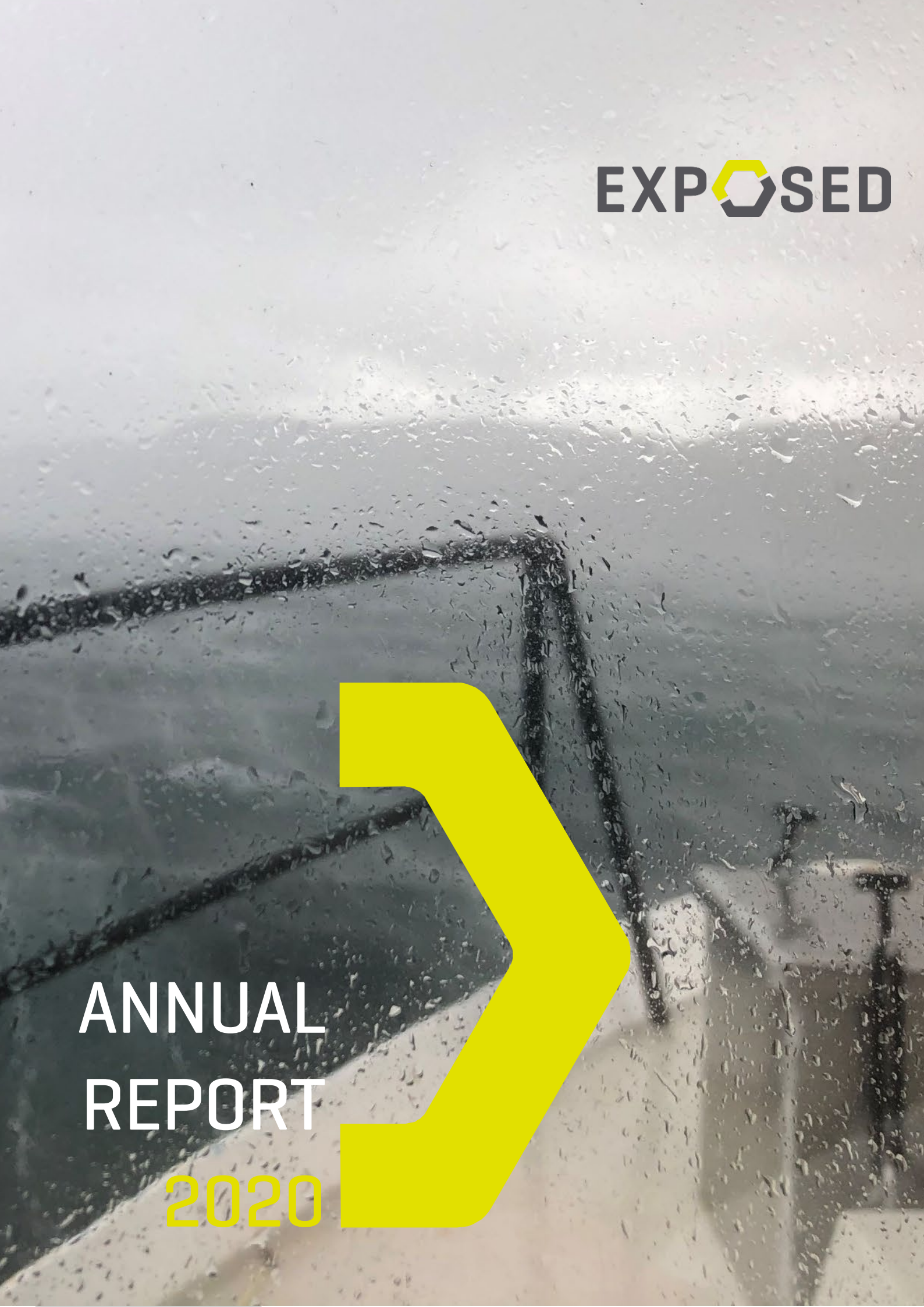


EXPOSED

ANNUAL REPORT 2020

CONTENTS

Centre host:
SINTEF Ocean
Postboks 4762 Torgarden
7465 Trondheim, Norway

Contact:
Centre Director
Hans V. Bjelland
hans.bjelland@sintef.no
(+47) 98829872

EXPOSED
AQUACULTURE OPERATIONS
CENTRE FOR RESEARCH-BASED INNOVATION
exposedaquaculture.

SUMMARY

In 2020, project activities at the EXPOSED Aquaculture Operations Centre were moderately affected by the Covid-19 pandemic. The centre adapted its networking arenas and developed new channels of communication.

EXPOSED is one of a number of Norwegian Centres for Research-based Innovation (CRIs) and is funded by the Research Council of Norway's Division for Innovation[1] and its partners. The main objective of the centre is to enhance the innovative capability of the business sector by focusing on long-term research generated by the creation of close alliances between research-intensive enterprises and prominent research groups. The EXPOSED centre brings together global salmon farmers, key service and technology providers, and leading research groups with the aim of developing knowledge and technology to support robust, safe and efficient fish farming operations in exposed locations.

In Norway, in particular, there is a strong innovation drive in the aquaculture industry, and major investments are being made. Moreover, new farm concepts and novel production opportunities in coastal areas require the authorities and industry to review current legislation and regulatory practice. The centre and its partners are regarded as valued contributors to this development, through their role as partners in R&D projects, in scientific and industrial fora, and in the public debate. The centre is also frequently contacted by foreign governments, industry and researchers with requests to support similar developments abroad.

The application of new concepts for aquaculture production systems is growing rapidly in Norway, with a focus on land-based, floating closed, semi-closed and exposed solutions. All of these have an impact on national strategies and the regulation of the industry, and the EXPOSED centre continues to make a highly relevant contribution in this field.

In the second half of its lifetime, the centre aims to increase its focus on transforming knowledge into innovations for its industry partners and the wider aquaculture industry.

Several of its ongoing projects develop and demonstrate technologies and solutions linked to exposed farming operations, such as decision support systems, the use of robotic arms to compensate for the relative motions of vessels and cages, and underwater navigation and manoeuvring.

The first PhD candidates working on projects linked to the centre have now successfully defended their theses, and will no doubt make a valuable contribution to future industrial and academic work carried out in the aquaculture industry.

sfi Centre for Research-based Innovation

[1] https://www.forskningsradet.no/om-forskningsradet/programmer/sfi/

VISION AND OBJECTIVES

*EXPOSED aims to develop knowledge and technology to support **robust**, **safe** and **efficient** fish farming operations in exposed locations.*

Major stretches of the Norwegian coastline are currently inaccessible to industrial fish farming due to their remoteness or exposure to unfavourably harsh wind, wave and current conditions. The aim of the EXPOSED Centre is to take advantage of Norway's strong position in the aquaculture, maritime and offshore sectors as a means of promoting safe and sustainable seafood production in exposed coastal and offshore areas. The industry requires technological innovation in the fields of autonomous systems, offshore structures and vessels in order to sustain aquaculture production under all conditions, and to enable more robust, safe, controlled and continuous operations.

EXPOSED brings together leading global salmon farmers, key service and technology providers, and leading research groups such as SINTEF, the Institute of Marine Research and the Norwegian University of Science and Technology (NTNU), including its affiliated Norwegian Centre of Excellence for Autonomous Marine Operations and Systems (AMOS).

The centre's objectives were reviewed as part of its Midway Evaluation carried out in 2019. The centre's vision and main objective remains unchanged. Since its launch, there has been a significant increase in industrial and political interest in the centre and its research and innovation activities. This interest, driven in part by licencing policy, has promoted changes in the focus of innovation as it applies to exposed aquaculture operations, resulting in the addition of a new industry-linked objective designed to support the centre's industry partners in their innovation processes.

This increased interest has also generated a new enthusiasm among students, allowing the centre to recruit large numbers of MSc candidates and well-qualified PhD students. In order to adapt to this trend, the centre has modified its second research objective and boosted its ambitions related to the recruitment of PhD candidates, post-doctorate researchers and MSc candidates.

Main objective

The main objective of the centre is develop knowledge and technologies to support EXPOSED aquaculture operations, thus enabling a sustainable expansion of the fish farming industry.

Industry objectives

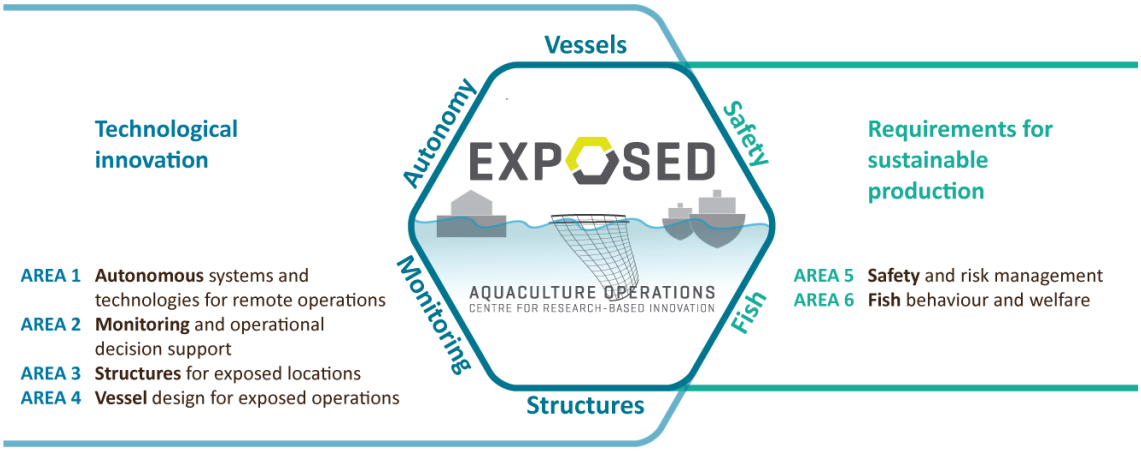
- To enable safe and profitable operations at exposed fish farming sites as a means of boosting sustainable seafood production.
- To develop new technologies that underpin Norway's leading global position in the aquaculture sector, its maritime expertise and technology.
- To help develop new technologies related to concepts identified in connection with development licences.
- To support innovation processes taking place at the centre's industry partners by facilitating access to relevant researchers.

Research objectives

- To conduct fundamental and applied research into key knowledge gaps related to exposed aquaculture operations by combining research fields linked to the aquaculture, maritime and offshore sectors.
- To build knowledge and expertise by the education of at least 20 doctorate, 5 post-doctorate and 70 MSc students.

RESEARCH STRATEGY AND PLAN

*EXPOSED has identified six core **research areas** aimed at addressing the challenges facing the industry.*



Four of the six core research areas highlight technological innovation with the aim of promoting safe and reliable aquaculture operations:

Area 1: Autonomous systems and technologies for remote operations

Day-to-day work and periodic aquaculture operations must become less dependent on close human intervention.

Area 2: Monitoring and operational decision support

Severe weather conditions and remoteness hinder access and increase the need for the robust monitoring of structures, systems and fish welfare as a means of assessing system state and supporting operational decisions.

Area 3: Structures for exposed locations

Aquaculture structures at exposed sites must be fully operational with respect to sea load response, personnel safety and fish welfare.

Area 4: Vessels design for exposed operations

Vessels, onboard equipment and logistical solutions must be designed to enable safe and efficient operations in exposed areas.

Two of the centre's research areas focus on key requirements for sustainable production:

Area 5: Safety and risk management

Exposed operations require improved risk management strategies and systems.

Area 6: Fish behaviour and welfare

The technologies and operational systems applied must ensure optimal fish performance and welfare under exposed conditions.

As a part of its Midway Evaluation, the centre management team decided that future project activities should be of shorter length than previously in order better to adapt to changing industry needs. The activities are organised in research areas, many of which will build on the results of completed projects carried out either at or in association with the centre. The new activities include fundamental research, additional industrial research, and an increased focus on the development of demonstrators used to promote future innovations. Six research areas were active in 2020, involving PhD students and one post-doctoral researcher. The centre also runs several associated projects that carry out relevant research activities, and involving other student candidates. The areas are presented in more detail below.

