenges associated with exposed aquaculture operations will require a multidisciplinary approach, the research in the EXPOSED Centre will be organized in projects, including PhD and post doc scholars, which combine different Areas, partners and methods. However, the general research strategy within EXPOSED will be built around a selection of research asks to address the research and innovation challenges identified above.

A. Autonomous systems and technologies for remote operations (Area 1)

1) Previously defined challenges

Develop tools and platforms for robust autonomous and remote operation of daily routine work and periodical operations to reduce the need for close human intervention.

2) Research tasks

- *Remote inspection, maintenance and repair using underwater vehicles*: Important research fields within this context are: 1) GNC systems, machine vision for aided navigation, dynamic path planning, wave zone operation and sensor fusion methods; 2) concepts and development of sensor systems and intervention tools for inspection, maintenance and repair operations such as net and mooring inspection, net cleaning and net repairs; and 3) underwater docking and launch and recovery of underwater vehicles in large waves.
- *Fish handling tools*: Robust tools which can interact with the fish inside the cages to enable crowding and transfer to well boats without the direct use of humans and vessels directly moored to cages. Research tasks within this context are concept studies for a cage integrated and remotely actuated crowding system and process control for efficient and safe crowding.
- *Cage integrated tools for frequent in-cage operations*: Daily operations for fish welfare monitoring, feeding and dead fish removal are required. Furthermore, tasks such as net cleaning must be done frequently. Integrated cage tools are necessary to perform these tasks without direct human assistance. Research tasks within this context are concept studies for such tools, manipulators, sensors and control systems.

3) Impact

Solutions for increased autonomy will reduce the dependence on human manual labor and presence and will enable increased regularity and safety of operations at more exposed sites.

B. Monitoring and operational decision support (Area 2)

1) Previously defined challenges

Develop robust and flexible monitoring systems that can be adapted to severe environmental conditions, and decision support tools to assess system states and drive the scheduling and performance of key operations.

2) Research tasks

- *System requirements*: Identify and analyze the various sub-systems and the parameters required for state assessment as a basis for defining sensor and infrastructure requirements. Qualify which sensors are needed to achieve adequate coverage of the total farm state and evaluate their data quality. Define a set of requirements for ICT infrastructures at exposed sites needed to ensure robust and reliable data capture.

- *Sensor and communication systems*: Identify and develop new technical solutions and sensors for monitoring sites, including the interaction between the site sub-systems during operations. Fault-tolerance and redundancy will be important requirements for developing new innovative solutions. Knowledge from the offshore industry can be actively used.

- *Prediction of site states and decision support*: Knowledge-based methods, in combination with numerical models and sensor data will be valuable for automating early warnings, incident mitigation, predictive maintenance and operations planning. The wide range of personnel and operations involved will necessitate automated context-based adaptation of information content and functionality. This task should tightly integrated with the other Areas defined.

3) Impact

Results will ensure fish welfare, reduced risks for personnel, reduced environmental impacts and contribute to economic benefits by reducing operating costs and improving end product quality.

C. Structures for exposed locations (Area 3)

1) Previously defined challenges

Develop aquaculture structure concepts that are operational at exposed sites with respect to sea load response, personnel safety and fish welfare.

2) Research tasks

- *Flexible structures*: Improved numerical models and methods for analysis of large and flexible structures with variable stiffness characteristics and spatial systems with uncorrelated varying sea conditions. The behavior of each component (cage, feeding barge, flexible feeding pipes, mooring systems) need to be analyzed and emphasis must be put on their interactions to understand the response characteristics and constraints in systems.

- *Active control of structure response*: To increase the safety and performance of aquaculture structures when subjected to varying sea states and current, response control of such systems needs to be addressed by utilizing model-based controllers that handle multi-regime conditions.

- *New concepts for aquaculture structures*: Develop rational design requirements for aquaculture structures based on first principles for simulations of the governing physical phenomena, structural load effects and structural resistance. Fatigue, ultimate strength and accidental limit state conditions must be addressed. Investigations should be performed in order to develop concepts for stabilizing the feeding barge by means of active control systems, new hydrodynamic designs or fixed platforms. Technologies for local energy production should be investigated.

- *Improved structural components:* Research on new and existing net structures and materials to understand and determine wear mechanisms to reduce the risk of tearing and prolong life time. Develop objective criteria for documentation of new and existing netting materials.

3) <u>Impact</u>

Research will result in structures that are able to operate safely and reliably at exposed locations, and are adapted to the operational needs of fish farming.

D. Vessel design for exposed operations (Area 4)

1) Previously defined challenges

Design vessels, on-board equipment and logistical solutions that enable safe and efficient operations in exposed areas.

2) Research tasks

- *Vessel design and sea-keeping capabilities*: Study and develop new designs for all three types of vessels with the sea-keeping, structure interaction and equipment required for operations at exposed locations.

- *Vessel and structures coupling*: Integrate simulation models and software tools to analyze the different floating objects and to account for hydrodynamic coupling effects between vessels and structures.