Figure 1. Research activities combine sets of research areas, partners and methods. PhD students and post-doctoral researchers will take part in the project teams.

*In order to further support research and innovation, the EXPOSED centre aims to initiate or encourage **associated projects**, in addition to its established centre-funded activities.*

Associated projects typically involve one or more existing centre partners, and perhaps also other external companies or research partners. The partners in any given project will vary depending on the main funding source (Research Council of Norway/RCN, EU, or innovation-driven). The centre will enter into agreements with these projects with the aim of promoting mutual benefits and synergies.

The centre also identifies potential in collaborating with other CRI centres and groups. EXPOSED has common activities and shares PhD students with NTNU AMOS, and collaborates on PhD training with two other maritime CRIs; the CRI Move (supporting the marine operations value chain) and the CRI Smart Maritime (supporting improved energy efficiency and harmful emissions reductions from the maritime sector). In the years ahead there is also potential for increased collaboration with the CRIs CtrlAqua (Centre for Closed-Containment Aquaculture) and SFI Blues.

Ongoing associated projects are listed in the table below.

Figure 1. Photo courtesy of NTNU.

Ongoing associated projects	Duration, project type and funding source	Host institution	Relevant current EXPOSED activity
ECHOFEEDING – Echo sounder technology for the appetite-led-feeding and welfare-monitoring of caged salmon	2017–2020 Researcher project (HAVBRUK2, RCN)	Institute of Marine Research	Area 6
FutureWelfare – Environmental requirements and welfare indicators for new cage farming locations and systems	2017–2021 Researcher project (HAVBRUK2, RCN)	SINTEF Ocean	Area 6
SalmonInsight – Unveiling links between salmon physiology and online monitored behaviour	2018–2022 Researcher project (HAVBRUK2, RCN)	SINTEF Ocean	Area 6
FASTWELL – Optimising feed withdrawal to safeguard fish welfare	2019–2022 Researcher project (HAVBRUK2, RCN)	Institute of Marine Research	Area 6
DEVELOP – Development licences as a driver for innovation in fish farming – effects on technology, industry and regulation	2020–2023 Researcher project (HAVBRUK2, RCN)	SINTEF Ocean	Areas 3 and 5
Opportunities and challenges with innovations in aquaculture production systems	2021–2024 Collaborative and knowledge-building project (RCN)	SINTEF Ocean	Areas 3 and 5

ORGANISATION

Organisational structure

The organisation and operation of the centre is governed by a **Consortium Agreement**, which sets out the rights and obligations of the partners, as well as the roles and responsibilities assigned to the different sections of the organisation. A **General Assembly**, with representatives from all the consortium partners, elects a **Board** comprising seven member representatives from among the centre's partners. The Board is the operative decision-making body for the centre. In 2020, the Board members were as follows:

Board member	Affiliation
Alf Jostein Skjærvik (Chair)	SalMar
Noralf Rønningen	Aqualine (ScaleAQ)
Bjørn Egil Asbjørnslett	NTNU
Arne Fredheim	SINTEF Ocean
Berit Floor Lund	Kongsberg Subsea
Ole Folkedal	Institute of Marine Research
Kjell Emil Naas (observer)	Research Council of Norway

Figure 2. From a meeting during the 'EXPOSED Day' in October 2019.

Hans V. Bjelland is the **Centre Director**, with responsibility for managing the centre on behalf of the host institution, SINTEF Ocean. Bjelland reports to the Board. The Centre Director, together with the **Management Group**, manages centre activities related to **projects**, **education** and **innovation**. The Management Group consists of a Research Manager for each of the six core research areas:

Management Group member	Role and responsibility
Hans V. Bjelland SINTEF Ocean	Centre Director
Esten Ingar Grøtli SINTEF Digital	Area 1
Heidi Moe Føre SINTEF Ocean	Area 3
Ørjan Selvik SINTEF Ocean	Area 4
Ingunn M. Holmen SINTEF Ocean	Area 5
Ole Folkedal Institute of Marine Research	Area 6
Jan Tore Fagertun SINTEF Ocean	Area 2
Kaja Haug SINTEF Ocean	Scientific Coordinator

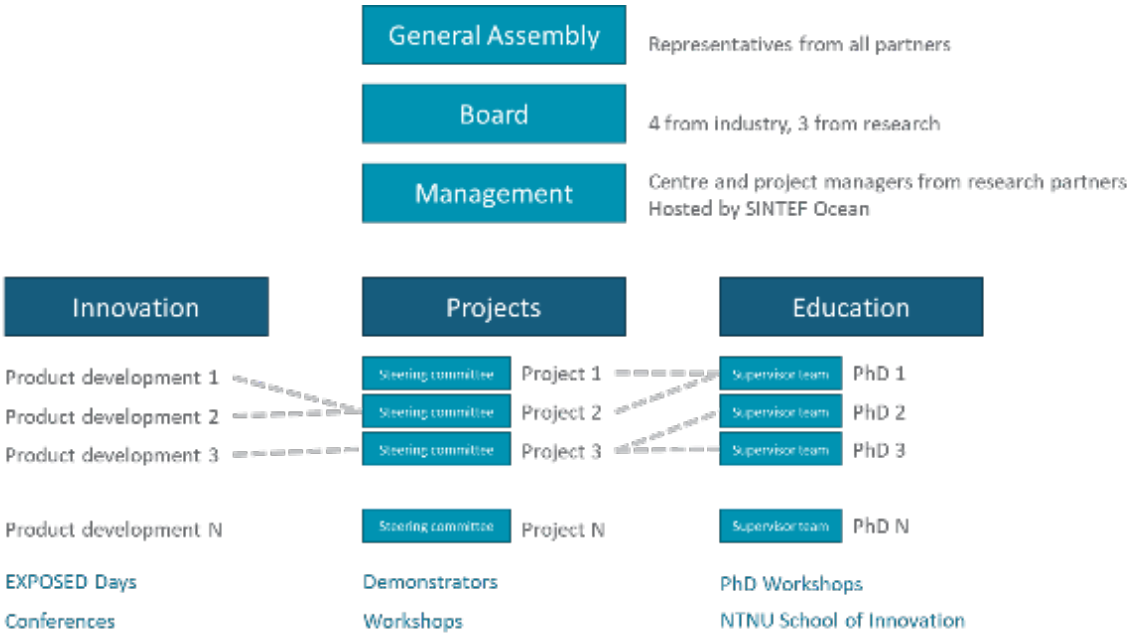


Figure 3. Organisational structure of the EXPOSED centre.

Projects are organised with a **Project Manager** and a **Steering Committee**. The Project Manager is responsible for carrying out the project, while the Steering Committee, headed by a representative of one of the industrial partners, focuses on the supervision of project progress and adherence to its objectives.

Education is implemented primarily via three departments at NTNU; Marine Technology, Computer and Information Science, and Engineering Cybernetics. In addition, some PhD and MSc students are educated at the University of Bergen, facilitated by a collaborative agreement with the Norwegian Institute of Marine Research. PhD students and post-doctorate researchers are assigned to related projects. In addition, several other NTNU departments have been involved in MSc and Bachelor degree studies related to projects carried out at the centre.

As a rule, **innovation** is supported by the organisation of an annual two-day event called 'EXPOSED Days', held during the spring, a one-day event in the autumn, and a number of PhD and post-doctorate workshops. The EXPOSED Days serve as a meeting place for innovation, the presentation of research results, exchanges of ideas and the generation of new projects. There is also scope for further partner involvement and cross-disciplinary interaction on individual projects. During the Covid-19 pandemic, digital meetings have been arranged as an alternative to the EXPOSED Days, workshops and related activities.

In the future, the EXPOSED centre aims to continue to support innovation by helping to identify and follow up innovation processes led by its industry partners, and to promote links between partners by promoting relevant projects and providing researchers.

The centre host, SINTEF Ocean, is located in Trondheim, and serves as a coordinating hub for activities performed at the centre. Several activities are also carried out in other parts of Norway, at partner locations and field sites.

Research facilities

The centre has access to an extensive research infrastructure, hosted by both its research and industry partners:

- **Full scale industrial fish farms with various levels of exposure.** These include the Aquaculture Engineering test site (SINTEF ACE) in the Hitra/Frøya area, as well as other locations in Mid-Norway, and more exposed farm facilities operated by MOWI, Cermaq and SalMar. The farms are equipped with measurement buoys and other instruments, integrated by a technical e-infrastructure and linked to a central and secure data access point for project partners. Experiments are now being carried out at new farms in Norway and the Faroe Islands that provide access to even more exposed sites.
- **Vessel motion monitoring** is facilitated by the service provider and vessel operator AQS, and is used to study operational limits.
- **Scaled-down biological trials** on fish swimming capacity have been conducted under varying conditions at IMR's land- and sea-based facilities at Matre, which include two swim tunnels and a push cage.
- **Hydrodynamic laboratories** in Trondheim, and Hirtshals in Denmark offer a wide variety of scales and capabilities, and will be utilised as a resource for future centre-financed activities.
- **A variety of simulation tools** developed by the centre's research partners have been used to model aquaculture systems and study the dynamics and interactions of structures and vessels, as well as the development of guidance systems for ROV and AUV systems.

Research partners	Research area
SINTEF Ocean (SO). Conducts ocean space research and innovation activities for Norwegian and international industries. Our ambition is to maintain Norway's leading position in the fields of marine technology and biomarine research.	All
SINTEF Digital (SD). Provides research-based expertise, services and products ranging from robotics, microtechnology, communications and software technology, computational software, information and security/safety systems.	1, 2
NTNU's Department of Marine Technology (IMT). Carries out research in the field of marine technology. It hosts the Centre for Autonomous Marine Operations and Systems (AMOS), which is a Norwegian Centre of Excellence. AMOS will have a key role within the EXPOSED centre.	1, 3, 4, 5
NTNU's Department of Computer and Information Science (IDI). Conducts research in the fields of computer and information science, including hardware-related research, intelligent systems and the social implications of information systems.	1, 2
NTNU's Department of Engineering Cybernetics (ITK). Conducts research in various fields associated with control theory, including mathematical modelling and simulation, autonomy, optimisation and automatic control. Together with IMT, ITK plays a major role in the Centre for Autonomous Marine Operations and Systems (AMOS).	1, 2, 6
Norwegian Institute of Marine Research (IMR). Norway's largest marine science centre, whose main task is to provide advice to the Norwegian authorities on aquaculture and related ecosystems.	6

SINTEF NTNU Norwegian University of Science and Technology HAVFORSKNINGSINSTITUTTET INSTITUTE OF MARINE RESEARCH AMOS

Partners

The EXPOSED centre brings together a number of leading global salmon farmers, key service and technology providers, and leading research groups.

	Industry partners	Contribution/role
MOWI	**Marine Harvest.** The world's largest salmon and trout farmer with major operations in Norway, Scotland, Canada and Chile. Name changed to **Mowi** on 1 January 2019.	End user of technology and solutions
cermaq	**Cermaq.** The world's third largest salmon and trout farmer, with operations in harsh environments, including offshore northern Norway.	End user of technology and solutions
SALMAR	**SalMar.** The world's fourth largest salmon and trout farmer, operating large fish farms at exposed locations in Mid-Norway.	End user of technology and solutions
KONGSBERG	**Kongsberg Seatex, Kongsberg Maritime Subsea and Kongsberg Maritime. A s**upplier of technology and systems to the global maritime and offshore sector. Provider of knowledge and systems for communication, control, navigation, decision support, AUVs, etc.	Technology/solution provider
SCALE AQ	**Aqualine (ScaleAQ).** A major international supplier of aquaculture equipment and complete fish farms.	Technology/solution provider
møre maritime	**Møre Maritime.** A provider of maritime consulting, engineering and 3D modelling services.	Technology/solution provider
Anteo	**Anteo.** Operates and develops technical solutions and decision support systems for fish farming companies.	Technology/solution provider
ARGUS	**Argus Remote Systems. Carries out R&D on, and is a** manufacturer of, electrical ROVs.	Technology/solution provider
AQS	**AQS.** Service provider of fish farm inspection and maintenance services, as well as other operations, including delousing.	Service provider
marin design as	**Marin Design.** A provider of vessel designs and maritime consulting services.	Technology/solution provider
DNV	**DNV.** A leading classification society and certification body, and a recognized advisor to a wide range of industries.	Certification, classification and advisory services
MACGREGOR	**MacGregor Norway**. A leading provider of maritime system handling solutions and services to the offshore, fisheries, research and mooring sectors.	Technology/solution provider
SAFETEC	**Safetec.** An innovative partner that generates wealth in the field of safety management. Became a partner in the centre in March 2020.	Safety management and risk analysis

SCIENTIFIC ACTIVITIES AND RESULTS

The six research areas operated by the EXPOSED centre cover fundamental research, industrial research, applied studies, industrial activities and the establishment of research infrastructure. Nine PhD students and one post-doctorate researcher are involved in these areas. The following provides a brief description of the research areas, as well as their main results and innovation potential.

Area 1: Autonomous systems and technologies for remote operations

Area 1 is concerned with the development of tools and platforms for use during robust autonomous and remote operations with the aim of reducing the need for direct human intervention at exposed fish farm sites. In 2020 we focused on developing functionalities that enhance the autonomy of underwater vehicles used for net cage inspection, as well as contact-free operations using a vessel-mounted manipulator arm.

Net-relative navigation of an ROV in fish cages

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Walter Caharija	**Argus Remote Systems, AQS, Kongsberg Maritime, SINTEF Digital and SINTEF Ocean**	**Fundamental**

Aquaculture net cage inspection and maintenance are key fish farming operations, and inspection using autonomous underwater vehicles represents a promising technology. Our work has involved investigation of the use of laser camera triangulation for pose estimation that enables autonomous net-following by an autonomous vehicle. The 3D laser triangulation data are compared experimentally to a doppler velocity log (DVL) in an active fish farm. We have shown that our system is comparable in performance to a DVL in terms of distance and angular pose measurements. Laser triangulation shows promise as a short distance ranging sensor for autonomous vehicles, which is inexpensive compared with acoustic sensors.

Dynamic positioning (DP) is one of the most important manoeuvres that an ROV is required to perform inside a fish cage. DP enables the operator to hold the ROV steady at one point while inspecting the cage for structural deformation, holes or other damage to the net. Our research focuses on the development and full-scale testing of robust DP controllers that can be tailored to aquaculture operations because of their ability to adapt to unknown ocean currents and model uncertainties.

Main results 2020

- We have shown experimentally that laser triangulation can be used to navigate relative to a net cage. The signal quality is almost as good as that of a DVL, at less than 1/25th of the price.
- We have shown experimentally that a backstepping DP controller can hold an ROV in position in the presence of currents and model uncertainties in a full-scale net cage.
- We have written an article describing our laser triangulation results that was published early in 2021: M. Bjerkeng, T. Kirkhus, W. Caharija, J. T. Thielemann, H. B. Amundsen, S. J. Ohrem and E. I. Grøtli, "ROV Navigation in a Fish Cage with Laser-Camera Triangulation", Journal of Marine Science and Engineering, vol. 9, no. 1, p. 79, Jan. 2021.

Innovation potential

Since the signal quality of laser triangulation is similar to that of a DVL, the technology has the potential significantly to reduce the cost of the autonomous control of underwater vehicles relative to the net cage.

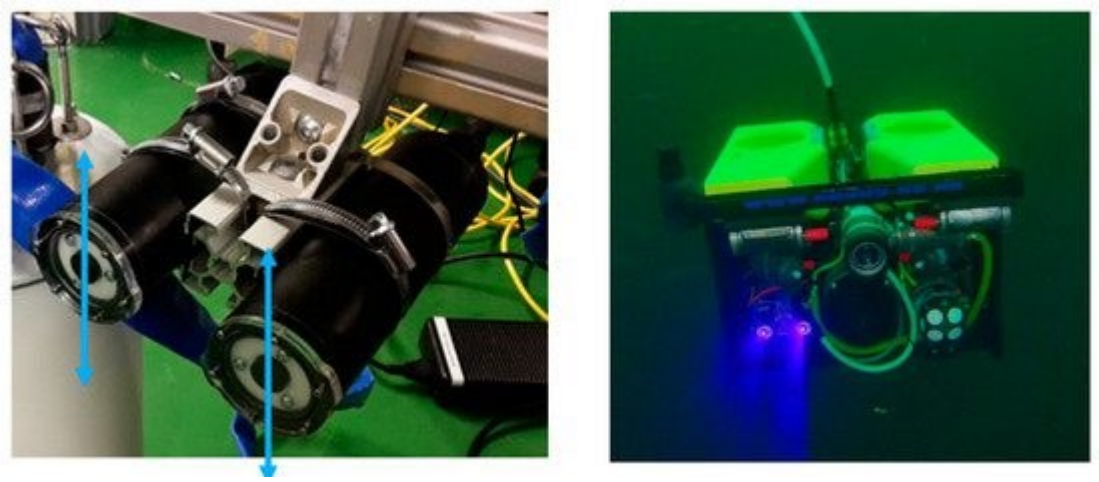


Figure 3. Left: The lasers are mounted inside watertight tubes. Photo courtesy of SINTEF Digital. Right: The lasers mounted onto the ROV. The camera used is the on-board ROV camera, seen in the center of the ROV. Photo courtesy of SINTEF Ocean

Contact-free operations using a vessel-mounted manipulator arm

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Martin Gutsch	**AQS, Cermaq, MacGregor, Mowi, Kongsberg Maritime, Kongsberg Seatex, Salmar, SINTEF Digital and SINTEF Ocean**	**Industrial**

The main objective of this project was to use simulations to demonstrate how service vessels can carry out aquaculture operations under different weather conditions without direct contact with the facility, except for intended use and contact between the vessel's manipulator arm and the facility.

An initial version of a robot arm controller was used to improve the existing simulation model. An investigation of the sensors and instrumentation required to perform selected sets of work tasks was carried out with the aim of establishing a test environment where it is possible to train machine learning algorithms to perform tasks with the manipulator arm operating in automated mode.

Main results 2020

- Relevant operations were selected, evaluated, and presented.
- A simulation of realistic wave motions was carried out using the simulation tool SIMA.
- A first version of a robot arm controller was implemented in SIMA.

Innovation potential

- The technology may enable:
- flexible operations with a reduced risk of injury to humans and fish, and damage to cage structures.
- an expansion of the weather window for aquaculture operations.
- the establishment of a test environment for the development and training of algorithms for innovative operational tasks in a safe environment.

Area 2: Monitoring and operational decision support

Area 2 focuses on data that are relevant to fish farm operations in exposed conditions. Such data are required for the validation of numerical simulations, which may provide decision support for whether or not a certain operation should be carried out at a given site. Projects linked to Area 2 develop the knowledge that is needed to create systems for data acquisition, digital twin technologies and decision support tools. This knowledge will help operators to improve fish welfare, reduce the risks to personnel, fish and equipment, and generate value by means of reduced operating costs and higher quality end products.

Data acquisition

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Jan Tore Fagertun	**Aqualine (ScaleAQ), Cermaq, Kongsberg Seatex, Mowi, Salmar and SINTEF Ocean**	**Fundamental**

The main aim of this project was to generate further knowledge in the field of data acquisition systems used in fish farming operations in exposed waters.

The aims of one of the activities were to systemize acquired data and make them available to the centre partners and other interests linked to the centre for further research. A further activity focused on improving logging times taken from the monitoring system with the aim of reducing downtime. The results of this work was presented to the partners during a video conference.

Main results 2020

- Data on waves, currents, water and air parameters from Buholmen were acquired throughout the year. The Seawatch buoy functioned satisfactorily.
- The buoy at Munkskjæra was not repaired after it was damaged in 2019, so no measurements were available.
- The buoy at Hjartøy was not in operation during 2020.
- The Motion Response Unit (MRU) and Vessel Motion Monitoring (VMM) unit on the Hosenøyan work boat were dismantled and taken onshore for maintenance. A redeployment was planned for Buholmen but has been delayed due to the Covid-19 situation.
- A new, smaller buoy was acquired in the latter half of 2020 and tested at Tristeinen in February 2021. It is planned to be moved to an exposed location during summer 2021.
- Data from Buholmen has been systematised using a spreadsheet that displays the findings.

Innovation potential

- New and emerging systems for open ocean and coastal monitoring are under development. Data acquisition, combined with numerical simulations, will provide a deeper understanding of environmental conditions and how these affect people, the fish, infrastructure and wider society. Data acquisition tools represent a key component of these new systems, and the development of buoys, as well as submerged and mobile systems, will make a major contribution.
- Onshore data requires connection by means of either hardwired or wireless networks. 5G mobile networks, combined with compact data shipment, may provide a foundation for the 'live' (real-time) presentation of sea conditions, fish behaviour and facility structure responses.
- Studios and screens for the presentation of simulated and/or monitored data must be developed and adapted to the needs of operators, design developers and the verification bodies.

Digital twin of an exposed fish farm

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Biao Su	**DNV, Salmar and SINTEF Ocean**	**Fundamental**

The main aim of this project was to further develop the existing simulation software and model of an exposed fish farm. Work focused on fish farm equipment responses such as floating collar movement, loads on bridles and mooring systems, and movements in the nets. Input data consisted of environmental conditions that were simulated based on monitoring results from an integrated wave/current buoy, combined with recorded weather conditions.

The simulation model was developed using artificial sensors employed for simulation validation with reference to real sensors installed at a specified site. In order to reflect the motions measured, the model was modified by adjusting the environmental conditions. In this way, the model may be used as a means of presenting, or 'measuring' environmental conditions.

Main results 2020

- A complete model of a fish farm cage was modelled, and software developed to improve computational (CPU) time.
- The simulation was validated based on monitored conditions and responses.
- The model was shown to be a means of presenting environmental conditions, once it has been calibrated with reference to the measured responses.
- The results were presented in a video conference meeting, where a use case was also demonstrated.

Innovation potential

- The use of digital twins may provide insights into responses to environmental conditions at fish farms for the benefit of operators, design developers and service providers.
- The technology may improve our knowledge of such responses, generating data that can be used for the planning of maintenance activities and the selection of cages, floaters, mooring systems, etc.
- The technology may expand operational windows by providing more accurate information, thus reducing uncertainties.
- The technology may enhance operational performance and decision making.
- The technology may improve the future design of fish farms.

Decision support system for operational planning

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Eivind Lona	**Anteo, MacGregor, Mowi and SINTEF Ocean**	**Industrial**

The main aim of this project is to demonstrate the use of historical and real-time data, combined with our knowledge of operational limits and risks, in a user interface that will serve as a tool designed to provide decision support and aid in the risk management of aquaculture operations performed or assisted by service vessels.

The project also aims to define operational limitations for different vessels and vessel operations, starting out with service vessels. A vessel's operational limitations, its position and intended destination, combined with (partly) automated data acquisition on environmental conditions and other relevant parameters, will be used to develop a tool designed to provide decision support and aid in the risk management of vessel operations.

Main results 2020

The project has relied on the use of environmental monitoring devices to determine operational limitations defined by parameters such as wave height, current and wind conditions. Due to both a lack of equipment, and downtime of existing equipment, on the farms selected for the project, the acquisition of relevant operational data was not started in 2020. The project has engaged in a discussion regarding which vessel types and operations would be most suited to this tool, resulting in a decision to shift focus from service vessels to well boat operations.

Innovation potential

Increased knowledge of operational limitations, combined with systematic and automated data acquisition, has the potential to contribute to the development of a decision support and risk management tool for use in vessel operations.