- *Analysis of operations*: Develop simulation scenarios for exposed aquaculture which allows simulation of critical operations. Simulations are a tool to evaluate the goodness of fit for the proposed vessel designs and may be used as a feedback loop in the design process.

- *Logistics optimization*: New logistics solutions need to cope with the changes in vessels and fleet operations. Important issues to consider are onshore and offshore storage, personnel and equipment logistics.

3) Impact

Robust vessel designs adapted to the harsh conditions will increase the operability and the production of exposed aquaculture sites, without compromising the safety level. Optimized logistics will be crucial for reducing the cost of moving the operations offshore.

E. Safety and risk management (Area 5)

1) Previously defined challenges

Develop improved risk management strategies and systems in fish farming, integrating technical, human and organizational factors, which provide systematic means for designing safe workplaces, as well as monitoring and follow up during operation.

2) Research tasks

- *Barrier management*: Identify and assess hazards in exposed aquaculture operations as the basis for the design of barrier functions and elements to prevent, control or mitigate these risks. Safety barriers can be organizational, physical/ technical, or human/ operational. The development of effective barrier functions should be based on best practice from industries with comparable exposures and/or structuring, as well as analyses of past accidents. Derive requirements and specifications for data input from Area 2 "Monitoring and operational costs" and develop barrier management systems that utilize and transform the data for barrier performance monitoring.

- *Automated work operations and risk*: Analyze the impact of increased automation, remote operation and autonomous systems on the general risk level of fish farming operations, and more specifically, how automation impacts the human operator's work situation and decision-making.

- *Risk management in manual operations*: Develop HSE requirements and workplace guidelines for the unavoidable manual operations at fish farming sites, in cooperation with the regulatory authority. Guideline regulations should be sought and adapted from the fisheries and offshore oil industries.

3) Impact

Methods, procedures, guidelines and operational practices developed will contribute to safer operations in exposed as well as conventional fish farming.

F. Fish behaviour and welfare (Area 6)

1) Previously defined challenges

Study fish performance and welfare under the conditions at exposed sites, as well as under the new operational solutions.

2) Research tasks

- *Biological prerequisites*: Identifying the tolerance limits of fish to exposure will define the boundaries for which exposed sites will be efficient while maintaining acceptable fish welfare. Using these results, new management techniques which alleviate the impacts of conditions beyond the tolerances of fish should be developed.

- *Welfare evaluation*: Science-based methods to assess fish welfare at exposed sites must be developed to ensure that technical solutions developed in this center adhere to Norwegian animal welfare law [39] and other national and international guidelines. Similar work conducted for conventional fish farms [e.g. 38] provides a basis and can be modified to account for the additional challenges encountered at exposed sites.

- *Behavioral responses*: It is important to identify how the fish will respond to prevailing currents and sea states at exposed sites. Such conditions will entail changes in the production environment (e.g. increased cage deformations and altered feed distribution in the cage volume) and lead to secondary effects whose impact on fish behavior needs to be studied. Outcomes should form the basis for the development of management strategies, technological equipment and production techniques better suited to farms at exposed sites.

3) Impact

The research will set some of the main premises for the technological research conducted in other research areas within the center, as systems must account for the needs of the fish.

V. Summary And Conclusion

This paper has presented six research areas identified as crucial to address the challenges of operating fish farms at exposed locations. The funding and initiation of the Exposed Aquaculture Operation Center will enable long-term research and innovation within these areas. The report "Et kunnskapsbasert Norge" [40] identifies the oil and gas, maritime and sea food industries as the three global knowledge hubs in Norway. Through its partners and collaboration with others, the EXPOSED Center will provide a platform for knowledge transfer between these industries to find solutions and create value for the industry partners. The long-term collaboration between industry and research partners will also enable valuable sharing of knowledge.

In addition to the research projects, PhD and post doc scholars, and internal workshops and industry forums of the EXPOSED Center, there is an aim to initiate various external activities. Associated projects and collaborations will be initiated, and the center participants will collaborate with related research groups and authorities, both in Norway and abroad. The center will also be a tool for realization of the innovation potential by the Centre for Autonomous Marine Operations and Systems (AMOS), a Norwegian Centre of Excellence.

In the report "Value created from productive oceans in 2050" [3], the potential for value creation in 2030 and 2050 for the Norwegian aquaculture production is estimated at 119 BNOK and 238 BNOK, respectively. Solutions that enable the use of exposed and remote sites will likely contribute to sustainable growth in the Norwegian salmon industry and global aquaculture production by improving operation safety and cost-efficiency. Focusing on exposed aquaculture operations will also provide competence and solutions that benefit more sheltered aquaculture production. This will also contribute towards fulfilling the ambition of Aquaculture Stewardship Council certification [2] set out by the Global Salmon Initiative[3].

Systems and technologies for exposed aquaculture are in worldwide demand and novel competence and solutions will increase existing and open new markets. New knowledge gained from exposed aquaculture will likely also benefit other industries by providing flexible and cost-effective maritime products and services.

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