Predictive maintenance and structural monitoring

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Sveinung Ohrem	**Aqualine (ScaleAQ), Kongsberg Seatex, Mowi and SINTEF Ocean**	**Industrial**

The main aim of this project is to demonstrate how digital twin models of aquaculture structures can be used to predict maintenance needs, and how such models can be used during real-time operations to provide information about net deformations, cage volume, floating collar motions and mooring loads. Operations in and around fish farms are often performed with a poor understanding of the environmental conditions (such as waves and ocean currents) at the specific site, and how these affect the facility's structures. This lack of understanding, and a consequent lack of ability properly to make prior on-site assessments, narrows the operational windows of potentially crucial tasks such as well boat and de-lousing operations.

This project aims to visualize fish farm structures and their motions by integrating data acquired from an operational farm into digital models, and thereafter calculate values that are not measured directly. Data recorded during long periods of operation can be integrated off-line and may serve as a basis for the development of predictive maintenance models.

In order to accommodate real-time implementations, complex models are replaced with faster, less complex models that are still able to capture the dynamics of interest. The results can provide fish farmers, and those performing operations close to the net pens, with a real-time overview of what is taking place below the water surface.

Main results 2020

- Data from an aquaculture facility were integrated in a digital twin model to validate and fine tune the model parameters.
- Real-time data from an accelerometer were input to a fast model of a floating collar to demonstrate the model's real-time visualisation capabilities.
- The measurement requirements for the different structural models have been investigated and defined.

Innovation potential

- The digital twin of a fish cage can provide a unique insight into the structural deformations taking place below the surface, and may thus serve as a decision support tool for fish farmers and service providers.
- The models have the potential to improve maintenance routines for farmers and reduce the risks of accidents related to structural damage.

Area 3: Structures for exposed locations

Fish farming at exposed sites require robust and reliable structures which facilitate safe and efficient production. To improve precision in design of fish farming structures, research area 3 have focused on establishing updated and precise load models for net structures. In addition, the process of defining and quantifying exposure has been initiated.

Hydrodynamic loads on fish farms

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Heidi Moe Føre	**AQS, Aqualine (ScaleAQ), Cermaq, DNV, Kongsberg Seatex, Mowi, NTNU, Salmar and SINTEF Ocean**	**Fundamental**

Increased precision in structural design is important for exposed structures, with estimation of hydrodynamic loads on nets as a central topic. Nets for fish farming are the main source of hydrodynamic loads acting on a conventional fish farm, and will have a large impact on total loads on new designs utilizing netting for containment of fish. Today, both load coefficients for nets and measured netting dimensions are given with relatively high uncertainties. Empirical formulas for estimation of drag and lift loads on nets were established about 30 years ago, and there is a need to adjust these according to current and new net materials, and more precise solidity measurements. To establish drag and lift loads on nets, towing tank tests with net panels have been performed to complement tests from 2019. New knowledge for both netting materials with high solidities and scaled netting commonly applied in model tests have been established during 2020. Combined, results from towing test have been applied to form new load models for netting materials.

Main results 2020

- Empirical data: New knowledge on drag and lift coefficients for aquaculture nets acquired through towing tests of net panels. Both new knowledge for netting materials with high solidities and scaled netting commonly applied in model tests are results from the 2020 test series. Towing test results of in total eight individual netting materials (from 2019 and 2020) were combined to give load coefficients and velocity reduction factors. The latter were close to proportional to the solidity within the tested solidity range.
- Solidity: Solidity is the net parameter with most influence on drag coefficients for nets and is thus the most important parameter in load coefficient estimation. Different methods for measurement of netting dimensions and solidity have been applied and assessed. Solidity measured through image analysis includes the full contribution of the knot area on the solidity. It was found that this method gives the most consistent results for establishment of load coefficients and load models. In addition, this method yields objective results as opposed to manual measurements.
- Drag load model: Results from towing tests and the development of a new mathematical expression for local drag coefficients (for netting twines), indicate that drag coefficients are dependent on solidity and Reynolds number, but may also be affected by the velocity reduction and the local velocity at the twines. Lift loads were found to vary between the net panels. No consistent general relationship is identified for lift coefficients. Lift may be dependent on local geometry of the netting structure.

Innovation potential

- Updated numerical methods for design of fish farms, and improved model test methods and results will benefit innovations in fish farming technology.

Exposure level

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Heidi Moe Føre	**AQS, Aqualine (ScaleAQ), Cermaq, DNV, Kongsberg Seatex, Mowi, NTNU, Salmar and SINTEF Ocean**	**Fundamental**

Fish farming at exposed sites will introduce additional challenges in structural design and operation of farms. There are several research questions that need to be answered: What determines whether a site is exposed? What are important factors from a technological point of view? Can exposure level be quantified, and can limit values be established?

We seek to answer these questions from a technological point of view, bearing in mind that this will also be of relevance to fish growth and welfare.

Main results 2020

- Exposed means without shielding or protection, and farm sites may have different exposure levels from different directions. It is important to consider both extreme values for design, and operational condition for daily and occasional fish farming activities.
- Waves and water currents are identified as the most important exposure factors for fish farms, affecting loads on and movements of the structures. Combining horizontal velocity contributions from water currents and waves into a horizontal exposure velocity has been suggested as one of several possible solution.

Innovation potential

- Defined exposure levels and limits will benefit regulation of the aquaculture industry, and may be a useful tool for exposed innovations.

Area 4: Vessel design for exposed operations

Harsh environmental conditions demand new approaches to the design of vessels performing aquaculture operations close to fish cages. Vessel handling in response to increased wave heights, wind velocities, and current conditions will make direct interaction between the vessel and cage structure more difficult and hazardous for both the crew and the structural integrity of the facility. The focus of research in area 4 is directed towards expanding operational weather windows by the use of contact-free systems and an understanding of the interactions taking place between vessel thrusters and fish cages. New contact-free systems that replace the need for personnel to work in hazardous areas on the fish cage are intended to contribute to enhanced operability and safety in aquaculture operations.

Concept for contact-free operations

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Martin Gutsch	**AQS, Cermaq, MacGregor, Marin design, Mowi, Møre Maritime, Salmar and SINTEF Ocean**	**Industrial/ Fundamental**

The main objective of this project is to identify suitable contact-free operations concepts that involve the use of an enhanced crane system or manipulator arm. The initial work is to establish an overview of aquaculture operations with the aim of creating a basis for the identification of main and subordinate tasks that can be used as demo cases for contact-free operations that will result in enhanced efficiency, combined with higher levels of personnel safety and greater protection for equipment and the environment. This work resulted in the identification of three operational tasks that are proposed as demo cases for the further development of requirements and technical specifications of contact-free systems.

Main results 2020

- A project memo providing descriptions of work operations used in the aquaculture sector.
- A project memo setting out a proposal for three selected operations suitable for contact-free implementation.

Innovation potential

- The identification of an operation suitable for contact-free implementation may result in the development of new equipment and systems.

Interaction between thrusters and cages

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Martin Gutsch	**AQS, DNV, MacGregor, Marin Design, Møre Maritime, Kongsberg Maritime, Kongsberg Seatex and SINTEF Ocean**	**Fundamental**

The main objective of this project is a general investigation of vessel propulsor slipstream characteristics as a basis for the estimation of the level of possible interaction effects between aquaculture structures and vessels operating close to a fish cage. To achieve this, the results of existing CFD calculations from a ducted thruster geometry were analysed, and the pressure forces acting on the cage generated by the thrusters as a function of distance were evaluated.

Main results:

- An evaluation of the axial, tangential and radial induced velocities induced along the slipstream of a propulsion system as a function of distance.
- An evaluation of the pressure field induced along the slipstream of a propulsion system as a function of distance.
- The development of a scaling tool used to estimate the minimum pressure pulses of a propulsor as a function of diameter and rotational speed.

Innovation potential

- The minimisation of the velocity and pressure distribution along the slipstream of a propulsor will better enable vessel operations close to aquaculture facilities.

Concept study for the contact-free transfer of fish

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Eivind Lona	**Aqualine (ScaleAQ), AQS, Cermaq, MacGregor Marin Design, Møre Maritime and SINTEF Ocean**	**Industrial**

The aim of this project is to perform a concept study for contact-free operations between vessels and aquaculture cages, with a focus on addressing technical and operational challenges. Contact-free operations may involve the use of a thruster-assisted station that has to avoid physical contact with the cages. A further aim of the project is to study the feasibility of introducing a higher degree of automation to the crowding and transfer of fish.

Main results 2020

- The project was launched at the end of 2020 and will continue during 2021.

Innovation potential

- A concept for contact-free operations may expand operational weather windows and contribute to reduced operational downtime at exposed locations.
- Increased levels of automation may enhance levels of personnel safety and reduce the risk of fish escapes resulting from manual handling operations.

Area 5: Safety and risk management

It is crucial during aquaculture operations in exposed areas that the safety of personnel is assured and that the fish, material assets and the environment are protected. The safety barriers employed may be human, technical, or organisational, and must be based on thorough knowledge and assessments of the different risks. Three main projects were selected in area 5 in 2020, addressing the topics of feed barges, emergency preparedness and operational limits.

Feed barge for exposed sites

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Trine Thorvaldsen	**AQS, Aqualine (ScaleAQ) Cermaq DNV MacGregor , , Kongsberg Maritime Kongsberg Maritime (Subsea), Marin Design, Mowi, NTNU, Safetec, Salmar and SINTEF Ocean, and**	**Fundamental**

The feed barge is a key component of traditional fish farms, and serves several functions, although some more recent fish farm concepts have integrated these functions into the facility's structures. If separate feed barges are to be used at exposed sites, new design elements may be required. The main aim of this project was to provide some recommendations for future work linked to the design of feed barges operating at exposed sites. Activities included studies of existing regulations as they apply to feed barges, a review of state-of-the-art barges, interviews with fish farm employees and workshops with partners at the EXPOSED centre. Current feed barges are designed for levels of exposure experienced at existing locations, and the interviews show that employees are generally satisfied with current conditions. However, both the interviews and a workshop resulted in the identification of a number of barge-related problems, such as personnel safety on entering a barge from a vessel, capacity challenges linked to handling ensilage, the uneven emptying of silos, and tilting. Some sites operate with two barges, where one serves as a base for the crew and the other for feed storage and ensilage. It is recommended that the regulations governing feed barges be improved, and that feed barge design for exposed locations must take current challenges linked to safe operations and workplaces into account.

Main results 2020

- Interviews showed that current feed barges meet most of the requirements set out for the safe and effective operation of fish farms. Several challenges were identified related to the safe entering of a barge from a vessel, ensilage handling, the uneven emptying of silos, and tilting.

Innovation potential

- Future regulations and the design of feed barges operating at exposed sites must take into account current challenges linked to safe operations and workplaces.

Emergency preparedness

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Trine Thorvaldsen	**Aqualine (ScaleAQ), Cermaq, DNV, Kongsberg Maritime, Kongsberg Maritime (Subsea), Mowi, NTNU, Safetec, Salmar and SINTEF Ocean**	**Industrial**

The main aim of this project was to enhance our knowledge of the status, current practice, and resources linked to emergency preparedness. Such knowledge is valuable both in terms of consolidating current emergency preparedness strategies and establishing adequate practices at more exposed locations in the future. The algal bloom of 2019 demonstrated the importance of efficient emergency preparedness. The authorities have stated that increased distance from shore, increased numbers of fish, increased automatization and more demanding logistics are key factors that must be taken into account during the design of emergency preparedness strategies at exposed sites. In this project, we reviewed the relevant

literature, regulations, and documents, conducted interviews with fish farm employees, and arranged a workshop. We documented descriptions of safety hazards and critical events, risks, preventive measures, resources, and emergency plans. The workshop included discussions of how other industries developed their emergency preparedness strategies. Our findings indicate a major potential for improvement regarding the systematisation, simplification and delegation of responsibility, the involvement of personnel and training. The current scope of regulations and reporting requirements to the various regulatory authorities may be perceived as challenging. There is also potential for greater cooperation and learning between companies. Since emergency preparedness is expected to be the object of even greater focus in connection with exposed sites, it was decided to continue this project in 2021.

Main results 2020

- Emergency preparedness may be improved by focusing on systematisation, simplification and the clear delegation of responsibility, the involvement of personnel and targeted training.

Innovation potential

- This project will be continued in 2021, and an industry guide for the establishment of a holistic emergency preparedness strategy for exposed offshore aquaculture sites will be developed.

Risk factors and operational limits

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Ingunn M. Holmen	**Anteo Aqualine (ScaleAQ), Cermaq DNV, Kongsberg Maritime, Kongsberg Maritime (Subsea), MOWI, NTNU Safetec, Salmar and SINTEF Ocean**	**Fundamental**

Operational limits that are based on relevant safety indicators derived from risk factors, and which describe the optimal conditions for a given operation, can be used as tools to promote improved operational safety at exposed sites. The main aim of this project was to gather knowledge of operational limits and risk factors as viewed from a fish farmer's perspective. The work included a literature study, a web meeting and a workshop with industry partners. The literature indicates that the risk factors that may influence operational limits in the aquaculture sector are related to the weather, vessel size and age, fish farm location, type of operation and crew. Examples of operational limits currently employed in other industries were also reviewed. For instance, in marine operations terms such as 'safe conditions' and 'points of no return' are used. This work has confirmed that while operational planning and weather conditions receive much attention from the companies, absolute and objective operational limits are seldom employed. However, it is common practice to manage the different aspects of operational risk. The risk assessments of experienced personnel are highly valued as a means of ensuring safe operations. Since the importance of operational limits and cut-off criteria is expected to attract major focus in connection with exposed sites, the topic of operational limits will be addressed in upcoming projects linked to area 5.

Main results 2020

- It was established that stipulated operational limits and cut-off criteria are seldom employed.
- Fish farmers are concerned with planning and operational risk management.
- Factors such as decision support, operational limits and cut-off criteria are expected to attract major focus in connection with exposed sites and offshore aquaculture.

Innovation potential

- There is potential for improving risk management practices at exposed sites by using tools that enable the implementation of operational limits based on relevant risk factors.

Area 6: Fish behaviour and welfare

Knowledge of fish behaviour and physiology under exposed conditions is crucial for understanding of the limitations and potential linked to safeguarding fish welfare. Such understanding is crucial to site selection, production planning, facility construction design and operational procedures. Moreover, the regulatory authorities are reliant on science-based advice on fish species' coping thresholds in exposed environments. A salmon's swimming capacity in strong currents and its coping strategies under high-energy wave conditions are of particular concern. Research area 6 addresses the acquisition of fundamental knowledge on the key aspects of fish welfare under exposed conditions, and has developed novel methods and analytical tools for welfare assessment, many of which have been disseminated in numerous scientific papers and meetings, and in formal advice provided to the authorities.

Standard measurement of fish welfare

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Martin Føre	**Cermaq DNV, IMR, Kongsberg Maritime (Subsea), Mowi, NTNU, Salmar, SINTEF Digital, SINTEF Ocean and University of Melbourne**	**Fundamental**

The main aim of this project is to develop standard tools and protocols for the assessment of salmon behaviour and energetics in exposed farms. The relationships between salmon tail-beat frequency, swimming speed, metabolic rate and heart rate, as measured in detailed laboratory studies, have been scrutinized in order to generate standard curves. Both tail-beat frequency and swimming speed can be assessed visually at farm locations, which enable easy read-outs of valuable information concerning swimming parameters and coping strategies in response to water current speeds and wave energies. While visual observations provide functional 'snapshots' of a given situation, the tagging of individual fish can provide continuous data and more detailed levels of understanding. For this reason, technological and analytical development to implement tail-beat frequency and swimming speed as proxies in fish tags have been conducted, and successfully tested in fish experiments. Further testing, involving forced swimming trials using larger groups of fish, and at full-scale at exposed sites, will enable the full validation of the tools and protocols used for the assessment of salmon coping abilities under exposed conditions.

Main results 2020

- A tag that records the heart rate of a tagged fish has been used in several experimental trials with post-smolt Atlantic salmon, and has been shown to be a suitable welfare indicator (Hvas et al., 2020a). It has been useful in the description of heart rate both during, and in recovery following, a critical swimming speed test (Hvas et al., 2021a), and is a robust indicator of post-surgical recovery (Føre et al., 2021).
- A Doppler shift-based technique for the measurement of free-swimming fish using acoustic telemetry tags has been developed and evaluated (Hassan et al., 2020).
- The experimental testing of compass fish tags has been carried out in sea-caged salmon, and demonstrates potential for the recording of fish orientation in opposing water currents and the effects of waves on behaviour.
- Experimental testing of activity tags to measure tail beat frequencies has been carried out in a pilot trial. Novel data analysis is being developed and future use of tags are promising.

Innovation potential

- Innovative methods developed for the measurement of swimming speed and tail-beat frequency using fish tags are important tools for the evaluation and documentation of coping abilities in strong water currents.
- Documented standards for the observation and scoring of fish welfare in exposed environments will establish a robust foundation for the evaluation of new farm sites and technologies.

On-site monitoring of fish welfare

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Åsa Johannesen	**Cermaq, Fiskaaling, IMR, Kongsberg Maritime (Subsea), Mowi, NTNU, Salmar, SINTEF Digital, and SINTEF Ocean**	**Fundamental**

The main aim of this project is to observe and understand fish behaviour and welfare in exposed environmental conditions, and to develop novel analytical tools for the automatic classification and detection of fish swimming behaviour.

Production cycles at exposed sites in the Faroe Islands have been monitored using cameras and echo sounders to monitor fish interactions with waves and currents. Fish have been sampled periodically in order to assess selected welfare indicators. Our results indicate the presence of a complex of interacting influences on fish behaviour and their vertical distribution as a function of wave parameters, currents, and time of day. During the day, hydrodynamic conditions exerted a stronger influence on vertical distribution than during the night. In weak currents, fish generally moved further down in the water in response to taller waves, while stronger currents generally caused them to move upwards regardless of wave conditions.

The use of echo sounder observations of farmed fish is a highly effective method for the continuous monitoring of fish distribution and density, as well for the recording of individual fish parameters such as size, swimming speed and direction. The method offers huge potential for the detection of behavioural anomalies, although full utilisation depends on the development of analytical tools and methods. A transformer-based approach (EchoBERT) was developed for the automatic detection of behaviour in caged salmon. This approach interprets the spatiotemporal dynamics of echograms through attention mechanisms as a means of classifying fish behaviour. The results from the analysis of group behaviour among salmon in sea cages, and the successful detection of disease, show that EchoBERT has major potential.

Main results 2020

The following papers have been published:

- Description of salmon behaviour in relation to waves and current at an exposed site (Johannesen et al., 2020).
- Automatic behaviour detection in caged salmon from echograms (Måløy, 2020).

Innovation potential

- Knowledge of salmon species' spatial requirements in high-energy wave environments must be taken into account during the construction and planning of new farm sites.
- Future applications of the EchoBERT tool in sea cages at exposed sites include the automatic detection and reporting of behaviours in response to water current speeds and waves.

Swimming capacity and basal physiology in Atlantic salmon

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Malthe Hvas	**Cermaq IMR Kongsberg Maritime (Subsea), Mowi, and Salmar**	**Fundamental**

The aim is to investigate basal physiological responses that are of relevance in exposed fish farming, where the focus is on different types of swimming capacities and how they are modulated by environmental and biological factors. A recent review paper summarized current knowledge and proposes welfare guidelines regarding biological limits at exposed sites. One of several concerns at exposed sites are periods without feeding, and the impacts on fish of such periods have been assessed in detail. In brief, salmon that fasted for up to four weeks exhibited mild metabolic constraints and normal critical swimming speeds. The impacts on acute stress responsiveness and subsequent recovery rate were minor. A highly relevant question that has recently has been addressed concerns the length of time for which a salmon can sustain a high swimming velocity. Salmon exhibited impressive endurance by maintaining sustained speeds at 85% of their critical swimming velocity for more than 72 hours.

Main results 2020

- The project has produced a description of metabolic rate response to feed withdrawal (Hvas et al, 2020b) and of the effects of fasting on swimming capacity, blood parameters and stress recovery in Atlantic salmon (Hvas et al., 2021c). Feed withdrawal is interpreted as a minor concern.
- A review of fish welfare in offshore salmon aquaculture (Hvas et al., 2021b) has been written.
- A description of sustained swimming capacity in Atlantic salmon has been written (Hvas et al., 2021d). This paper is relevant to the estimation of coping ability among fish in strong current conditions over periods of several days.

Innovation potential

- The knowledge acquired during this project is highly relevant to fish welfare risk assessments in the context of site selection, production planning, construction designs and operational procedures.
- Salmon is a dynamic species with high degree of coping ability also in exposed conditions.

INTERNATIONAL COOPERATION

Exposed fish farming generates significant interest around the world.

The potential of exposed fish farming and the research carried out by the EXPOSED centre has generated interest in many countries, including Scotland, the Faroe Islands, Chile, Australia, China, South Korea and Japan.

A collaboration with the research organisation *Fiskaaling* in the Faroe Islands has to date resulted in a mutual post-doctorate project that was launched in 2018.

The University of Melbourne in Australia has also been involved in the activity *Standard measurement of fish welfare* in the *Area 6: Fish behaviour and welfare*.

Other current projects that involve international partners and funding include 'Echofeeding', which studies echo sounder technology for the appetite-led-feeding and welfare-monitoring of caged salmon, 'FlexAqua', which addresses aquaculture operations with reliable flexible shielding technologies for infestation prevention in offshore seas and coastal areas, and 'SalmonInsight', which reveals links between salmon physiology and online monitored behaviour.

A collaboration with Memorial University in St. John's, Newfoundland in Canada has been established to address competency in the field of occupational health and safety (OHS).

Researchers from the EXPOSED centre have been invited to take part in a new International Council for the Exploration of the Sea (ICES) working group on Open Ocean Aquaculture (WGOOA).

The host institution, SINTEF Ocean, and its partner DNV, have been incorporated as partners in the recently launched Blue Economy Cooperative Research Centre in Australia (2019).

The global pandemic has hindered several planned conferences and events where the EXPOSED centre would have presented results or chaired sessions on relevant topics.

RECRUITMENT

The EXPOSED centre provides funding for eight PhD projects, and several PhD students and post-doctoral researchers are involved in associated projects.

These students and researchers were invited to shared activities, including two aquaculture workshops in collaboration with NTNU AMOS. In order to advance collaboration, knowledge sharing and industrial insights, the EXPOSED centre has entered into partnerships with other maritime research centres in joint initiatives to boost awareness of, and expertise in, innovation among PhD students and researchers.

PhD candidate profile: Sverre Herland
Reinforcement learning for contact-free operations

Sverre completed his MSc in Computer Science at NTNU in the spring of 2020, and started his PhD at the Department of Computer Science in the autumn of the same year.

His PhD project is related to the centre's research area 1, addressing autonomous systems and technologies for remote operations.

His primary research objective is to investigate opportunities and limitations linked to Reinforcement Learning (RL), and its application in the field of robotic manipulation at exposed fish farm locations. More specifically, his aim is to develop RL-based controllers for manipulator arms that enable the contact-free servicing of fish farm constructions in exposed settings. He is currently collaborating with SINTEF Digital and SINTEF Ocean to develop a simulator that is suitable for future experimentation.

Sverre's work is being supervised by Associate Professor Kerstin Bach, and co-supervised by Professor Helge Langseth, at the Department of Computer Science at NTNU.

COMMUNICATION AND DISSEMINATION ACTIVITIES

As a Centre for Research-based Innovation, EXPOSED has a responsibility to disseminate its research results to the public, and to meet the need for effective communication of project activities among the centre's partners.

In order to support cross-disciplinary innovation and effective internal communication, the centre arranged a two-day event called 'EXPOSED Days' in the spring, and a one-day EXPOSED Day event in the autumn. It is planned to arrange such events annually, and to supplement these with PhD and post-doctorate workshops and targeted, project-specific meetings. The EXPOSED Days events serve as a meeting place to promote innovation, present research results, exchange ideas and generate new projects.

In 2020, the centre has had to adapt its activities to the ongoing Covid-19 pandemic, and meetings and workshops have been arranged online. The centre has made use of the professional affiliations that it has established during its lifetime to date, and new projects have been generated in spite of the challenges it has faced during the year.

The main channels used by the centre to communicate with the public are as follows:

- A Norwegian Facebook page (https://www.facebook.com/eksponert) is used as a medium for sharing relevant news.
- The centre attends and makes presentations at Norwegian and international conferences and other fora. It has been invited to make presentations at a number of events in Norway.
- The centre submits and publishes articles in relevant scientific, trade and popular science media (see below).
- A website (http://exposedaquaculture.no/) has been established to present information about the centre to both internal and external audiences.

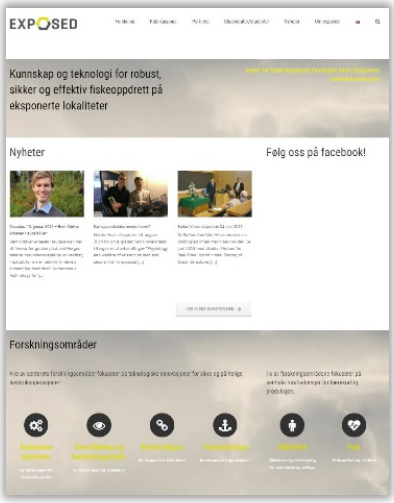


Figure 4. The homepage on the EXPOSED website.

In 2018, the centre established the EXPOSED Catalogue, which is an internal, living document that aims to boost the accessibility of the knowledge generated by the centre and promote future wealth creation. The catalogue provides an overview of completed projects, as well as links to relevant articles, memos, associated projects and personnel. It links to relevant documents that are stored in the centre's internal document sharing web hotel.

Figure 5. The EXPOSED Catalogue.

PUBLICATIONS

EXPOSED makes every effort to register all its dissemination activities in the Current Research Information System in Norway (CRIStin). We refer to the website https://www.cristin.no/app/projects/show.jsf?id=536331. Scientific papers are listed below.

Journal papers

2015

Utne, I.B., Scjølberg, I. and Holmen, I.M., 2015. Reducing risk to aquaculture workers by autonomous systems and operations. *Safety and Reliability of Complex Engineered Systems. CRC Press, Switzerland*.

2016

Bui, S., Dempster, T., Remen, M. and Oppedal, F., 2016. Effect of ectoparasite infestation density and life-history stages on the swimming performance of Atlantic salmon Salmo salar. *Aquaculture Environment Interactions*, *8*, pp.387-395.

Remen, M., Solstorm, F., Bui, S., Klebert, P., Vågseth, T., Solstorm, D., Hvas, M. and Oppedal, F., 2016. Critical swimming speed in groups of Atlantic salmon Salmo salar. *Aquaculture Environment Interactions*, *8*, pp.659-664.

Rundtop, P. and Frank, K., 2016. Experimental evaluation of hydroacoustic instruments for ROV navigation along aquaculture net pens. *Aquacultural Engineering*, *74*, pp.143-156.

Wienhofen, L.W. and Mathisen, B.M., 2016, October. Defining the initial case-base for a CBR operator support system in digital finishing. In *International Conference on Case-Based Reasoning* (pp. 430-444). Springer, Cham.

2017

Hvas, M., Folkedal, O., Imsland, A. and Oppedal, F., 2017. The effect of thermal acclimation on aerobic scope and critical swimming speed in Atlantic salmon, Salmo salar. *Journal of Experimental Biology*, *220*(15), pp.2757-2764.

Hvas, M. and Oppedal, F., 2017. Sustained swimming capacity of Atlantic salmon. *Aquaculture Environment Interactions*, *9*, pp.361-369.

Hvas, M., Karlsbakk, E., Mæhle, S., Wright, D.W. and Oppedal, F., 2017. The gill parasite Paramoeba perurans compromises aerobic scope, swimming capacity and ion balance in Atlantic salmon. *Conservation physiology*, *5*(1), p.cox066.

Hvas, M., Folkedal, O., Solstorm, D., Vågseth, T., Fosse, J.O., Gansel, L.C. and Oppedal, F., 2017. Assessing swimming capacity and schooling behaviour in farmed Atlantic salmon Salmo salar with experimental push-cages. *Aquaculture*, *473*, pp.423-429.

Holmen IM, Utne IB, Haugen S (2017). Organisational safety indicators in aquaculture – a preliminary study. *Risk, Reliability and Safety: Innovating Theory and Practice -Walls, Revie & Bedford (Eds). Taylor & Francis Group, London. ISBN 978-1-138-02997-2.*

Mathisen, B.M., Aamodt, A. and Langseth, H., 2017. Data driven case base construction for prediction of success of marine operations. CEUR Workshop Proceedings.

Vilsen, S.A., Sauder, T. and Sørensen, A.J., 2017. Real-time hybrid model testing of moored floating structures using nonlinear finite element simulations. In *Dynamics of Coupled Structures, Volume 4* (pp. 79-92). Springer, Cham.

2018

Eidsvik, O.A.N., Haugaløkken, B.O.A. and Schjølberg, I., 2018, June. SeaArm-A Subsea Multi-Degree of Freedom Manipulator for Small Observation Class Remotely Operated Vehicles. In *2018 European Control Conference (ECC)* (pp. 983-990). IEEE.

Eidsvik, O.A.N., Haugaløkken, B.O.A. and Schjølberg, I., 2018 SeaArm - A Subsea Multi-Degree of Freedom Manipulator for Small Observation Class Remotely Operated Vehicles. In *European Control Conference 2018 Limassol, Cyprus.*

Faltinsen, O.M. and Shen, Y., 2018. Wave and current effects on floating fish farms. *Journal of Marine Science and Application*, *17*(3), pp.284-296.

Haugaløkken, B.O.A., Jørgensen, E.K. and Schjølberg, I., 2018. Experimental validation of end-effector stabilization for underwater vehicle-manipulator systems in subsea operations. *Robotics and Autonomous Systems*, *109*, pp.1-12.

Holmen, I.M., Utne, I.B. and Haugen, S., 2018. Risk assessments in the Norwegian aquaculture industry: Status and improved practice. *Aquacultural Engineering*, *83*, pp.65-75.

Hvas, M., Folkedal, O., Imsland, A. and Oppedal, F., 2018. Metabolic rates, swimming capabilities, thermal niche and stress response of the lumpfish, Cyclopterus lumpus. *Biology open*, *7*(9), p.bio036079.

Hvas, M., Nilsen, T.O. and Oppedal, F., 2018. Oxygen uptake and osmotic balance of Atlantic salmon in relation to exercise and salinity acclimation. *Frontiers in Marine Science*, *5*, p.368.

Shen, Y., Greco, M., Faltinsen, O.M. and Nygaard, I., 2018. Numerical and experimental investigations on mooring loads of a marine fish farm in waves and current. *Journal of Fluids and Structures*, *79*, pp.115-136.

2019

Bore, P.T., Amdahl, J. and Kristiansen, D., 2019. Statistical modelling of extreme ocean current velocity profiles. *Ocean Engineering*, *186*, p.106055.

Bore, P.T., Amdahl, J. and Kristiansen, D. Joint modelling of vertical current velocity profiles for design of coastal and ocean structures (to be submitted), *Coastal Engineering, 2019*.

Hassan, W., Føre, M., Ulvund, J.B. and Alfredsen, J.A., 2019. Internet of Fish: Integration of acoustic telemetry with LPWAN for efficient real-time monitoring of fish in marine farms. *Computers and Electronics in Agriculture*, *163*, p.104850.

Hvas, M. and Oppedal, F., 2019. Physiological responses of farmed Atlantic salmon and two cohabitant species of cleaner fish to progressive hypoxia. *Aquaculture*, *512*, p.734353.

Hvas, M. and Oppedal, F., 2019. Influence of experimental set-up and methodology for measurements of metabolic rates and critical swimming speed in Atlantic salmon Salmo salar. *Journal of fish biology*, *95*(3), pp.893-902.

Holen, S.M., Yang, X., Utne, I.B. and Haugen, S., 2019. Major accidents in Norwegian fish farming. *Safety Science*, 120, pp.32-43.

Jónsdóttir, K.E., Hvas, M., Alfredsen, J.A., Føre, M., Alver, M.O., Bjelland, H.V. and Oppedal, F., 2019. Fish welfare-based classification method of ocean current speeds at aquaculture sites. *Aquaculture Environment Interactions*, 11, pp.249-261.

Mathisen, B.M., Aamodt, A., Langseth, H. and Bach, K. 2019 Learning similarity measures from data. Progress in *Artificial Intelligence*

Oldham, T., Nowak, B., Hvas, M. and Oppedal, F., 2019. Metabolic and functional impacts of hypoxia vary with size in Atlantic salmon. Comparative Biochemistry and Physiology Part A: *Molecular & Integrative Physiology*, 231, pp.30-38.

Shen, Y., Greco, M. and Faltinsen, O.M., 2019. Numerical study of a well boat operating at a fish farm in long-crested irregular waves and current. *Journal of Fluids and Structures*, *84*, pp.97-121.

Shen, Y., Greco, M. and Faltinsen, O.M., 2019. Numerical study of a well boat operating at a fish farm in current. *Journal of Fluids and Structures*, *84*, pp.77-96.

Slette, H.T., Asbjørnslett, B.E. and Fagerholt, K., 2019, October. Cost-Emission Relations for Maritime Logistics Support in Aquaculture. In *Journal of Physics: Conference Series* (Vol. 1357, No. 1, p. 012029). IOP Publishing.

Vilsen, S.A., Sauder, T., Sørensen, A.J. and Føre, M., 2019. Method for real-time hybrid model testing of ocean structures: Case study on horizontal mooring systems. *Ocean Engineering*, *172*, pp.46-58.

Yuen, J.W., Dempster, T., Oppedal, F. and Hvas, M., 2019. Physiological performance of ballan wrasse (Labrus bergylta) at different temperatures and its implication for cleaner fish usage in salmon aquaculture. *Biological Control*, *135*, pp.117-123.

Yu Z, Amdahl J, Kristiansen D, Bore PT, (2019) *Numerical analysis of local and global responses of an offshore fish farm subjected to ship impacts.* Ocean Engineering; Volume 194

Yu, Z., Amdahl, J., Kristiansen, D. and Bore, P.T., 2019. Numerical analysis of local and global responses of an offshore fish farm subjected to ship impacts. *Ocean Engineering*, *194*, p.106653.

2020

Hassan, W., Føre, M., Pedersen, M. O., Alfredsen, J. A. 2020. A new method for measuring free-ranging fish swimming speed in commercial marine farms using Doppler principle. IEEE Sensors Journal;Volum 20.(17) s. 10220-10227 OCEAN NTNU

Hvas, M., Folkedal, O., Oppedal, F. 2020. Fish welfare in offshore salmon aquaculture. Reviews in Aquaculture.

Hvas, M., Folkedal, O., Oppedal, F. 2020. Heart rate bio-loggers as welfare indicators in Atlantic salmon (Salmo salar) aquaculture. Aquaculture ;Volum 529.

Hvas, M., Folkedal, O., Oppedal, F. 2020. Heart rates of Atlantic salmon Salmo salar during a critical swim speed test and subsequent recovery. Journal of Fish Biology.

Hvas, M., Stien, L. H., Oppedal, F. 2020. The metabolic rate response to feed withdrawal in Atlantic salmon post-smolts. Aquaculture ;Volum 529.

Riseth, E. N., Fraser, T. W. K., Sambraus, F., Stien, L. H. & Hvas, M. 2020. Is it advantageous for Atlantic salmon to be triploid at lower temperatures? *Journal of Thermal Biology*, 89, 102548

Yang, X., Utne, I.B. and Holmen, I.M., 2020. Methodology for hazard identification in aquaculture operations (MHIAO). *Safety Science*, *121*, pp.430-450.

Conference papers

2016

Bjelland, H.V., Føre, M., Lader, P., Kristiansen, D., Holmen, I.M., Fredheim, A., Grøtli, E.I., Fathi, D.E., Oppedal, F., Utne, I.B. and Schjølberg, I., 2015. Exposed aquaculture in Norway: Technologies for robust operation in rough conditions. In *Proc. of MTS/IEEE OCEANS'15*. Washington, USA, 19-22 October 2015.

2017

Arnesen, B.O., Lekkas, A.M. and Schjølberg, I., 2017. 3D path following and tracking for an inspection class ROV. In ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering. American Society of Mechanical Engineers Digital Collection.

Bore, P.T. and Amdahl, J., 2017. Determination of Environmental Conditions Relevant for the Ultimate Limit State at an Exposed Aquaculture Location. In ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering. American Society of Mechanical Engineers Digital Collection.

Bore, P.T., Amdahl, J. and Kristiansen, D., 2017. Modelling of hydrodynamic loads on Aquaculture net cages by a modified Morison model. MARINE 2017 Computational Methods in Marine Engineering VII. At Nantes, France

Grøtli, E.I., Bjerkeng, M., Rundtop, P., Vagia, M., Haugli, F.B. and Transeth, A.A., 2017, June. Canvas as a design tool for autonomous operations: With application to net inspection of a sea-based fish farm using an underwater vehicle. In OCEANS 2017-Aberdeen (pp. 1-5). IEEE.

Holen, S.M., Utne, I.B., Yang, X. (2018) Risk dimensions of fish farming operations and conflicting objectives, Safe Societies in a Changing World: Proceedings of ESREL 2018, June 17-21, 2018, Trondheim, Norway, CRC Press LLC.

Holmen, I.M., Utne, I.B. and Haugen, S., 2017. Organisational safety indicators in aquaculture–a preliminary study. *Risk, Reliability and Safety: Innovating Theory and Practice: Proceedings of ESREL 2016 (Glasgow, Scotland, 25-29 September 2016)*.

Holmen, I.M., Utne, I.B., Haugen, S. and Ratvik, I., 2017. The status of risk assessments in Norwegian fish farming. *Safety & Reliability, Theory and Applications*.

Kristiansen, D., Aksnes, V., Su, B., Lader, P. and Bjelland, H.V., 2017, June. Environmental description in the design of fish farms at exposed locations. In *ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering*. American Society of Mechanical Engineers Digital Collection. OMAE2017-61531, June 25-50, 2017, Trondheim, Norway.

Lader, P., Kristiansen, D., Alver, M., Bjelland, H.V. and Myrhaug, D., 2017. Classification of aquaculture locations in Norway with respect to wind wave exposure. In *ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering*. American Society of Mechanical Engineers Digital Collection.

Mathisen, B.M., Aamodt, A. and Langseth, H., 2017. Data driven case base construction for prediction of success of marine operations. CEUR Workshop Proceedings. ICCBR-17 Workshop on Workshop on Case-based Reasoning and Deep Learning - CBRDL 2017; 2017-06-26 - 2017-06-26, NTNU

Sandøy, S.S. and Schjølberg, I., 2017. Underwater positioning using near surface long baseline transponder's induced by wave motion. In *ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering*. American Society of Mechanical Engineers Digital Collection.

Utne, I.B., Schjølberg, I., Sandøy, S., Yang, X. and Holmen, I.M., 2018. Reducing risk in aquaculture through autonomous underwater operations. *PSAM 2018, LA, USA*.

Vilsen, S.A., 2017, September. Numerical models in real-time hybrid model testing of slender marine systems. In *OCEANS 2017-Anchorage* (pp. 1-6). IEEE.

Yang, X., Utne, I.B. and Holmen, I.M. 2018 Review of hazard identification techniques for autonomous operations in Norwegian aquaculture. In *Probabilistic Safety Assessment and Management PSAM 14*, Los Angeles, USA.

Yang, X., Utne, I.B., Holen, S.M. and Holmen, I.M. 2018 Implications from major accident causation theories to activity-related risk analysis - An application in Norwegian Atlantic salmon farming industry, Safe Societies in a Changing World: *Proceedings of ESREL 2018*, June 17-21, 2018, Trondheim, Norway, CRC Press LLC.

2018

Fredheim, A. and Reve, T., 2018, October. Future Prospects of Marine Aquaculture. In *OCEANS 2018 MTS/IEEE Charleston* (pp. 1-8). IEEE. ISBN 978-1-5386-4814-8.

Haugaløkken, B.O.A., Sandøy, S.S., Schjølberg, I., Alfredsen, J.A. and Utne, I.B., 2018, June. Probabilistic Localization and Mapping of Flexible Underwater Structures using Octomap. In *2018 European Control Conference (ECC)* (pp. 268-275). IEEE. ISBN 978-3-9524-2698-2.

Jin, J., Selvik, Ø., Yin, D., Yang, X., Aksnes, V. and Fathi, D., 2018, July. Review on Typical Marine Operations in Aquaculture and Numerical Simulation of One Example Operation Scenario. In *The 28th International Ocean and Polar Engineering Conference*. International Society of Offshore and Polar Engineers.10-15 June, Sapporo, Japan; 2018-06-10 - 2018-06-15. SINTEF OCEAN, NTNU

Sandøy, S.S., Matsuda, T., Maki, T. and Schjølberg, I., 2018, May. Rao-Blackwellized Particle Filter with Grid-Mapping for AUV SLAM Using Forward-Looking Sonar. In 2018 OCEANS-MTS/IEEE Kobe Techno-Oceans (OTO) (pp. 1-9). IEEE.

2019

Bach, K., Mathisen, B.M. and Jaiswal, A., Demonstrating the myCBR Rest API. *CEUR Workshop Proceedings* 2019

Hassan, W., Føre, M., Ulvund, J.B. and Alfredsen, J.A., 2019. Internet of Fish: Integration of acoustic telemetry with LPWAN for efficient real-time monitoring of fish in marine farms. *Computers and Electronics in Agriculture*, *163*, p.104850.

Hassan, W., Føre, M., Urke, H.A., Kristensen, T., Ulvund, J.B. and Alfredsen, J.A., 2019. System for Real-time Positioning and Monitoring of Fish in Commercial Marine Farms Based on Acoustic Telemetry and Internet of Fish (IoF). In *The 29th International Ocean and Polar Engineering Conference*. ISOPE.

Hassan, W., Føre, M., Pedersen, M.O. and Alfredsen, J.A., 2019. A novel Doppler based speed measurement technique for individual free-ranging fish. *2019 IEEE SENSORS Proceedings*.

Hassan, W., Føre, M., Pedersen, M.O. and Alfredsen, J.A., 2019. A novel Doppler based speed measurement technique for individual free-ranging fish, *2019 IEEE SENSORS*, Montreal, QC, Canada, 2019, pp. 1-4.

Mathisen, B.M., Aamodt, A., Bach, K. and Langseth, H., 2019. Learning similarity measures from data. *Progress in Artificial Intelligence*, pp.1-15.

Vilsen, S.A., Sauder, T., Føre, M. and Sørensen, A.J., 2018, June. Controller analysis in real-time hybrid model testing of an offshore floating system. In *ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering*. American Society of Mechanical Engineers Digital Collection.

2020

Føre, H. M., Endresen, P. C., Norvik, C., Lader, P. F., Hydrodynamic Loads on Net Panels With Different Solidities. International Conference on Offshore Mechanics and Arctic Engineering (OMAE) [proceedings] 2020 s. - OCEAN NTNU

Mathisen, B.M., Bach, K., Meidell, E., Måløy, H. and Sjøblom, E.S. Fishnet: A unified embedding for salmon recognition. *In To appear in proceedings of the Twenty-second European Conference on Artificial Intelligence. IOS Press, 2020.*

Mathisen, B.M., Bach, K., and Aamodt, A. Using extended siamese networks in a cbr system to provide decision support in aquaculture operations. *ICCBR 2020, 3001 Accepted in Applied Intelligence.*

Doctoral theses

2018

Shen Y. 2018 Operational limits for floating-collar fish farms in waves and current, without and with well-boat presence. Doctoral thesis at NTNU; 2018:367

2019

Hvas M. 2019 Physiology and welfare of Atlantic salmon and cleaner fish in exposed aquaculture. Doctoral thesis at University of Bergen. ISBN 9788230845271

Vilsen S.A. 2019 Method for Real-Time Hybrid Model Testing of Ocean Structures Case Study on Slender Marine Systems. Doctoral thesis at NTNU, 2018:166. ISBN 978-82-326-3930-4 2019

2020

Haugaløkken, BOA. 2020 Autonomous Technology for IMR Operations in the Norwegian Aquaculture. Doctoral thesis at NTNU, 2020:9

PERSONNEL

Key researchers	Institution	Main research area
Hans V. Bjelland	SINTEF Ocean	Decision support systems and aquaculture operations
Ingunn Marie Holmen	SINTEF Ocean	Safety and risk management
Trine Thorvaldsen	SINTEF Ocean	Safety and risk management
Leif Magne Sunde	SINTEF Ocean	Aquaculture operations
Heidi Moe Føre	SINTEF Ocean	Materials science
Per Christian Endresen	SINTEF Ocean	Aquaculture structures
Jan Tore Fagertun	SINTEF Ocean	Aquaculture structures, field measurements and e-infrastructure
Andrei Tsarao	SINTEF Ocean	Aquaculture structures
Ørjan Selvik	SINTEF Ocean	Vessel design
Martin Gutsch	SINTEF Ocean	Marine operations
Frode Oppedal	Institute of Marine Research	Fish behaviour and welfare
Ole Folkedal	Institute of Marine Research	Fish behaviour and welfare
Esten Ingar Grøtli	SINTEF Digital	Autonomous systems
Trine Kirkhus	SINTEF Digital	Optical measurement systems and data analysis
Pål Lader	NTNU, Department of Marine Technology	Aquaculture structures
Jørgen Amdal	NTNU, Department of Marine Technology	Marine structures
Trygve Kristiansen	NTNU, Department of Marine Technology	Marine structures
Bjørn Egil Asbjørnslett	NTNU, Department of Marine Technology	Marine operations and systems
Ingrid B. Utne	NTNU, Department of Marine Technology	System safety engineering, risk assessment, and maintenance management of marine systems
Stein Haugen	NTNU, Department of Marine Technology	Risk monitoring and analysis
Agnar Aamodt	NTNU, Department of Computer and Information Science	Intelligent systems and decision support
Kerstin Bach	NTNU, Department of Computer and Information Science	Intelligent systems and decision support
Helge Langseth	NTNU, Department of Computer and Information Science	Intelligent systems and decision support
Martin Føre	NTNU, Department of Engineering Cybernetics	Telemetry and biological modelling
Jo Arve Alfredsen	NTNU, Department of Engineering Cybernetics	Telemetry and biological modelling

PhD students with financial support from the Centre budget

Name	Nationality	Period	Gender (M/F)	Topic
Bjørn Magnus Mathisen	Norwegian	Q3 2015 – Q4 2020	M	Monitoring and operational decision support
Pål Takle Bore	Norwegian	Q1 2015 – Q3 2018	M	Intelligent aquaculture structures
Ingunn Marie Holmen	Norwegian	Q1 2016 – Q2 2021	F	Safety and risk management
Bent Arnesen	Norwegian	Q3 2016 – Q3 2020	M	Remotely-controlled and automated underwater vehicles
Malthe Hvas	Danish	Q2 2016 – Q2 2019	M	Physiology and behaviour of salmon in strong water currents
Waseem Hassan	Pakistani	Q4 2016 – Q4 2020	M	Acoustic fish telemetry for real-time fish performance monitoring in aquaculture
Håkon Måløy	Norwegian	Q2 2018 – Q2 2022	M	Recognizing ecological behaviour patterns using deep learning
Hans Tobias Slette	Norwegian	Q3 2018 – Q3 2021	M	Methods and models for marine system design of vessels and vessel operations in exposed aquaculture
Muhammad Mukhlas	Indonesian	Q4 2018 – Q4 2022	M	Closed cage aquaculture structures in waves and currents
Martin Slagstad	Norwegian	Q4 2019 – Q4 2022	M	Advanced and rational analysis of steel fish farms in exposed waters
Sverre Herland	Norwegian	Q3 2020 – Q3 2024	M	Reinforcement learning for contact-free operations

PhD students working on projects with financial support from sources outside the Centre

Name	Nationality	Period	Gender (M/F)	Funding	Topic
Kristbjörg Edda Jónsdóttir	Norwegian	Q3 2016 - Q3 2019	F	Strategic research project at SINTEF Ocean	Dynamics of water flow and turbulence in large-scale aquaculture sea cages
Stian Sandøy	Norwegian	Q3 2016 - Q3 2019	M	Reducing risk in aquaculture – improving operational efficiency, safety and sustainability (HAVBRUK2, RCN)	Sensor fusion for autonomous underwater inspection of aquaculture structures
Yugao Shen	Chinese	Q3 2013 - Q3 2016	M	NTNU AMOS – Centre for Autonomous Marine Operations and Systems	Limiting operational conditions for a well boat
Stefan A. Vilsen	Danish	Q1 2014 - Q1 2018	M	NTNU AMOS – Centre for Autonomous Marine Operations and Systems	Hybrid model testing of marine systems

Eirik Svendsen	Norwegian	Q3 2018 - Q3 2022	M	SalmonInsight (HAVBRUK2, RCN)	Links between salmon physiology and online monitored behaviour

Postdoc. researchers with financial support from the Centre budget

Name	Nationality	Period	Gender (M/F)	Topic
Ása Johannesen	Faroese	Q3 2018 – Q3 2020	F	Fish behaviour and welfare in waves
Malthe Hvas	Danish	Q3 2019 – Q4 2022	M	Physiology and behaviour of salmon in strong water currents

Postdoc. researchers working on projects with financial support from sources outside the Centre

Name	Nationality	Period	Gender (M/F)	Funding	Topic
Xue Yang	Chinese	Q2 2017 - Q1 2019	F	Reducing risk in aquaculture – improving operational efficiency, safety and sustainability (HAVBRUK2, RCN)	Operational risk assessment

Master's students

Name	Gender (M/F)	Period	Affiliation	Topic
Lene Erdal	F	Q1–2 2016	Industrial Economics and Technology Management, NTNU	Shared value creation in an industry context – assessing how governmental policies can contribute to increased corporate sustainability in the Norwegian aquaculture industry
Marianne Wethe Koch	F			
Fredrik Lindahl Roppestad	M	Q1–2 2016	Department of Computer Science, NTNU	Decision support for predictive maintenance of exposed aquaculture structures
Niklas Bae Pedersen	M			
Helene Nordtvedt	F	Q2 2016	Department of Production and Quality Engineering, NTNU	Development of a risk model for fish farming operations
Alexander Wallem Berge	M	Q1–2 2017	Department of Marine Technology, NTNU	Fleet scheduling of service vessels used in a more exposed Norwegian aquaculture industry
Henrik Theodor Ramm	M			
Marius Gyberg Haugland	M	Q1–2 2017	Department of Marine Technology, NTNU	Use of clusters in a route generation heuristic for distribution of fish feed
Sondre Thygesen	M			
Simen Aleksander Haaland	M	Q1–2 2017	Department of Marine Technology, NTNU	Semi-closed containment systems in Atlantic salmon production – comparative analysis of production strategies
Jens Kristian Hole	M	Q1–2 2017	Department of Marine Technology, NTNU	*Risiko-basert design av fartøy og merde for eksponert havbruk* (Risk-based design of vessels and cages for use in exposed aquaculture settings)

Name	Gender (M/F)	Period	Affiliation	Topic
Hanne Hornsletten	F	Q2–3 2017	Department of Marine Technology, NTNU	Optimization model aimed for the aquaculture industry for fleet composition and routing of well boats
Henrik Håkonsen	M	Q1–2 2017	Department of Marine Technology	Emergency preparedness and response in aquaculture
Marte Tuverud Kamphuse	F	Q1–2 2017	Department of Marine Technology, NTNU	Modeling of seaborne transport of fresh salmon. Inventory routing with continuous time formulation for a perishable product
Runar Stemland	M	Q1–2 2017	Department of Marine Technology, NTNU	assessment of service vessel operability in exposed aquaculture. An exploratory approach combining vessel response and discrete event simulation
Arne Jacob Eide	M	Q1–2 2017	Department of Marine Technology, NTNU	Analysis of ocean farming's steel cage concept subjected to environmental loads
Lars Sunde Gjengseth	M	Q1–2 2017	Department of Marine Technology, NTNU	Rational analysis of Nordlaks' 'Havfarm' aquastructure concept for exposed waters
Nikolai Hanevik	M	Q1–2 2017	Department of Marine Technology, NTNU	Analysis of ocean farming's steel cage concept in very exposed waters
Vegard Holen	M	Q1–2 2017	Department of Marine Technology, NTNU	Ultimate limit state analysis of 'Havfarm'
Ole-Johan Nekstad	M	Q2–3 2017	Department of Marine Technology, NTNU	Modularization of aquaculture service vessels – an approach to the implementation of operational flexibility
Erik Andreas Næstvold	M	Q1–2 2017	Department of Marine Technology, NTNU	*Simuleringsmodell som beslutningsstøtte for valg av tiltak mot lakselus på lokalitetsnivå* (Simulation model as decision support for selection of site-specific measures against salmon lice)
Adrian Stenvik	M	Q1–2 2017	Department of Marine Technology, NTNU	Fleet size and mix in the Norwegian aquaculture sector. A stochastic fleet renewal problem with an uncertain future
Vetle Skavraker Evju	M	Q1–2 2017	Department of Marine Technology, NTNU	Competitiveness in construction of offshore fish farms – assessment of cost and strategic aspects
Ronja Eide Lilienthal	F	Q1–2 2017	Department of Marine Technology, NTNU	Discrete event simulation of a multimodal downstream supply chain for future Norwegian aquaculture
Ragni Rørtveit	F			
Odin Dybsland	M	Q1–2 2017	Department of Marine Technology	*Risikostyringsverktøy for oppdrettsnæringen* (Risk management tool for the aquaculture sector)
Solveig Sæbø	F	Q1–2 2017	Faculty of Science and Technology, UiT	*Integrering av ytre miljørisiko i HMS-arbeidet - En casestudie av et fiskeoppdrettselskap* (Integration of HSE-related external environment risk – case study using an aquaculture company)
David Williams	M	Q3 2016 – Q2 2017	Department of Marine Technology, NTNU	Extreme loads on a feeding barge

Name	Gender (M/F)	Period	Affiliation	Topic
Yuyang Zang	F	Q1–2 2018	Department of Marine Technology, NTNU	Experimental and numerical investigations of global motions and slamming loads on an aquaculture feed barge
Øyvind Haug Lund	M	Q1–2 2018	Department of Marine Technology, NTNU	Evaluation and comparison of operability and operational limits of service vessel designs in exposed aquaculture
Trym Sogge Sjøberg	M			
Gøran Bredahl Woll	M	Q1–2 2018	Department of Technology and Safety, UiT	*Sertifiserer de seg sikrere? – En casestudie av frivillige miljøsertifiseringers innvirkning på sikkerhetsstyringen i oppdrettsnæringen* (Does certification make them safer? – A case study of voluntary environmental certifiers' influence on safety management in the aquaculture sector)
Loenard O. Cheri	M	Q3 2017 – Q1 2018	Department of Physics, UiO	Net-relative localization algorithm for fish cage inspection operation
Erling Nilsen	M	Q3 2017 – Q3 2018	University of Agder	Effect of ploidy on oxygen uptake and swimming performance in the lower end of the thermal niche of Atlantic salmon.
Amalie Almenning Bu	F	Q1–2 2019	Department of Marine Technology, NTNU	AIS-Data for increased insight into navigational impacts post-installation of man-made structures at sea
Katarina Staalesen	F	Q1–2 2019	Department of Marine Technology, NTNU	Exploring the digital twin concept for a rigid aquaculture cage – insight through structural analysis and sensor application
Roald Hartvigsen	M	Q1–2 2019	Department of Marine Technology, NTNU	Inventory management, scheduling and routing in fish feed distribution
Hanne Buan	F	Q1–2 2020	Department of Marine Technology, NTNU	Simulation-based analysis of salmon encounters with delousing operations
Mats W. Langseth	M	Q1–2 2020	Department of Marine Technology, NTNU	Strategic planning in Norwegian aquaculture: A decision-support system for fleet size and mix problems with processing vessels
Carina Nygård	F	Q1–2 2020	Department of Marine Technology, NTNU	An investigation of methods and value of information in routing of priority-based operations – using a rule-based routing method tested with discrete event simulation
Jørn Larsen Ringvall	M	Q1–2 2020	Department of Marine Technology, NTNU	Mobile slaughterhouses at sea – do stun-and-bleed vessels meet Norwegian salmon farming requirements?
Vilde Xiu Drønen	F	Q3 2020 – Q2 2021	Department of Marine Technology, NTNU	Guidance and navigation principles for autonomous ROV missions in an aquaculture context
Henning Ødeby Karlsen	M	Q3 2020 – Q2 2021	Department of Marine Technology, NTNU	Autonomous Aquaculture: Implementation of autonomous mission control for unmanned operations
Kenny Hoang Nguyen	M	Q3 2020 – Q2 2021	Department of Engineering Cybernetics, NTNU	Cybernetics control of unmanned surface and subsea vehicles operating at exposed fish farms in the presence of time-varying environmental disturbances

Name	Gender (M/F)	Period	Affiliation	Topic
Kyrre Haugland	M	Q3 2020 – Q2 2021	Department of Engineering Cybernetics, NTNU	Cybernetics smart and resilient sensor fusion and bathymetric SLAM for future autonomous aquaculture
Esten Solem Dalseg	M	Q3 2020 – Q2 2021	Department of Engineering Cybernetics, NTNU	Smart and resilient visual tracking for future autonomous aquaculture

Figure 6. From EXPOSED Days in April 2019.

STATEMENT OF ACCOUNTS

Name		Funding	Cost
Research Council of Norway	12 676	(55.2%)	-
Host institution (SINTEF Ocean)	1 448	(6.3%)	10 116
Research partners*	2 684	(11.7%)	7 303
Enterprise partners**	6 162	(26.8%)	5 112
Public sector partners	-	-	-
Equipment	-	-	440
Total	**22 970**		**22 970**

(All figures in NOK 1000)

* IMR, SINTEF Digital, NTNU IMT, NTNU IDI, NTNU ITK, *Fiskaaling (Faroe Islands)*

** Mowi, Cermaq, SalMar, Kongsberg Seatex, Kongsberg Maritime Subsea, Kongsberg Maritime, Aqualine (Scale AQ), Møre Maritime, Safetec, Anteo, Argus Remote Systems, AQS, Marine Design, DNV and MacGregor Norway

sfi Centre for Research-based Innovation

The Research Council of Norway

EXPOSED

AQUACULTURE OPERATIONS

CENTRE FOR RESEARCH-BASED INNOVATION

SINTEF Ocean · Mowi · Cermaq Norway · SalMar Farming · Kongsberg Maritime
Kongsberg Seatex · Aqualine · Marine Design · Møre Maritime
Argus Remote Systems · DNV · SINTEF Digital · Institute of Marine Research
Anteo · Norwegian University of Science and Technology · AQS · MacGregor Norway · Safetec Nordic

exposedaquaculture.no